

Master Thesis in Geosciences

Structural Development of the Ypresian – Lutetian Sequence of the northeastern Ainsa Basin, Pyrenees, Spain

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UNIVERSITY OF OSLO

FACULTY OF MATHEMATICS AND NATURAL SCIENCES

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Discipline: Petroleum Geology and Geophysics

Department of Geosciences

Faculty of Mathematics and Natural Sciences

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ABSTRACT

This master thesis involves the geological mapping, correlation and interpretation of the major fold-fault scheme and detail fracture analysis with emphasis on determining the structural evolution of the area highlighting the development of palaeo-stress fields under which these structures were generated. The structural evolution of the study area is viewed in perspective of the deformation related to the frontal part of the south central Pyrenean thrust and fold system. The study includes field mapping of folds, faults and fracture populations and statistical analysis of fractures.

Preface

This thesis has been carried out at the department of Geosciences, Petroleum Geology and Geophysics section, University of Oslo under the supervision of Professor Roy H. Gabrielsen. I am greatly indebted to him not only for his invaluable suggestions, but also for his encouragements. I owe special appreciation to Professor Johan Petter Nystuen, my co-supervisor, for his constant guidance especially during field work phase of this thesis.

I wish to acknowledge with great thanks, Hydro now, StatoilHydro for its pertinent role in financing this project.

My gratitude also goes to my thesis project fellow Erlend J. Morisbak for sharing ideas and for his support accorded me during this work. I also do acknowledge the excellent cooperation I enjoyed among the staff and students of the department of Geosciences, especially Asfaw T. Woyesa, Burca Florin, Williams E., Raja Usman, Sultan Iftikhar, Simonsen Theresa and Islam Tanjina.

I am extremely grateful to my family Celina Achere Awoh, Ojong Gilbert Jr. and Ojong Solange, my sisters Ako Comfort and Ako Cecilia and my friends John Mbeng Ako and Nkengasu William O. for their encouragement throughout my educational career.

Finally, I would like to give thanks to the Almighty God for his mercy, love and guidance.

Ako, Ojong Gilbert

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Chapter 1 Introduction

In the study of hydrocarbon reservoirs, it is very important to take into account the general structuring of the study area in perspective of folds and faults because such structures contribute in the definition of hydrocarbon traps and its geometry. Furthermore, smaller structures (like fracture systems) are also important because within exploration targets in prospective sedimentary basins they would enhance or destroy their potential. Fracture systems are a major source of fluid flow capacity in low permeability reservoirs. The Tertiary sedimentary successions within the Pyrenean foreland basins are acknowledged in petroleum exploration as challenging deep water analogs for hydrocarbon exploration and relationship between sedimentation and tectonics. Tectonics has influenced base level fluctuations culminating in variation in sedimentary facies and structural style within the Pyrenean foreland basin. The Pyrenees became an area of foreland sedimentary outbuilding from the upper Cretaceous to Tertiary (Cenomanian to Oligocene) following the collision of the Iberian and the Eurasian plates. The sedimentary succession of the South Central Unit of the Pyrenees is considered to be driven southwards by an advancing thrust sheet which was consequently compartmentalized or evolved to piggy-back basins. A dynamic system involving a complex interplay between a variety of controlling factors such as uplift and subsidence, climate, sediment supply from different source points, sediment transport mechanism and synsedimentary tectonics can account for the development of such a diverse and large scale sedimentary architecture and structural style as seen in the Ainsa basin and related foreland basins. The study area is located in a foreland basin where different structural processes may have been active before, during and after lithification. Tectonic processes which may be active during the structural development of the basin probably include syn-sedimentary and thrust deformations.

The study area is located in the eastern part of the Ainsa basin (Fig.1.1). Widespread evidence of tectonics is preserved in the sediment within this area and their recognition is crucial in this study. Within the Ainsa basin the two areas under focus are the Ainsa Quarry (UTM; 65340E/98819N) and *Los Comunes* area (UTM; 274789E/4697808N to 274808E/44697780N). *The Ainsa Quarry*, is located south of Ainsa, it consists of Eocene turbidites (mainly sandstone units alternating with mud). Within the quarry, focus was made on the measurement of fractures. The field work in the Ainsa Quarry is joint work. The measurement of joints found in the Ainsa Quarry was carried out together with Erlend Morisbak. *Los Comunes* is made up of a succession of slope mud intercalated with thin bedded sandstones overlain by shallow marine mixed carbonates-siliclastics of Eocene age and affected by macro-scale folds and faults and a number of associated secondary structures that together constitute the main focus in this study.

1.1 Field Work

The field study was carried out under the supervision of Professor Roy H. Gabrielsen and Professor Johan Petter Nystuen. Professor Cai Puigdefabregas was very useful in briefing us on the geological processes in strategic locations within the Ainsa basin apart from being our field guide for the first two days of field studies. The regional outline of the study area is to a large extent based on his reports. This work was supported by Norsk Hydro now StatoilHydro. While in Ainsa, excellent accommodation including an office at Appolo Hotel was at our disposal. Daily transportation to the field and back was complimented by hired cars. The field work was carried out in the period of July 9 to August 5, 2007.

1.2 Aim

The aim of these studies is to present a master thesis to the University of Oslo (Petroleum Geology and Geophysics section) in structural geology.

The objective is to study the structural development of the Ypresian-Lutetian sequences of the NE, central, Ainsa Basin. The work has been to analyze the structural development of the frontal part of the central Pyrenees.

This work has been carried out from the following approach,

- 1) *Regional scale mapping of the folds and faults was achieved by careful study of satellite images and aerial photographs.*
- 2) *In a sub-regional context, mapping of folds and faults was performed by measurement of the planar surfaces such as fold axes, inclined beds, lineation and deformation lenses from outcrops.*
- 3) *Analysis of secondary structures such as parasitic folds was also made in order to determine the style of deformation of the rocks.*
- 4) *Detail analysis of fractures systems within individual beds was carried out.*

The conditions leading to the formation of the individual structures may be linked to the major structure. By combining these data one hopes to infer the paleo-stress fields, and relate this to the impact on the reservoir quality and communication of the rocks in the study area.

1.3 Equipment and infrastructure

Mapping of the area was carried out by use of the following instruments:

- Sighting compass (Silva Rangers15) and clinometer (Silva type 15TD-CL)
- Magiland GPS.
- The Winfull Stereo net was freely used plot structural data such as the planes, poles and direction roses for the fractures and to determine the fold axes (developed by Allmendinger, at <http://www.cornell.edu/geology/faculty/RWA/>)
- Measuring tape was an indispensable tool used for fracture frequency measurements.
- Topographic maps of scale 1:25000, aerial photographs and satellite images (from Google earth) have been used
- The Excel was used for fracture frequency analysis
- Adobe Illustrator has been used to construct the geological maps and cross sections
- Digital camera

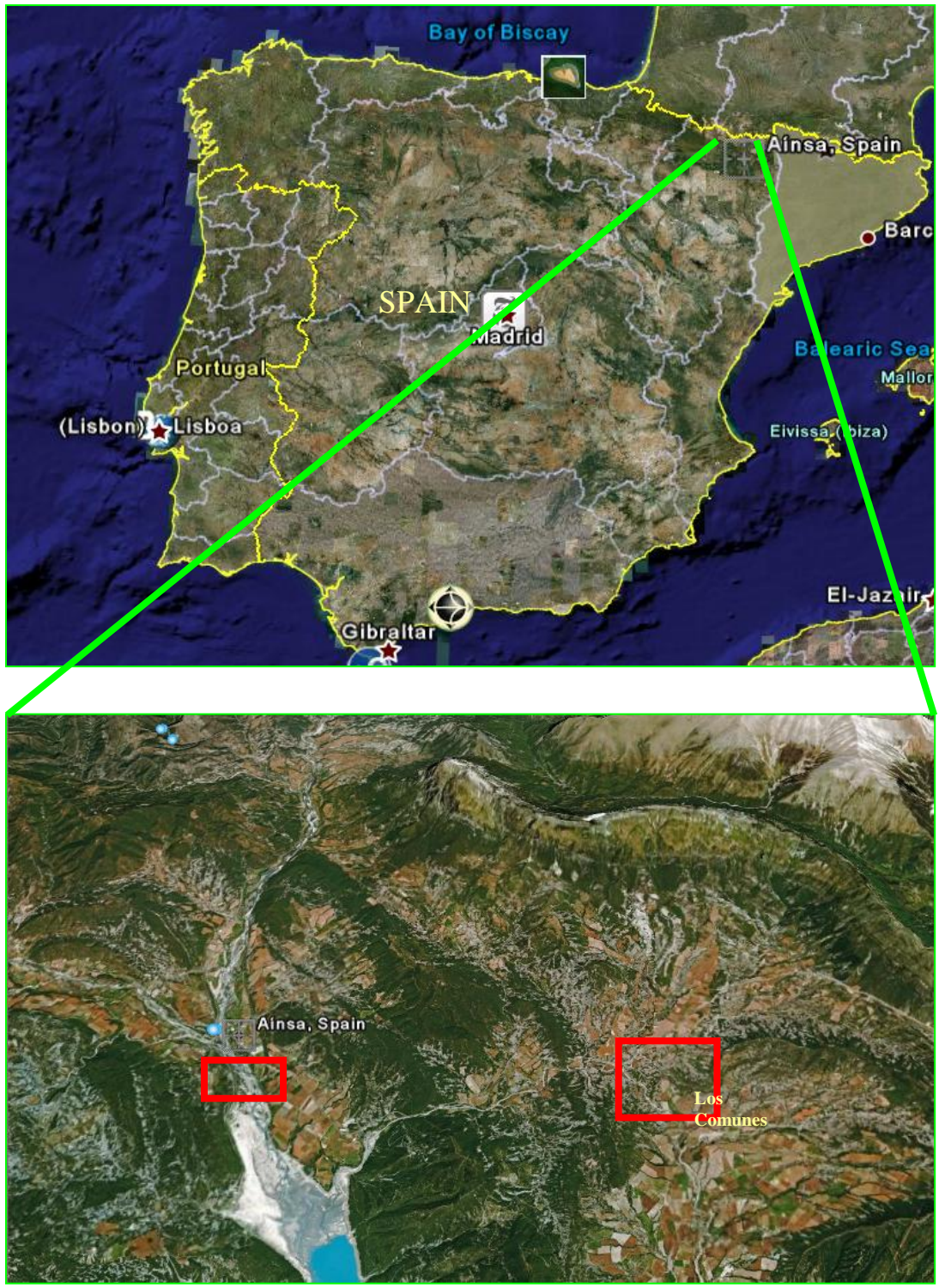


FIGURE 1.1 Regional setting and location of the study area, Ainsa basin, (Red rectangles) in the South Central Pyrenees (Google Earth)

1.4 Geological concepts and terminology

1.4.1 Introduction

The Ainsa basin is within a thrust and fold belt and has been more or less affected by tectonism. The main structural geological concepts which are defined below, have been applied in the context of the study area and will be met in most of the chapters of this work. A full account of the thrust tectonic terminology is not within the scope of this work, therefore only a few with relevance to this study have been presented, mostly drawn from the works of McClay (1992), Davis and Reynolds (1996) and Van Der Pluijm and Marshak (2004)

1.4.2 Fold-fault relation

Anatomy of folded surfaces

Inflection points; This is the point in a fold limb where the sense of curvature changes. The *hinge* of a folded surface may be a single point known as the hinge point. On the contrary the *hinge zone (hinge area)* is distinguished by the maximum curvature achieved along the folded surface; the midpoint of a hinge zone is the *hinge point*. The distance between the two hinges of the same orientation is referred to as the *wavelength* (Fig. 1.2). The *amplitude* of a fold is half the height of the structure measured from crest to trough (Davis and Reynolds, 1996; Van Der Pluijm And Marshak, 2004)

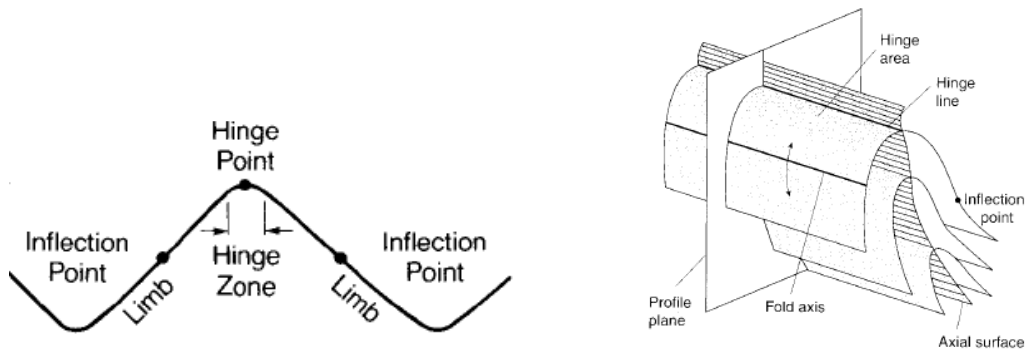


FIGURE 1.2 Geometric and physical elements of fold surface (Davis and Reynolds, 1996; Van Der Pluijm And Marshak, 2004)

Synform and antiform

A fold is said to be overturned if at least one of its limbs or flanks is overturned. These imply that the fold limb has been rotated beyond vertical such that the facing direction of the limb points downwards at some angle. The term anticline /syncline indicate that stratigraphic succession within the folded sequence has been determined on the basis of the conventional geological column. In an anticline, the beds young away from the core and in a syncline, the reverse is true.(These are upward facing folds). In the case the original sequence is turned upside down,(downward ward facing folds), the antiform and synform respectively, will have the younging characteristics of a syncline and an anticline. They are therefore commonly referred to as antiformal syncline and synformal anticline respectively (Fig. 1.3; Van Der Pluijm And Marshak, 2004). In the case whereby facing and stratigraphic order cannot be determined, the terms anticline or syncline must have to be wiped at least temporarily in favour of antiform or synform (Davis and Reynolds, 1996). Therefore this terms are normally used to refer to folds in sedimentary or volcanic sequences in which there is uncertainty in the facing or / and stratigraphic order.

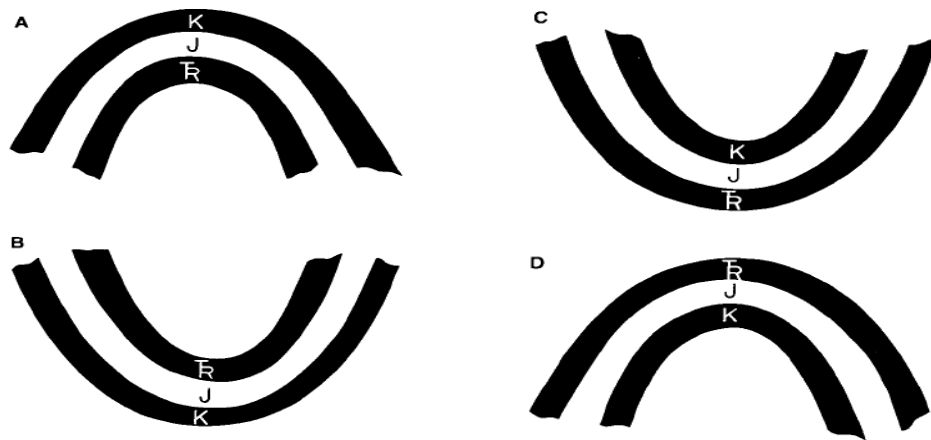


FIGURE 1.3 Folds. Anticline (A) Synclinal anticline (B) Syncline (C) Antiformal syncline (D). TR= Triassic (oldest layer) J= Jurassic (in-between) K= Cretaceous (youngest layer) (Davis and Reynolds, 1996).

Detachment folds – these folds developed within fold-thrust belts above a detachment fault even if no ramp develops (Fig.1.3a). This results when the strata above a detachment buckle. Detachment folds are particularly common in belts where detachment faults lie within thick shales or salt layers. In some cases during the late stage of the fold evolution a break thrust may develop when a fault cuts across the forelimb of the initially formed detachment fold. (Van Der Pluijm And Marshak, 2004)

Fault-propagation folds - these are fault-related folds in which the advancing thrust fault loses slip and terminates up-section by transferring its shortening to a fold developing at its tip. This is simply a transfer of fault related shortening to fold related shortening. These structures have been recognized and interpreted in a number of fold and thrust belts. (Fig.1.4b; Mitra and Fisher, 1992).

Fault-bent folds – these are fold types, characterized by staircase geometry (Fig.1.4c) They are formed when beds are displaced along thrust-faults comprising ramp flat geometries. Fault-bent fold type represents a predominant regional tectonic folding mechanism in thin-skinned thrust and fold belts in foreland settings (Davis and Reynolds, 1996).

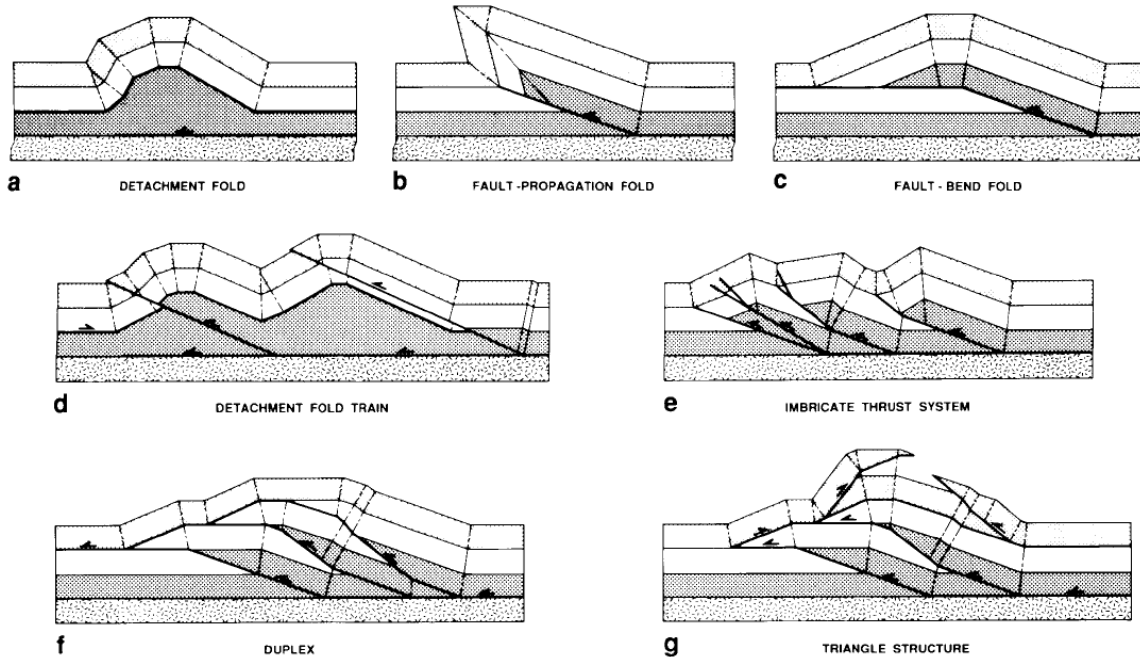


FIGURE 1.4 Common compressional structures of fold and thrust belts. (a) Detachment fold (b) Fault-propagation fold (c) Fault-bent fold.(d) Detachment fold train with small forelimb and back limb thrust (e) Imbricate thrust system made up of a system of fault-propagation folds (f) Duplex made up of a sequence of Fault-bent fold (g) Triangular structure made up of opposite-dipping fault-bent folds.(Mitra & Fisher,1992)

Fold nappe: This is generated by a large recumbent over fold in which the lower limb is much attenuated. Large recumbent folds are common in thrust and fold belt and are formed when plastically deformed deep seated rocks are move upwards and towards the foreland. Thrust nappes commonly comprise of thrust sheet with significant displacement and may be generated from a recumbent fold in which the lower limb has been faulted to constitute the sole thrust of the nappe (Fig.1.5; Van Der PLuijm and Marshak, 2004; McClay, 1992)

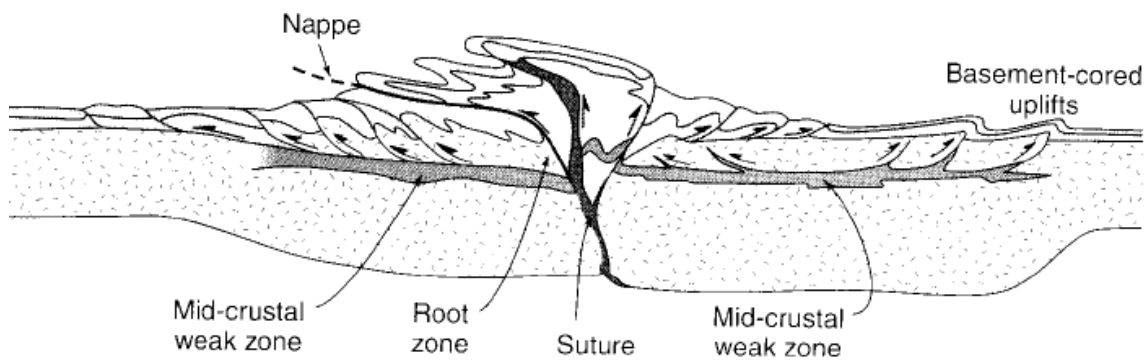


FIGURE 1.5 Cross section of collision orogen showing the geometry of a fold nappe (Van Der PLuijm And Marshak, 2004; McClay, 1992).

Criteria for identifying sense of slip on a fault surface

Three main criteria are commonly used to identify the sense of fault slip. (1) stratigraphic offset or the separation of various markers predicting fault motion (2) the use of drag (parasitic) folds near a fault surface is easy (3) There are nine criteria in use based on the striations on the fault surface. A ‘Positive’ criterion indicates that when an observers hand moves in the same sense as did the lacking fault side, there is the easiest motion. On the contrary, in a ‘negative’ criterion, the friction felt will be greater (Fig. 1.6; Hancock, 1994).

Accretionary mineral steps; these are formed as a result of fibrous minerals developing along slickenside lineations generate steps that indicate the sense of motion. This criterion is ‘positive and 100% reliable. Others with same magnitude of reliability are;

Tectonic tool marks and Stylolitic peaks. Others of decreasing reliability are: Polish and rough facet, a 'positive' criterion and 80% reliable; riedel shears a 'negative' criterion and 75% reliable; tension gashes and conjugate shear fractures are 'negative' criteria and 70% reliable (Fig1.6).

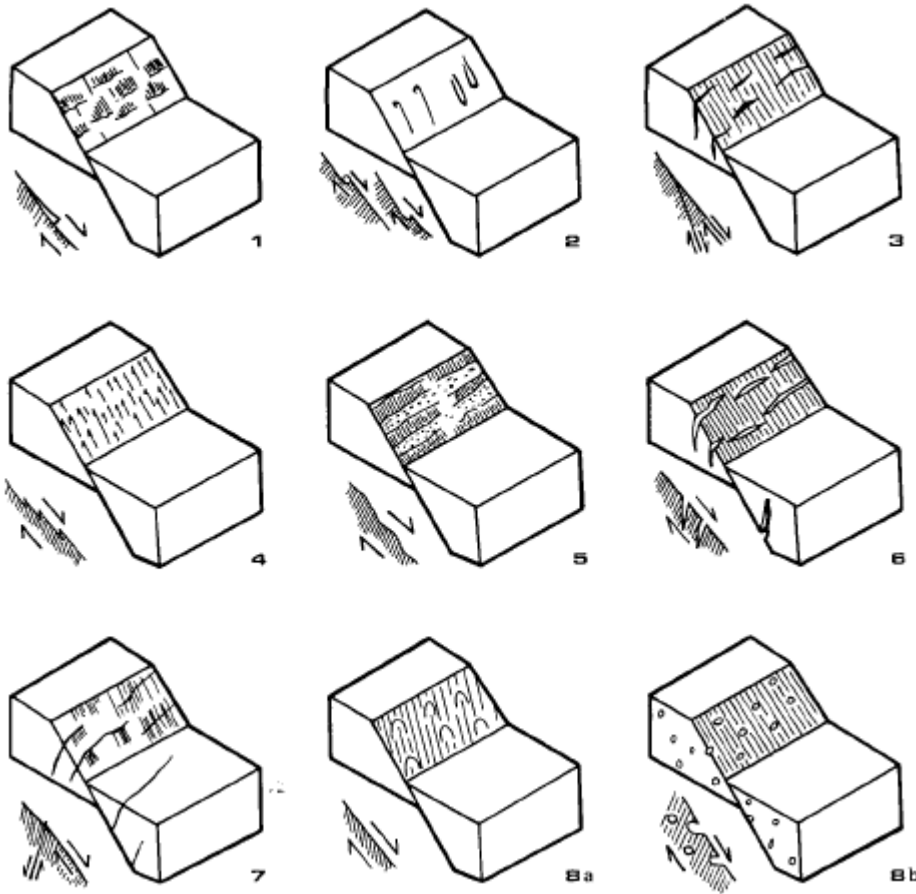


FIGURE 1.6 Criteria determining the sense of slip on fault surfaces. The criteria shown above do not discriminate fault slip orientation. (1) Mineral steps (2) Tectonic tool marks (3) Riedel shears (4) Stylolitic peaks (5) Alternating polished (crushed or striated) and rough facet (5) Tension gashes (7) Conjugate shear fractures (8) Miscellaneous criteria: (8a) parabolic marks and (8b) deformed bubbles in lava (Hancock, 1994).

1.4.3 Joint terminology

Modes of crack surface displacement

The three modes of crack displacement: *Mode I* fractures are tensile and form perpendicular to σ_3 direction (Figs.1.7 and 1.8) and can grow in their plane without altering orientation. The *Mode II* fractures are shear fractures whereby slight movement on one side of the rock is parallel to the fracture surface and perpendicular to the fracture front. In *mode III* (*shear fracture*) rock mass on one side of the fracture moves very slightly parallel to the crack in the direction parallel to the fracture front (Figs.1.7 and 1.8).

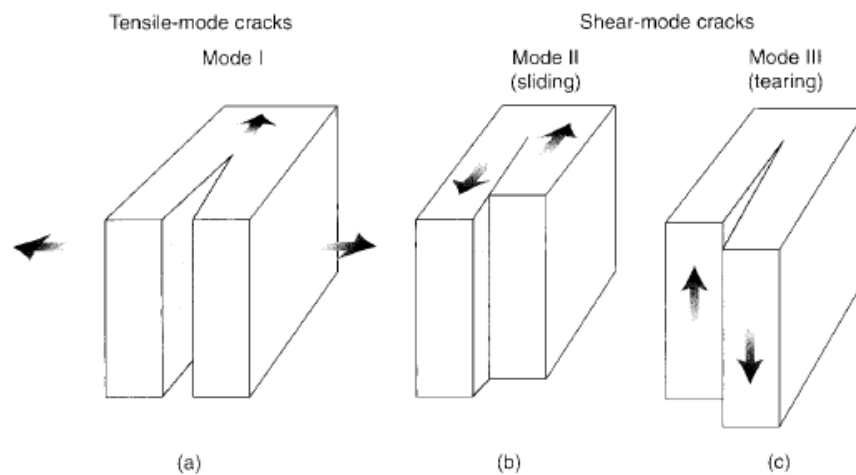


FIGURE 1.7 Block diagram illustrating the three modes of crack surface displacement A) Mode I b) Mode II c) Mode III. Mode I is tensile crack Mode II and III are shear mode cracks (Van Der Pluijm and Marshak, 2004).

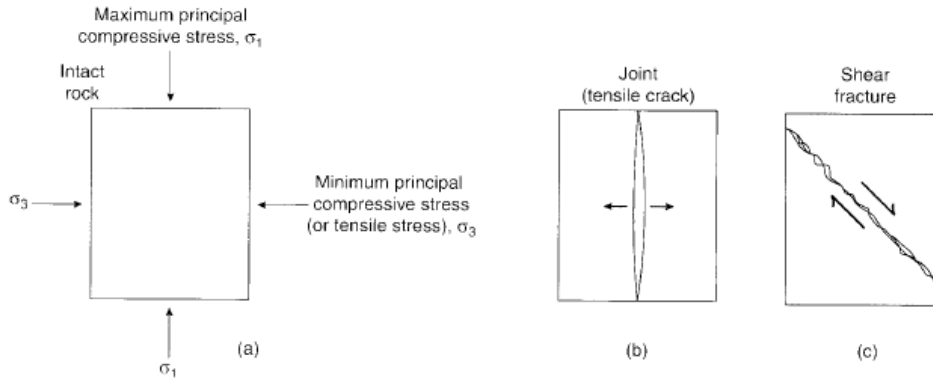


FIGURE 1.8 A) Orientation of remote stress direction with respect to an intact rock body B) A tensile crack forming parallel to σ_1 and perpendicular to σ_3 (which may be tensile) C) A shear fracture forming an angle of about 30° to σ_1 direction

Age relation of joints

The relative ages of neighboring joints can be determined by applying these three methods: (a) In the situation where there is offset of a joint across a fault, vein or stylolite the joint predate these structures. (b) The trace of a younger joint normally abuts that of an older joint. This is the case when a joint propagating through intact rocks intersects an unsealed crack and is incapable to jump the gap (c) In a situation where short traces of small sealed joint are cut by the long traces of large joints, the former are older structures. (d) Two cross cutting joints of unknown age relation occur when one of them was sealed at the time of propagation of the other across (Fig.1.9; Hancock 1994)

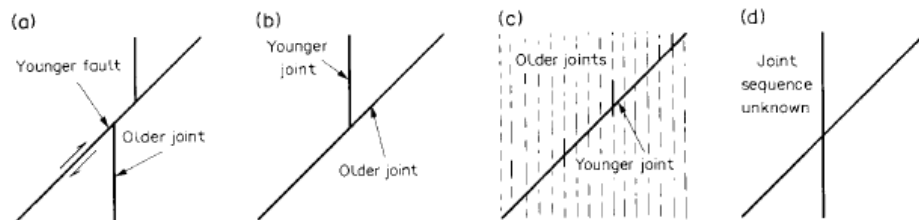


FIGURE 1.9 a) older joint set offset by a younger joint b) a younger joint trace abutting an older joint trace c) Short traces of older sealed joints, cut by a long trace of the younger one. d) Crossing traces of joints of non-determinable age relationship (Hancock 1994)

Relation of joints to folds

There is a common geometrical link between the folded layers and the joints within them.

Figure 1.10 shows the three classes of joints which can be distinguished as follows;

Cross joints are mode I fractures which are usually aligned perpendicular the fold axis.

Longitudinal joints are mode I joints usually oriented parallel to the folds axial surface.

Oblique joints essentially comprise of two conjugate sets of shear joints which may be mode II or III (Davis and Reynolds 1996)

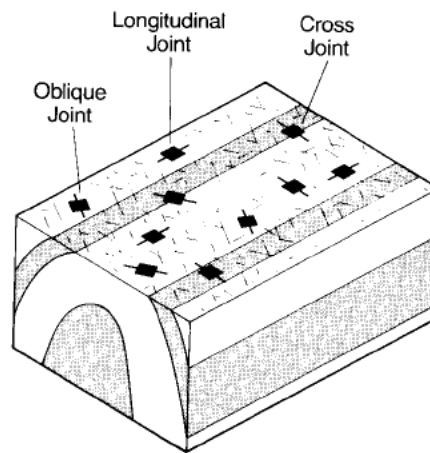


FIGURE 1.10 Relation of joints to folds. Oblique joints, Longitudinal joints and joints are highlighted (Davis and Reynolds 1996)

1.4.4 Thrust terminology

RAMPS and FLATS

Hanging-wall and foot-wall ramps, cut across the beds of the foot wall and hanging wall respectively. Hanging-wall and foot-wall flats lie parallel to bedding in the hanging wall and foot wall respectively.

A *frontal ramp* is a ramp segment that strikes approximately perpendicular to the transport direction of the thrust sheet. A *lateral ramp* is a ramp segment which is approximately parallel to the direction of transport of the thrust sheet. An *oblique ramp* is the ramp segment that strikes at an acute angle to the transport direction of the thrust sheet. Frontal ramp, lateral ramp and oblique ramp folds are folds formed by translation of the thrust sheet over frontal ramp, lateral ramp and oblique ramp respectively (Fig.1.11).

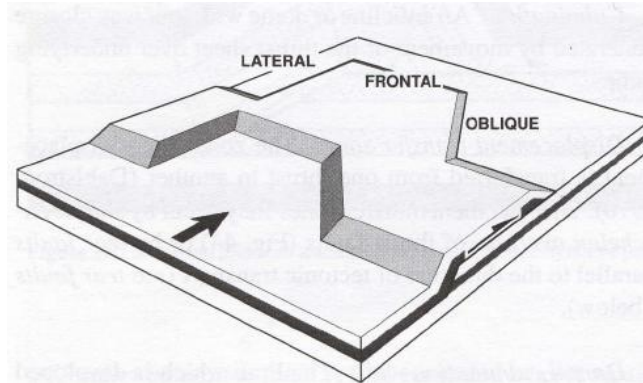


FIGURE 1.11 Ramp related folds in the hanging wall system of thrusts (McClay, 1992).

An *imbricate thrust* is any thrust fault that has an echelon arrangement when viewed in cross-section.

Duplexes are thrust systems consisting of a floor thrust, a roof thrust and two or more horses (imbricates) linking these two thrusts. They are commonly formed by the superposition of fault-bent folds (Fig.1.12; Mitra and Fisher, 1992).

Horses are the individual thrust-bounded slices in a duplex.

Antiformal stack A duplex formed by overlapping ramp anticlines with the individual horses stacked on top of each other, resulting in an antiform.

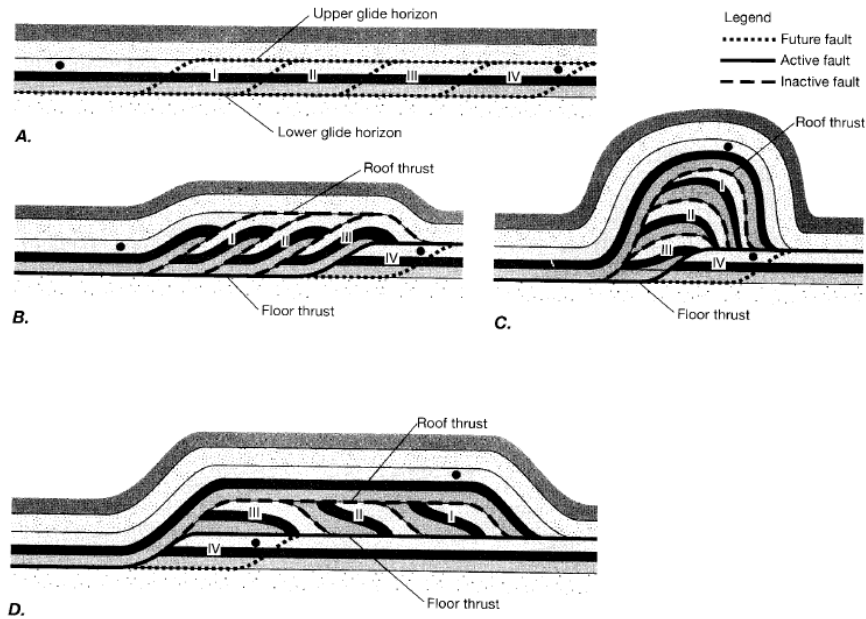


FIGURE 1.12 Geometry of duplex structures generated from the progressive cutting of the thrust fault into the footwall block A=undeformed rock section B= hinterland dipping duplex C= antiformal starck D=foreland dipping duplex.(Moores and Twiss, 1995)

Basin inversion

This encompasses a switch in tectonic mode within a basin from extension to compression. As a consequence, extensional basins are contracted and become regions of positive structural relief. It is generally accepted that inversion tectonics involves the reactivation of pre-existing extensional faults to an extent that they undergo reverse slip and may eventually become thrust faults (Fig.1.13; McClay, 1992)

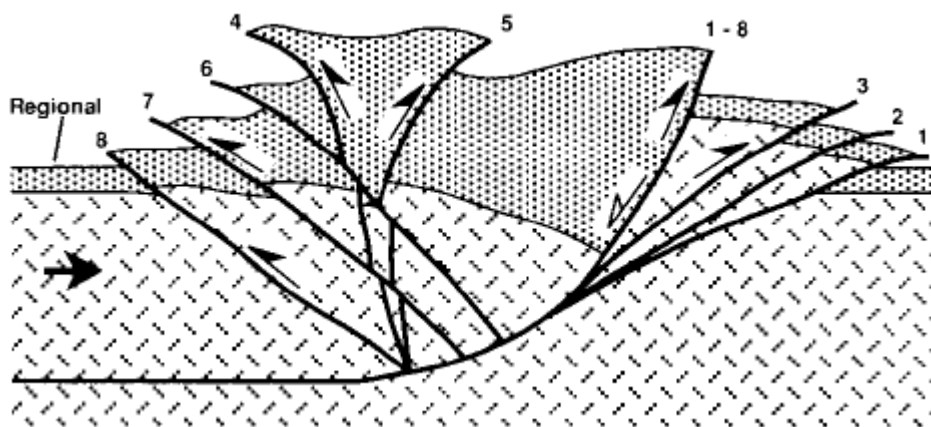


FIGURE 1.13 Tectonic inversion model showing thrust faulting developed in an inverted listric extensional fault system (McClay, 1992).

Chapter 2 Relevant literature review

Several workers have studied the tectonic evolution and geometry of the Pyrenean thrust and fold belt.

An outline of the Ebro basin with the first relationships between tectonics and sedimentation was given by Riba (1976). He also proposed a kinematics model for the unconformities in the northern margin of the Ebro basin and correlated this with the different stages of synchronous emplacement of the Pyrenean thrust system.

The geometry and the infill history of the southern Pyrenean foreland basin has been analyzed by Puigdefabregas et al (1992) who concluded that it has initiated as a response on the tectonic subsidence related to the flexure of the foreland. They identified four main stages in the evolution of the southern Pyrenean foreland basin and ascribe their presence to the stages of structural evolution of the mountain chain.

Munoz (1992) constructed balanced cross-sections, for the Pyrenean based on the deep seismic data furnished by the ECORS deep seismic profile. This work serves to constrain the geometry and the amount of contraction across the Pyrenean thrust system. Also it provides further insight in the tectonic evolution of the Pyrenean mountain chain.

Dreyer et. al. (1999) described the syntectonic sedimentation within the South Central Pyrenees. They focused on the Sobrabe delta complex of the Eocene Ainsa Basin and noted that the Sobrabe delta complex is confined by lateral thrust ramps and also influenced by intrabasinal growth anticlines. Six facies regimes were identified in the delta complex and a number of composite sequences and the segmented nature of the regressive unconformities led them to infer incremental growth of thrust-related structures. Beaumont *et. al.* (2000) described how integration of geodynamical numerical modeling with crustal structural restoration of the central Pyrenees is used to modify the amount of contraction in the central Pyrenees. The geometry of the four turbidite systems outcropping around the Buil syncline or Ainsa basin has been reconstructed with reservoir-scale resolution in 3-D by Fernandez et al (2004). The reconstruction has been effected by use of a new methodology that utilizes 3-D dip domain geometrical model and 3-D restoration techniques.

Chapter 3 Regional setting

3.1 Plate Tectonic Configuration

The Pyrenees is located between the north eastern part of the Iberia plate (or Spain) and the southern part of Eurasian plate (or France) (Fig. 3.5). It is a typical example of a fold and thrust belt which was formed as a consequence of contraction between two colliding continental plates (Fig. 3.4 Iberia and Eurasia). This event resulted in the formation of an orogen which in this case consists of fold and thrust belts, foreland and piggy – back basins (Figs.3.2 and 3.3). Interplay between sedimentation and tectonics govern the formation of these units. This occurred when the oceanic basin completely closes with the complete elimination of the oceanic crust by subduction and subsequent collision of the plates (Fig.3.1). Thrust propagates into the well stratified beds of the down-going plate as contraction continuous. This regional horizontal tectonic shortening of the upper crust (cover structure) yields a characteristic suits of thrust faults, folds and associated minor structures referred to as *FOLD-and-TRUST belt* and with time, this grows towards the foreland. The edge of the continent with the stack of thrust slices yields by forming a gap or depression between the main orogenic belt and the undeformed continental platform. This depression when filled with continental clastics derived from rising hinterland becomes a *foreland sedimentary basin*. The earlier basin deposits may latter be compartmentalized by thrusting into piggy-basins (Ori and Friend, 1984).

The main Alpine deformation began in the Upper Cretaceous/Lower Eocene and continued until the Miocene as a result of N-S directional shortening and subduction of Iberian plate beneath Eurasia (Fig.3.4). The movement saw the Iberian Plate colliding with Eurasian plate, and rotating (anti-clockwise) up to 30 degrees relative to it, during the opening of the Bay of Biscay (Fig.3.1).

Pyrenean deformation is superimposed on an older (Hercynian) tectonometamorphic event that was followed by magmatism. Post-Hercynian comprises localised Upper Cretaceous, followed by Permo-Triassic, Jurassic, Cretaceous and Tertiary sediments. The path of the Iberian plate shows lateral motion relative to the African and Eurasia during most of the Mesozoic time (Fig.3.1). These lateral motions therefore have produced the appropriate conditions for a transtensional and extensional tectonic setting, under which the main Mesozoic sedimentary basins generated(Fig.3.2). During the Late Cretaceous (84Ma), the motion of this plate changed to a convergent regime. This marks the beginning of subduction of both the north and the south boundaries of the Iberian plate. The result is the propagation of the inversion and contraction of the Mesozoic basins and the rise of the Alpine ranges of which the Pyrenees is an important element (Fig.3.5). The ECORS-Pyrenees profile shows that the Iberian plate is subducted beneath the Eurasian one (Fig.3.4; Munoz, 1992).



FIGURE 3.1 Reconstruction of Iberian plate motion from Late Jurassic to Oligocene (Ramon *et. al.* 2002).

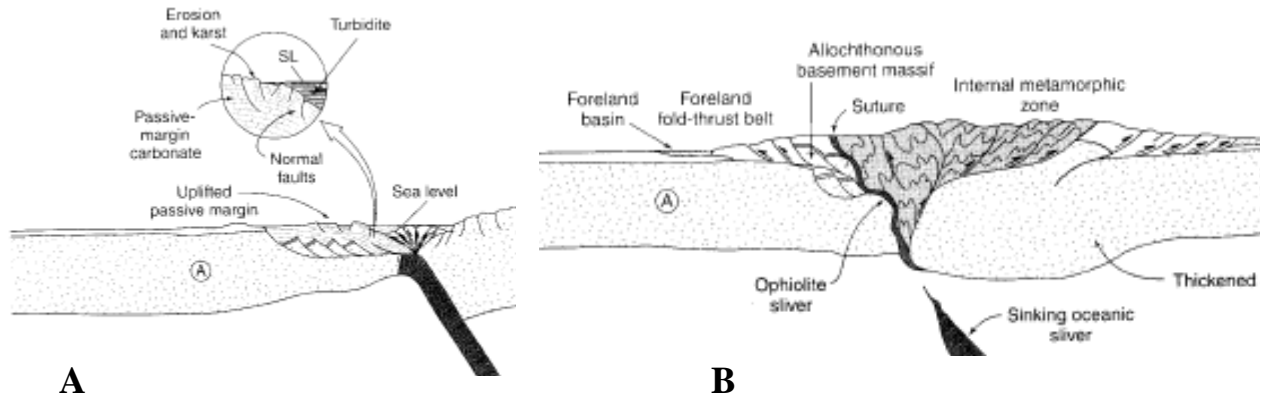


FIGURE 3.2 Plate tectonic configuration during the formation of inversion and foreland basins due to convergence continental plates. **A**= before inversion and formation of foreland basins. **B**= after inversion and formation of foreland basins. (Van Der Pluijm and Marshak, 2003)

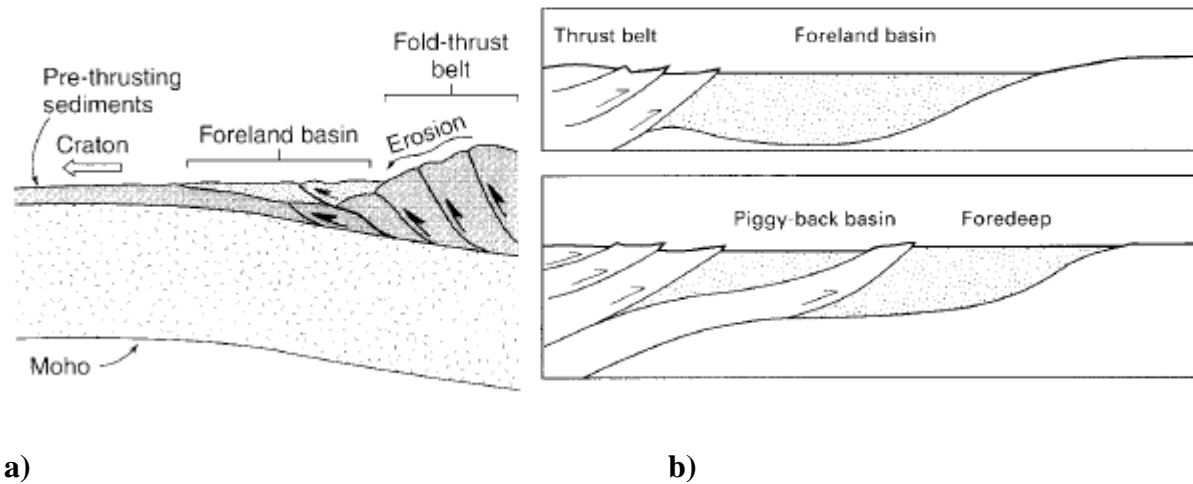


FIGURE 3.3 From foreland to piggy back basins. Section showing how thrust slices produces a depression at the edge of the continent which later fills with sediment eroded from the hinterland and becomes a foreland basin (a) and the evolution of the foreland basin to piggy-back basin(b) (Van Der Pluijm And Marshak, 2003)

3.2 Regional geological setting of the Pyrenees

3.2.1 ECORS-Balanced and restored cross-sections for the Pyrenees

A set of balanced and restored geological crustal cross-sections across the Southern side of the Pyrenees depicts the cover structure restored by integration of geological and geophysical data (Fig.3.4). The ECORS cross-section has been restored using line length balancing techniques for the cover upper thrust sheets and for the basement units including an attached lower Triassic and Permian series. The trace of the ECORS seismic line coincides reasonably well with the regional transport direction as deduced for the cover thrust sheets which is consistently N-S to NNE-SSW in the most part of the tectonic evolution (Munoz, 1992; Dinares *et al.* 1992). These directions applies for the frontal, lateral and oblique structures found within the cover south Pyrenean thrust sheets as deduced by cartographic pattern, kinematics criteria along the thrust planes and the absence of large rotation around a vertical axis in the central Pyrenees. This imply a near normal convergence during the major orogenic phase (Dinares *et al.* 1992). According to Munoz (1992), a geometrical solution of a crustal cross-section of the Pyrenees along the ECORS transect gave a total shortening of 145 km. However, Beaumont *et al.* (2000) pointed that this value increases to 165 km, if the internal deformation of the crust below the sole thrust of the Pyrenean thrust system is restored. Recent study of the kinematics of the Iberian plate has indicated that the amount of shortening in the central Pyrenees cannot be less than 150 km. However, proposed models for the reconstruction of the Iberian plate and cross-section indicate that shortening decreases westwards, of the ECORS transect, down to 100 km (Olivet, 1996). A mean shortening rate of 2.5 mm/year for the central Pyrenees have been deduced from an estimated duration of convergence of approximately 60 Ma (Ramon *et al.* 2002). The restored cross-sections have conserved pre-collisional geometry of the crust which present listric configuration over the lower layered crust.

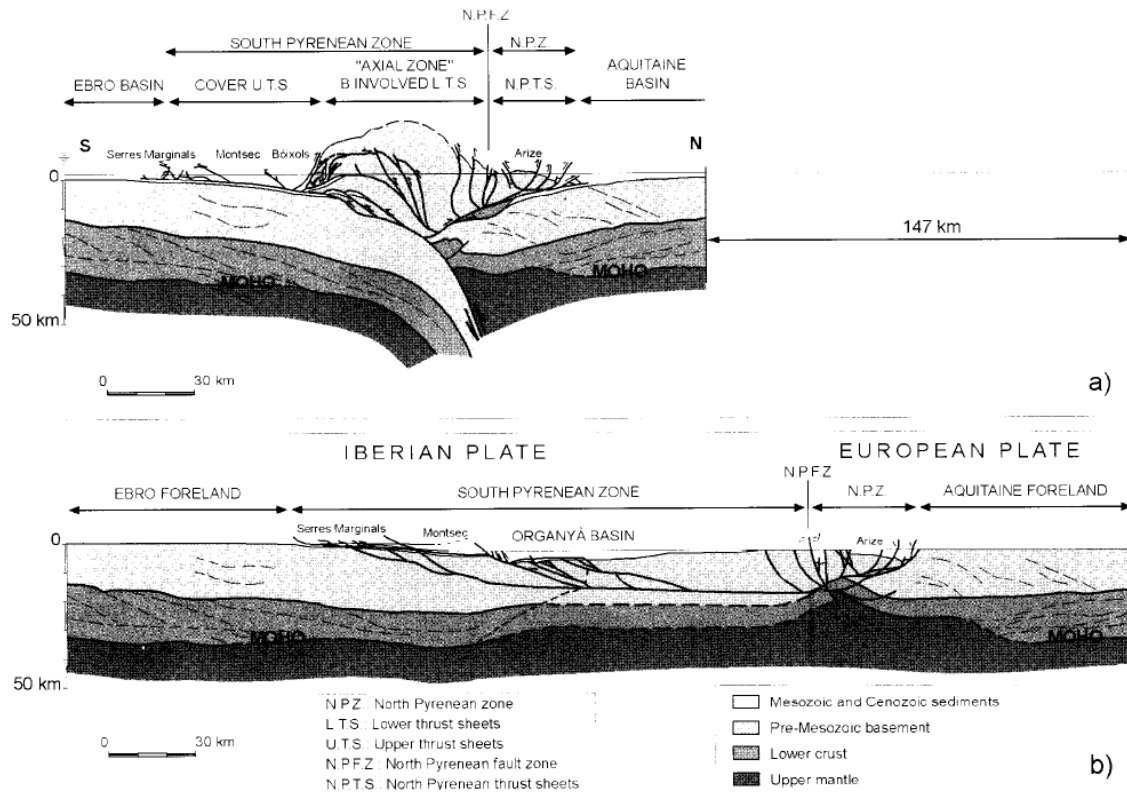


FIGURE 3.4 Evolution of a continental collision belt. ECORS crustal cross section showing the subduction of the Iberian plate beneath the Eurasian plate and the resulting amount of shortening in the present (above). Balanced and restored cross-section showing the stage prior to convergence of the Iberia and Eurasia in the Cenomanian (below). Note the final amount of shortening and the locations of Sierras Marginales (SM), Montsec and Boixols, within the southern Pyrenees (Munoz , 1992).

The location of these discontinuities favored the delamination of the crust, with the upper part forming an orogenic double wedge, shortened by an upper crustal thrust system. According to Beaumont et. al. (2000), major part of the upper crustal mass that entered the orogen through the calculated extent of convergence was accommodated by an

increase in the upper crustal cross sectional area or lost by denudation. The crust beneath this middle crustal detachment was then subducted beneath Eurasia.

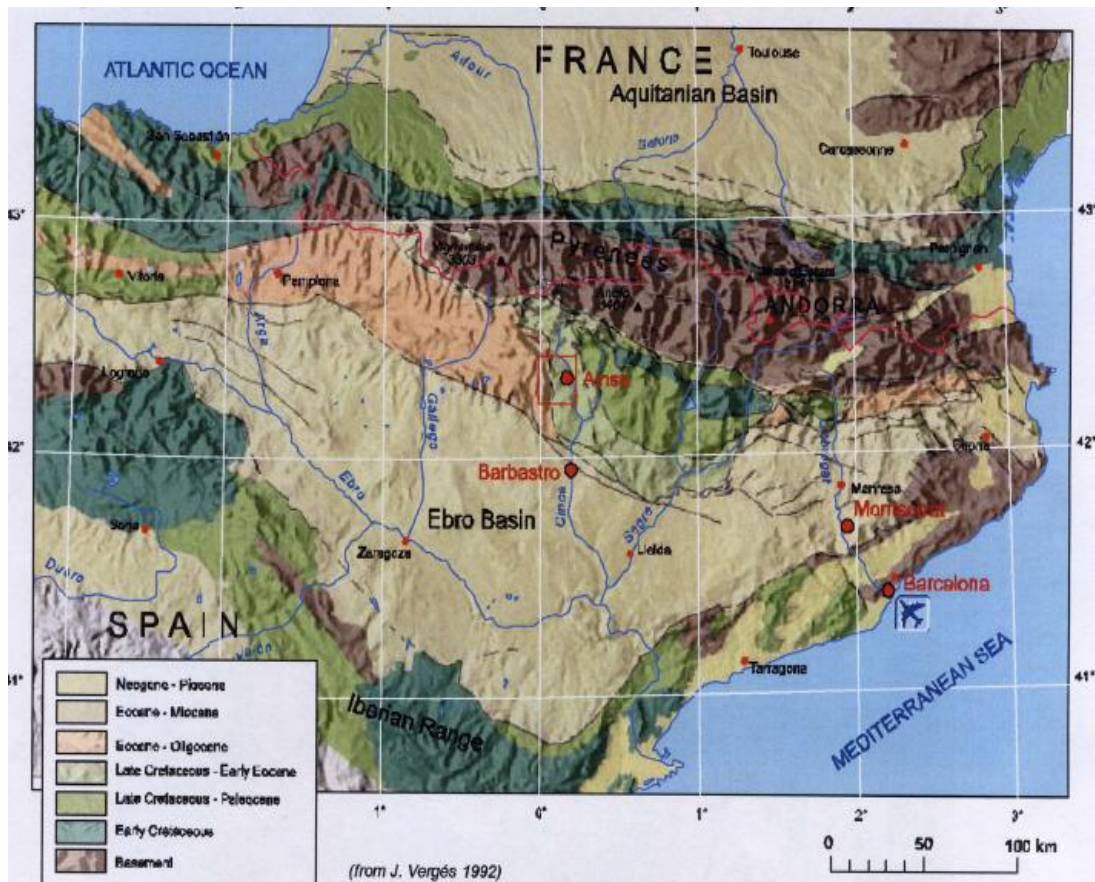


FIGURE 3.5 Regional setting of the Pyrenee and location of the study area, Ainsa basin, (Red rectangle) in the South Central Pyrenees (Vergés 1992)

3.3 Thrusting and foreland basin development

According to Puigdefabregas *et al.* (1992) the development of a thrust system in a mountain belt occurs synchronously with accumulation of sediments in the related foreland basins. The alpine age collision that range from Upper cretaceous to Miocene times developed two foreland basins. The northern foreland or Aquitanian basin mainly developed in the footwall of the northern Pyrenean frontal thrust and was not greatly involved in the north Pyrenean thrust system (Ramon *et al.* 2002). The south Pyrenean

foreland basin is an excellent case to illustrate the interplay between tectonics and sedimentation because the erosional levels are shallow such that the relationships between thrusts and their related deposits are remarkably exposed. The related thrust system includes a basement-involved antiformal stack sandwiched by cover imbricated thrust system (Munoz, 1992). Thrusts within the central antiformal stack are south directed. This south imbricated system involves more shortening when compared to the northern one. The floor thrust of the southern thrust system coincides with the sole thrust of the Pyrenean chain. This indicates that the Iberian central and east Pyrenees, has been subducted to the north below Eurasia (Puigdefabregas et. al.1992). The south Pyrenean foreland basin is wider and has a thicker complex succession than the Aquitanian basin (Ramon *et. al.* 2002). The south Pyrenean foreland basin has a triangular outline and is located south of the Pyrenees with a large portion of its area representing the latest stage of the basin fill southwards from the south Pyrenean frontal thrust (Ebro foreland basin). The earlier stages of the thrust system involve basin partitioning and the development of piggy-back basins (Ori and Friend 1984; Ramon *et. al.* 2002).

The Pyrenean foreland basin is characterized by the preservation of the synorogenic strata that closely constrain several stages of its evolution. Puigdefabregas *et. al.* (1992) has characterized four distinct stages involved in the structural evolution of the south Pyrenean foreland basin. These stages can be linked to the structural evolution of the crust as deduced from the crustal partial restored cross-sections made for the central Pyrenees. Deformation within the southern Pyrenees migrated southwards.

3.3.1 Upper Santonian to Maastrichtian development (Stage 1)

Before the onset of the Pyrenean collision the Early Cretaceous extensional system developed (Puigdefabregas and Souquet 1986). After the Lower Cretaceous rifting, Late Cenomanian transgression, started as recorded in the central Pyrenees in the Late Santonian times. This period also marked the development of initial Pyrenean thrusts as a result of reactivation or inversion of the Early Cretaceous extensional faults. This stage

is characterized by strong subsident turbiditic troughs deposited over thinned crust (Puigdefabregas *et. al.* 1992)

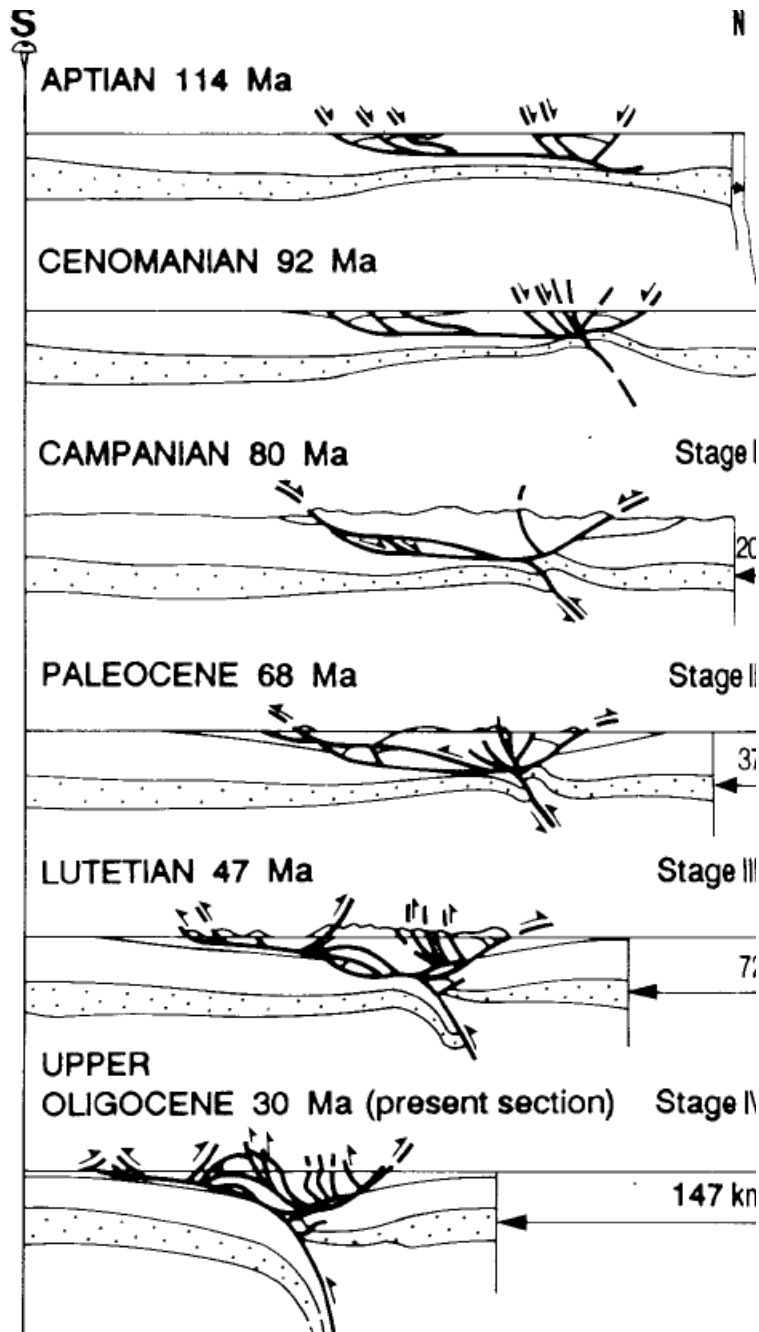


FIGURE 3.7 Partially restored cross-section showing the configuration of the lower Cretaceous basins and stages I to IV during the foreland basin evolution (Puigdefabregas *et. al.* 1992)

3.3.2 Uppermost Maastrichtian-Paleocene development (Stage II)

The main characteristic of stage two is the widespread distribution of continental facies strata and the restoration of the crust to its initial thickness. Deposition of fluvial and lacustrine red beds (or Garumnian deposits) are widely spread (over central, eastern, north and south Pyrenees) with thickness up to 1000 m in some areas. The Boixols thrust (the inverted extensional faults) is overlain by conglomerate formations which are contemporaneous with southward Piggy-back propagation of the southern thrust system within the central Pyrenees. The newly formed thrust (Montsec thrust) coeval with the Garumnian sedimentation (Puigdefabregas *et. al.* 1992).

During this stage the Cretaceous extensional faults were completely inverted, therefore the stretched upper crust attained its pre-Cretaceous dimensions of both length and thickness as deduced by the ECORS balanced crustal cross-section for Paleocene age (Mutti, 1991).

3.3.3 Early and middle Eocene development (Stage III)

In stage three, turbiditic troughs developed synchronously with the onset of subduction of the lower crust. The thrust sheet geometry imposed control on the arrangement and geometry of the turbidites and the contemporaneous shallow marine to continental deposits including facies distribution. The southern Pyrenean upper thrust sheets at this time consisted of the Mesozoic units previously inverted (in stages one and two) and formed a reduced cover, which unconformably overlies the basement. This cover was subsequently displaced to the south in a piggy-back mode over the foreland (Puigdefabregas *et. al.*1992). The structural emplacement of these thrust sheets within the South Pyrenean Central Unit (SPCU) was delineated by the Mesozoic extensional fault system, which controlled the locations of the oblique and lateral ramps and the disposition of the ensuing foreland facies. Overlying the thrusts sheets (Boixols, Montsec and Serres Marginals), a third generation of foreland basin developed, whose infill consists of fluvio-deltaic facies within an elongate basin. The alluvial fan system forming the Montanyana Group prograded southwards from the north and drained axially by westward flowing river system (Mutti 1988). The increase in clastic supply at this stage is

attributed to the increase in relief resulting from synchronous emplacement of the upper Nogueres thrust, accompanied by passive roof back thrusting and out of sequence thrusting in the rear (Puigdefabregas *et. al.* 1992). Tectonic control on sedimentation within periods of intermittent forward thrusting and aggradation was at a minor scale. The E-W orientation of the turbiditic troughs together with their fluvio-deltaic equivalent, suggests subcrustal subsidence involvement in the tectonic subsidence and not due to loading of the thrust sheets alone at this stage.

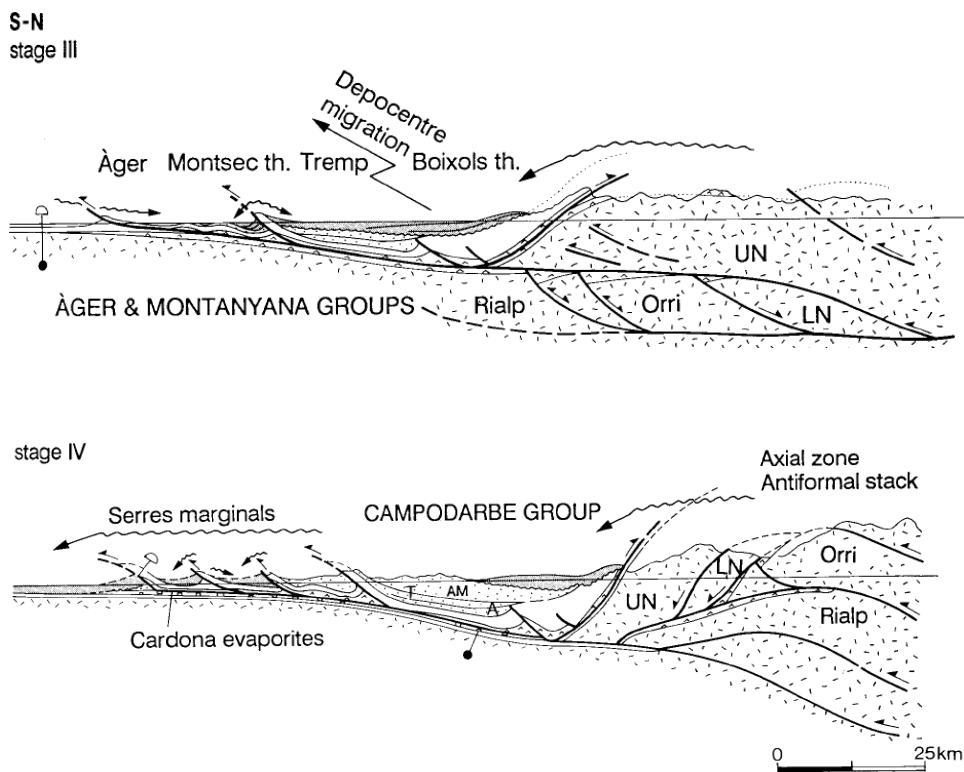


FIGURE 3.8 Partially restored cross-section during stage III and IV in Figure 3.7. These sections are from the southern parts of the ECORS seismic profile. Note the southwards migration of depocenters with time (Puigdefabregas *et. al.* 1992).

3.3.4 Upper Eocene-Oligocene development (stage IV)

This stage is characterized by a major increase in crustal cross-sectional area generated by piggy-back and break-back thrust sequences which are synchronous with the deposition of continental sequences. The final filling of the earlier turbiditic basins by deltaic systems was accomplished at this stage. As in the previous stage, the disposition of facies is controlled by the geometry of the SCU. The infill of the basins was effected by incoming clastic supplies from; 1) the erosion of newly formed relief in the hinterland mostly from the north 2) alluvial fan system overlying the SCU and channeled through the lateral ramps and 3) the alluvial fans and fan-deltas from the southern and eastern foreland basin margin (Puigdefabregas *et. al.* 1992). During this last stage of its evolution deformation in the SCU was modified by break-back thrusts, the development of new and minor out of sequence thrust sequences. These younger thrust structures are well recorded within the younger continental sediments (conglomerates) of the south Pyrenean foreland basin from the moment it was detached from the Atlantic ocean during early Priabonian to configure the internally draining Ebro foreland basin (Coney *et. al.* 1995). As a result of the progressive burial of the Pyrenean thrust front there was a change in the thrust kinematics from a major forward thrust propagation mode to a synchronous thrusting mode (i.e. coeval forward and hindward thrusting (Ramón *et. al.* 2002). From the characteristics of the external structures, the break-back displacements developed synchronously with the overall piggy-back propagation. The break-back thrusting in the external areas was analogue to the basement antiformal stacking in the inner part of the mountain chain. This is because both tend to exhibit the tendency to increase the taper in order to allow the progression of the orogenic wedge (Dahlen and Suppe 1988; Ramón *et. al.* 2002). Deposition of coarse-grained alluvial fan sediments was the main characteristic of this stage. This represents an enhancement in supply of clastic materials in response to the increase in cross-sectional area or relief.

Four basins can be distinguished within the SCU (Fig.3.4):

1. The Tremp-Graus Basin
2. The Ainsa Basin
3. The Jaca Basin
4. Ebro Basin

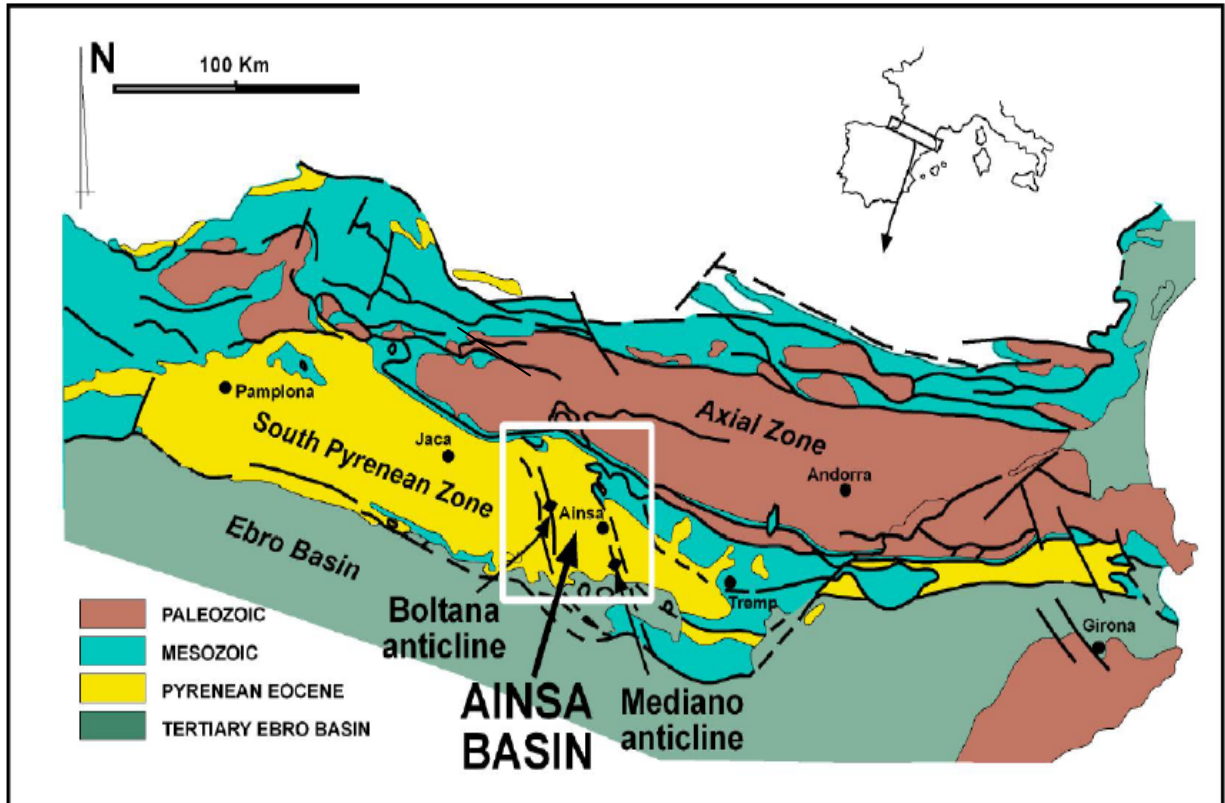


FIGURE 3.9 Sketch map of the regional geographic and geological setting of the Pyrenees highlighting the location of the main foreland basins. Note the Ainsa basin (Study area (Melik *et. al.* 2004)).

The Tremp-Graus, Ainsa, the Jaca and the Ebro basins are the four main fore land-basins formed within the SCU which are separated by major N-S trending structures and the basin themselves are elongated, east-west features where the main sediment transport was parallel to the tectonic strike from east to west.. To the south is the very large and mainly Miocene Ebro Basin.

3.4 Main structural features of the Pyrenees

The Pyrenean fold-and-thrust-belt, especially its southern flank, exhibits some of the most spectacular and well-studied examples related to the interplay between tectonics and sedimentation.

The Pyrenees have been traditionally regarded as a symmetrical mountain belt, 450 km long and 200 km wide, with related structures making the total length of about 1000 km. The Pyrenees is divided into the following structural units; the north Pyrenean zone (NPZ), the north Pyrenean fault zone and the south Pyrenean zone (Fig.3.2). Detail subdivision from N-S is as follows: the north Pyrenean thrust sheets and the Aquitaine basin belongs to the North Pyrenean Zone (NPZ). The axial zone, the cover upper thrust sheets and the Ebro basin belongs to the Southern Pyrenees. The North Pyrenean fault zone is the boundary between the N and S Pyrenees. The south central Pyrenean unit, within the upper thrust sheets, is the focus of this work with emphasis on the NE Ainsa basin (Fig. 3.9).

3.4.1 Southern Pyrenees

The South Central Unit (SCU) of the southern Pyrenees is bounded to the east by the Segre fault and to the west by the Atlantic Ocean (Fig. 3.4; Peter *et. al.*, 1992). Basins within the southern Pyrenees developed during the Paleocene to early Eocene times as thrust sheets advanced to the south as a consequence of thrust-wedge loading and subduction related flexure of the Iberian plate (Munoz *et. al.* 1991). The south Pyrenean basins originated as a foredeep but started to evolve into coeval break-back and piggy-back setting during the Early Eocene time in response to incorporation of the proximal parts of the foreland into the thrust wedge, with thrust motions indicating a complex pattern of forward and hindward-imbrications including major phases of out sequence fault reactivation (Peter *et. al.* 1992; Puigdefabregas *et. al.* 1991). The South-Central Unit (SCU) of the southern Pyrenees serves as a linked panel of southward-directed cover-involved thrust sheets and related piggy-back basins (Puigdefabregas *et. al.* 1991). From the ECORS seismic profile (ECORS 1988), three main structural units can be distinguished representing the south central cover thrust sheets.

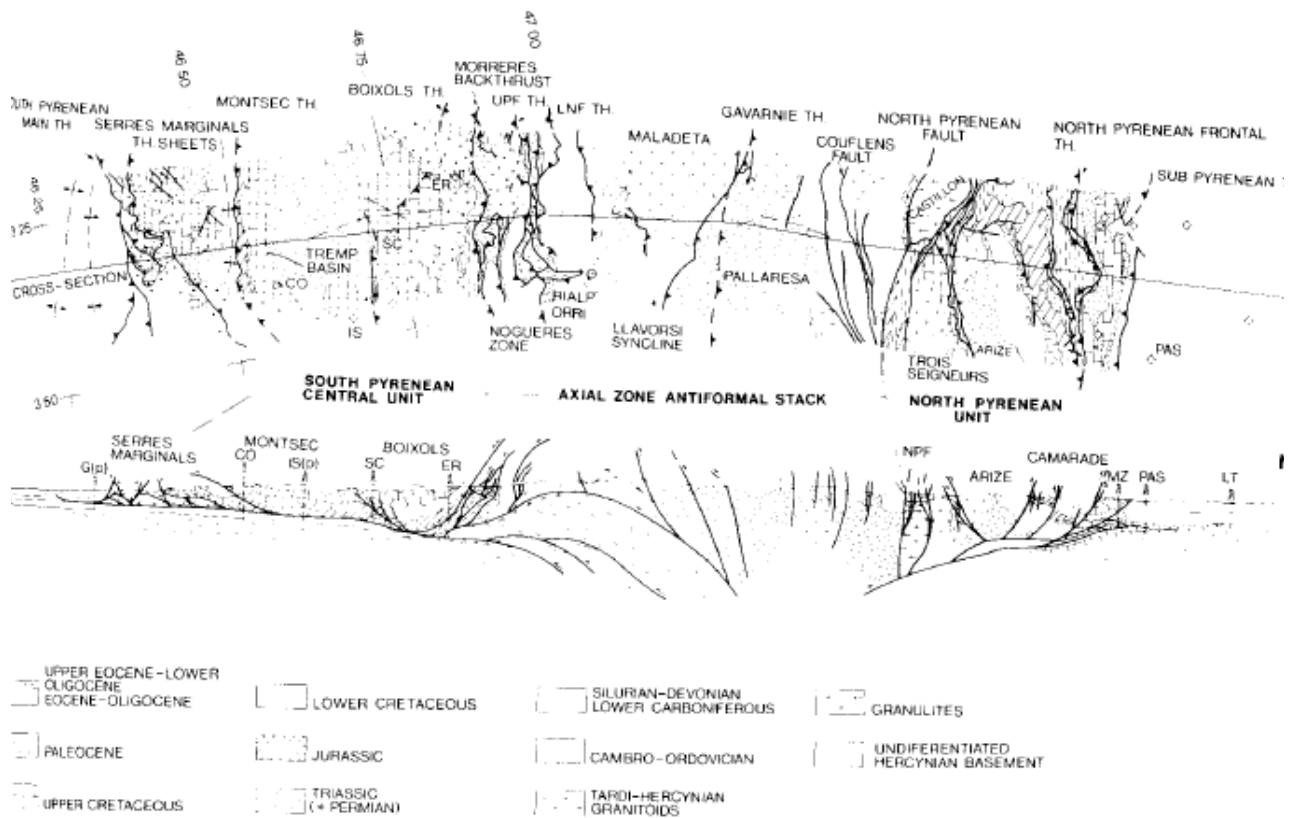


FIGURE 3.10 Structural map and section of the Pyrenees showing; the N-S and the E-W configuration, the location of the south central Pyrenees south along the ECORS profile (Munoz,1991)

There are from the north to south, *Boixols* (uppermost), *Montsec* and *Sierras Marginales* the (lowermost). The Montsec thrust merges with the Sierras Marginales thrust in the east by an oblique ramp (Segre fault Zone). The western boundary of the central cover sheets is characterized by a less well defined NW-SE oblique ramp system and the transport-oblique Mediano and Boltana anticlines bounding the Ainsa basin along the E-W axis (Fig.3.4)

3.5 *The Ainsa basin - Description*

The Eocene Ainsa basin represents a piggy back basin above a basal detachment within the middle Triassic evaporites. The detachment is part of the South Pyrenean thrust units (Fig.2.9). The Ainsa basin originated in a foredeep position and evolved into a piggy-back basin as the thrust advanced towards the south. The basin axis measures approximately 40 km long. The basin is 30 km wide and 4000 m deep (Munoz *et al.* 2002). The basin is bounded by the Sierras Marginales to the south, the Mediano anticline to the east, the Boltana anticline to the west, and the southern margin of the Antiformal Stack to the north. The basal detachment separates the basin fill from its Variscan basement. The propagation of the thrust front caused the Ainsa basin fill to be divided into four tectonostratigraphic units by four major unconformities. These unconformities reflect changes within the basin like compression rates, isostatic uplift, gravity and back thrusting accompanying the development of the Pyrenean chain and its foreland basins (Fig.3.10; Muñoz *et al.* 2002). Ainsa basin has four main stratigraphic formations from bottom to top:

- San Vincent Formation (deep marine mud, turbidite sandstone)
- Sobrarbe Formation (prograding delta)
- Escanilla Formation (Fuvial)
- Collegate formation(Oligocene conglomerates)

3.5.1 Structural development of the Ainsa Basin

The Mediano Anticline is an asymmetrical detachment fold (Poblet *et al.*,1992; Muñoz *et al.*, 1994, 1998; Travé *et al.*, 1998). It developed at a thrust termination as the displacement is translated into folding of the leading edge of the thrust sheet. Poblet *et al.* (1998) suggested that the Mediano Anticline was still active through the deposition of the Escanilla Formation in the latest Eocene. On the western margins of the Ainsa basin it is bounded by the Boltana anticline. This anticline represents a regional-scale asymmetric anticline and is located above the western oblique ramp of the Gavarnine

thrust sheet (Holl and Anastasio, 1995) and probably a fault propagation fold (Muñoz *et al.*, 1998). The internal folds in the Ainsa basin are growth folds.

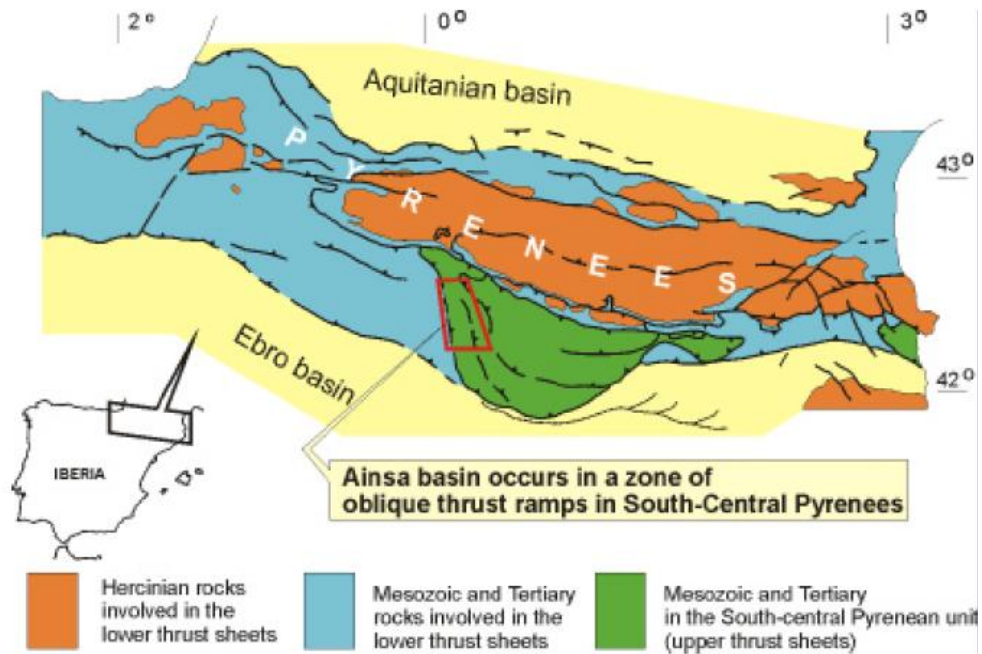


FIGURE 3.11 Location of Ainsa basin in the Pyrenean context showing the Ainsa basin as it occurs within the upper thrust sheets and the oblique thrust ramps. The positions of the lower thrust sheet, the aquitanian and Ebro basins is also shown here. (Munoz et al 2002)

3.5.2 Stratigraphy of Ainsa basin

During early Palaeocene to early Eocene, the Ainsa basin acted as a transfer basin to the coastal and delta top/front in the Tremp/Graus basin to the east (Fig.3.11). This basin prograded towards the WNW and accumulated delta slope deposits and turbidites which were transported into the basin via extensive channels. A very significant amount of this turbidites bypassed this basin and were deposited in the Jaca basin to the west where they formed huge turbidites of the Hecho group.

SW – NE Not to scale

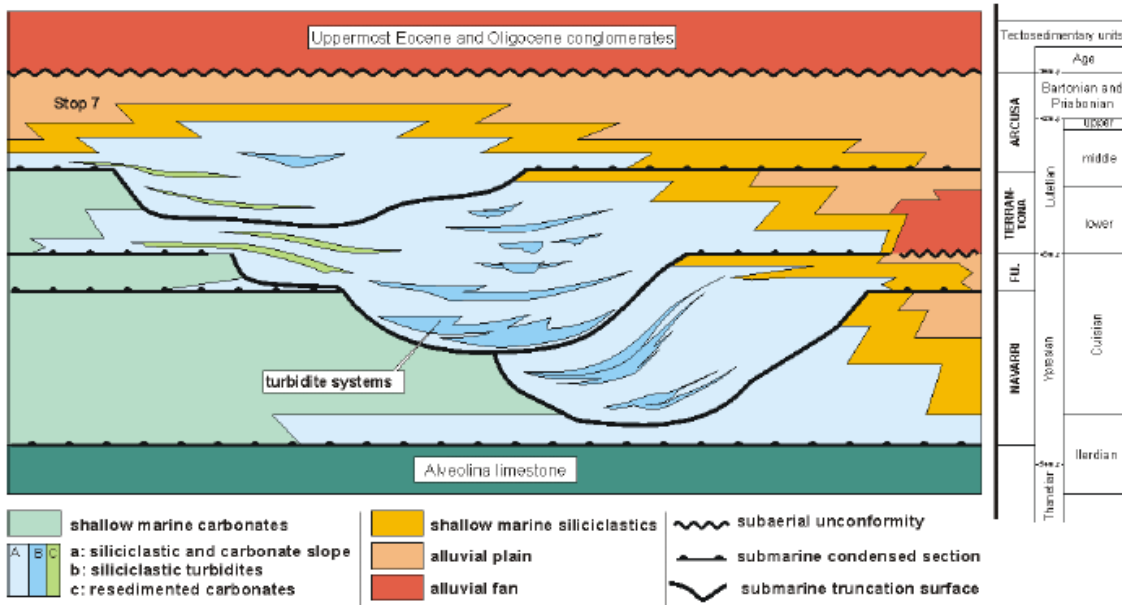


FIGURE 3.12 schematic representations of the major stratigraphic units of the Ainsa basin (Munoz et. el 2002).

From the Middle to Late Eocene the N-S trending Boltana and Mediano Anticlines developed (Fig.3.4) above the lateral ramps which separated the Jaca, Ainsa and the Tremp/Graus (Gjelberg , 2001). These two anticlines acted as a barrier to the ESE-WSW sediment transfer. An anticlockwise rotation of 30 degrees was recorded in Ainsa basin during the Eocene to Oligocene times. During Late Eocene the top of Mediano anticline which acted as an isolated high experienced sub aerial exposure creating an angular unconformity ontop of the late Cretaceous to lower Eocene carbonates within the anticlinal core. The contemporaneous deltaic and prodelta deposits onlap the flanks of

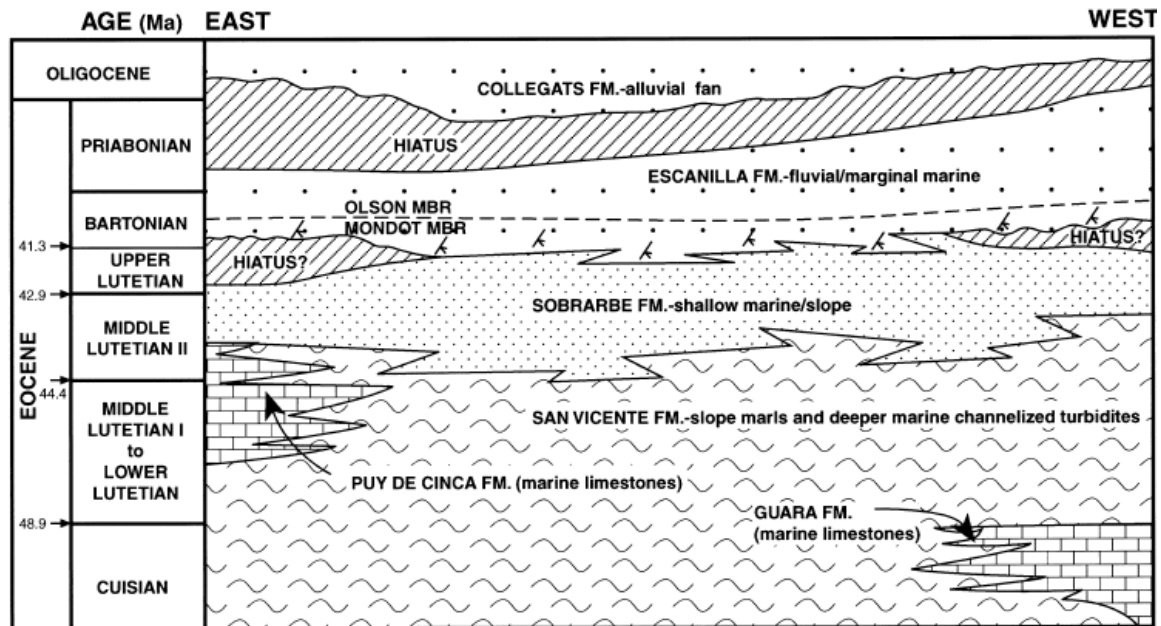


FIGURE 3.12b stratigraphy of Ainsa basin. Note the stratigraphic position of San Vicente Formation (Dreyer et al, 1999)

the anticline. Submarine deposition occurred during middle to late Eocene and small isolated carbonate platforms develop on top of the Mediano anticline. A large-scale late Eocene transition from alluvial plain to delta top depositional environment is recorded within the Ainsa Basin. This transition is a component of the Sorbrabe delta which was sourced from the S and SE (Dreyer et. al. 1999). This Deltaic-alluvial deposit is bounded at the top by an erosional unconformity in turn overlain by middle to late Eocene braided stream-alluvial system of the Escanilla Formation. Alluvial sediments were derived from the N to NNE, the central Axial Zone and the southerly adjacent antiformal stack of the Pyrenean chain (Fig.3.11). The final infill of the Ainsa piggy-back basin was recorded by the Escanilla Formation through the development of a braided stream network (Kjemperud 2004). The alluvial fan systems of the Collegat group unconformably overlie the Escanilla Formation forming a major erosional and angular unconformity. A major shift in the depositional system was triggered by increase uplift of the Central Pyrenean chain which accelerated the thrust wedge propagation in response to peak Iberian/Eurasian collision during the middle Oligocene time. All these rock successions are preserved within the Ainsa basin (Fig. 3.12; Peter et al. 1992).

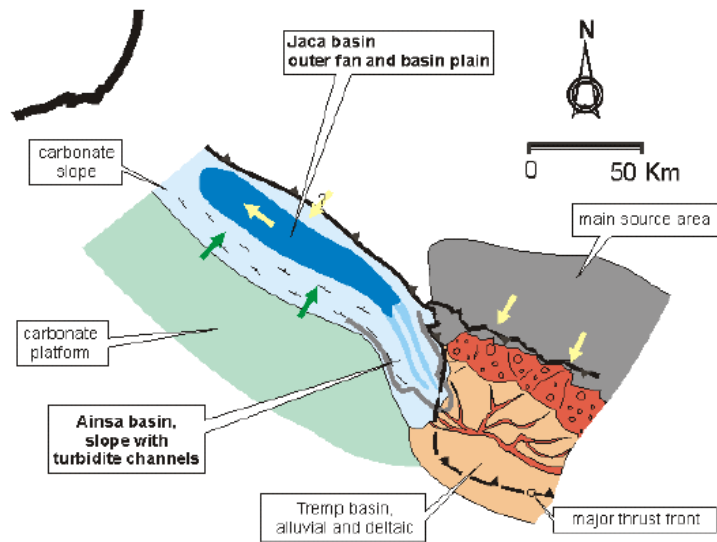


FIGURE 3.13 Situation of the Lower-Middle Eocene depositional system showing the provenance area of clastics Arrows indicate source areas note the main NE source areas (Abues and Corregidor, 1994)

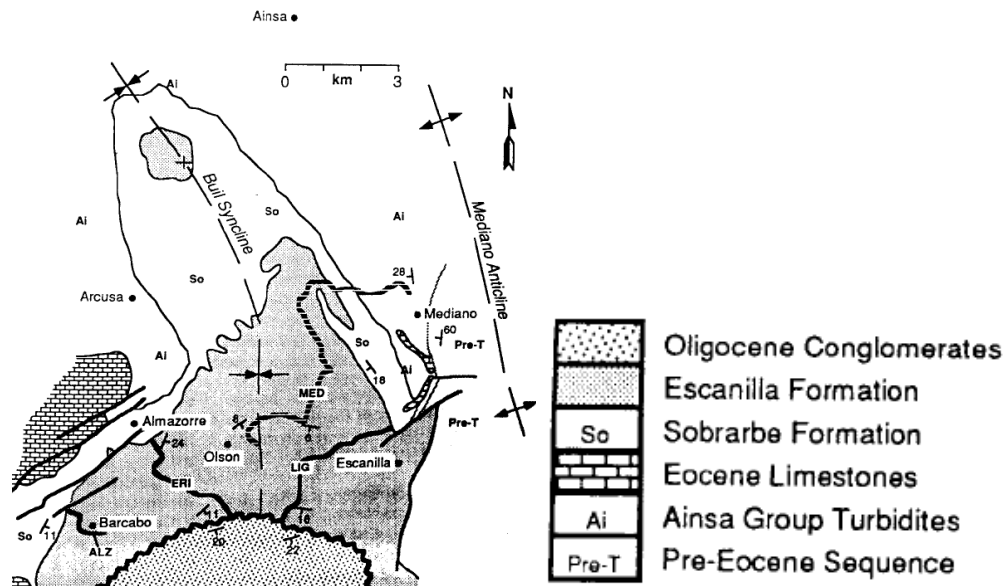


FIGURE 3.14 The geological map of Ainsa basin (Peter et al. 1992)

3.5.3 Ainsa Turbidite Sedimentation

The Ainsa Turbidite Channel System, south-central Pyrenees, occurs in the oldest part of the Campodarbe Group and it is of Upper Eocene age. The Ainsa Channel Complex is perhaps the most famous of the submarine channel outcrops within Western Europe. The Ainsa Channels consists of two principal channel complexes (Ainsa I and Ainsa II) which are separated by very thin-bedded sandy turbidites and marls. The Ainsa Channel Complex is an example of an erosional-depositional system. The Ainsa II Channel Complex contains significant erosional cut downs, with infill of essentially non-erosive sandy facies. The channel dimensions are seismic scale. A classical channel infill of sand is well exposed in Ainsa quarry, south of Ainsa. Careful mapping indicated alternation of fine to medium grained sandstones and mud.

Chapter 4 Description of Field Data

4. 0 Introduction

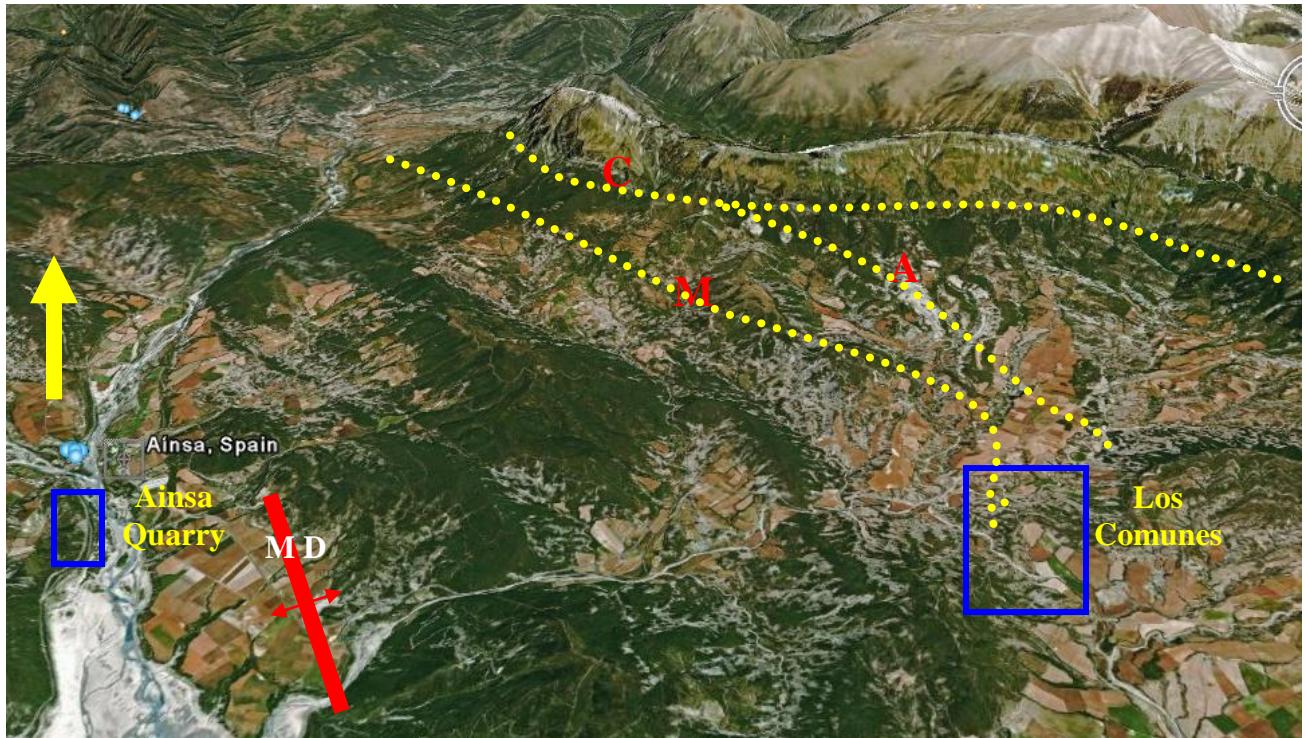


FIGURE 4.1 Satellite image of study area; showing the locations of the Ainsa Quarry and the fold and thrust Los Comunes area (Blue Rectangles) C= Cortiella, A= Atiart, M= Molinos thrusts and MD=Mediano Anticline Yellow arrow for north. (Puigdefabregas pen .com; Google earth)

In the present section, descriptions of localities and data obtained from them are presented. The data presented is based upon measurements obtained from outcrops from two main parts within the study area. They are: the Ainsa Quarry, which is located South of Ainsa Town and the Los Comunes area to the N-E of Ainsa (Figure 4.1). These two major areas offer a chance to access the variability in syn-sedimentation and tectonic deformation across the western oblique ramp of the South Central Pyrenees developed as the thrust wedge advanced southwards during the Pyrenean orogeny. The data are presented starting with those obtained from the less deformed deep marine channel

turbidite deposits, Ainsa turbidites, exposed at the Ainsa Quarry, followed by the deformed frontal part of the study area around Los Comunes. The north-eastern part of the Ainsa basin has been deformed by west to southwest vergent imbricate thrust system and related folds (Munoz *et al.*, 1994, 1998; Travé *et al.*, 1998),.

Previous studies in the area (Puigdefabregas personal communication) has shown that a major thrust system extends from the master thrust beneath the greater nappes. This is associated with regional-scale south to south-west imbricate thrust and related fold system. The influence of this deformation vanes towards the south so that at the Quarry, the beds are only slightly tilted towards the south. On the contrary, within the Los Comunes area which is in close proximity to the frontal zone, the rocks have been deformed into folds and faults.

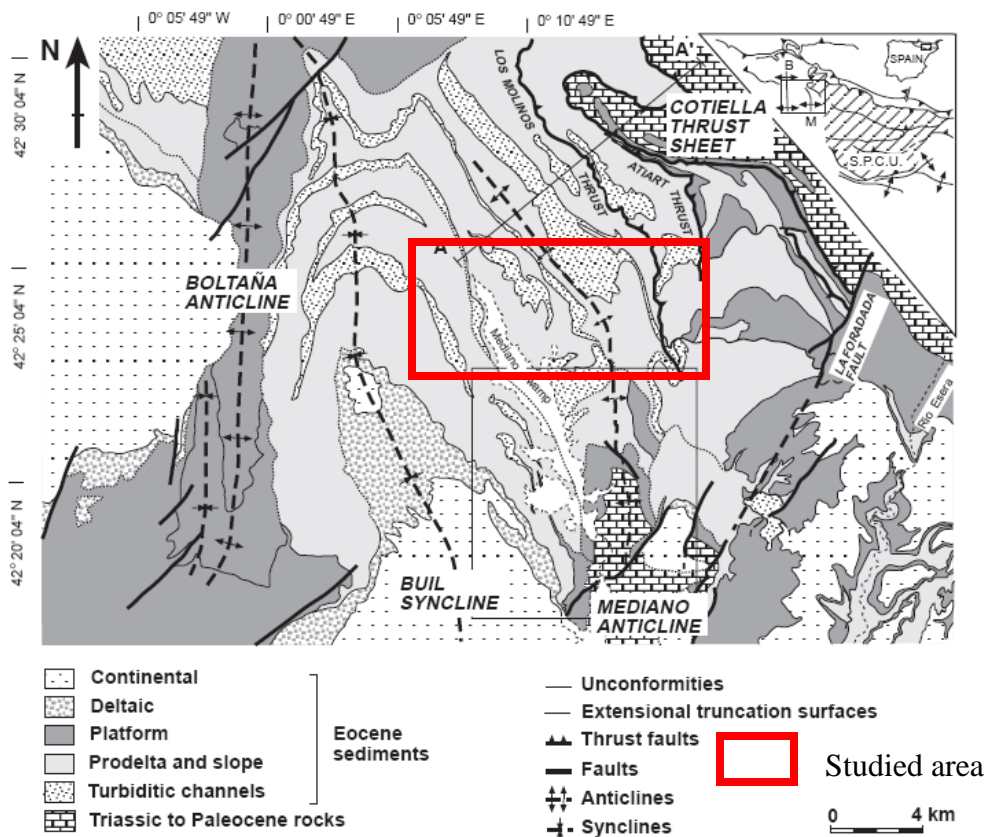


FIGURE 4.2 Structural map of the Ainsa basin showing the location of the study area red rectangle(Travé *et. al.*1998). Note the positioning of the Ainsa Quarry and the Los Commune areas. The former is situated about 6 km SE of the thrust front and the later within it. A=Ainsa Quarry. L=Los Commune area.(Travé *et al.*,1998)

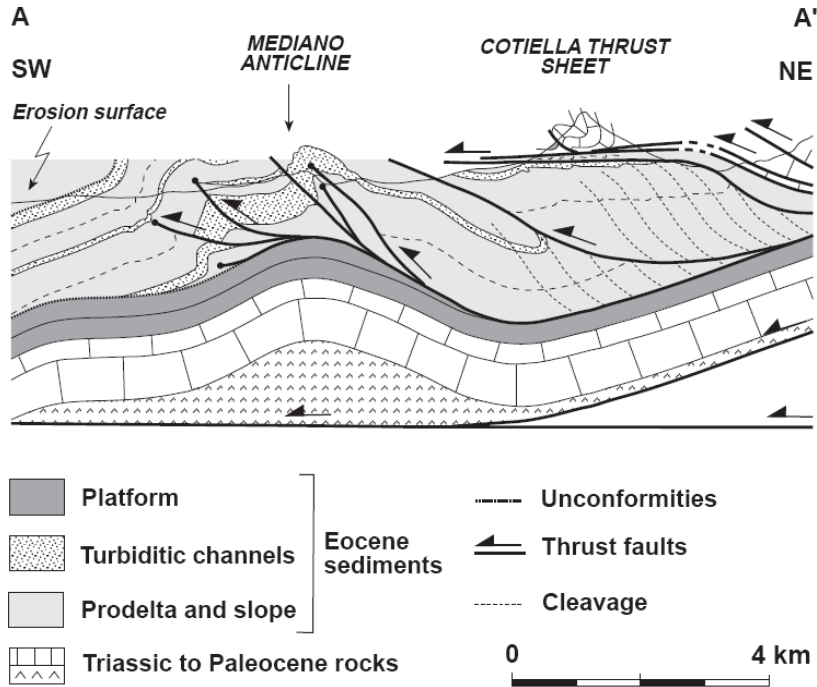


FIGURE 4.3. Cross section A-A' of the north eastern part of the Ainsa basin taken from the map in Figure 3.2 above. Note that the beds at the far SW end (where the quarry is located) of the cross section have not been cut by the thrust faults as it has in the centre and NE of the section (Travé et. al. 1998).

4.1 Treatment of data

Field data from both the Ainsa Quarry and Los Comunes have been successfully processed. The software, “Winfull stereonet” has been used in determining the poles, planes, best fits of folds and direction roses of fractures. The use of Excel for fracture frequency analysis and “Adobe Illustrator” for construction of structural maps is worth mentioning.

The lithology is characterized by deep marine mud overlain by shallow marine mixed carbonate siliciclastics of Eocene age (Figs.4.2 and 4.3).

A separate fracture study was carried out in the strata affected by the Los Comunes syncline. The intention was to

1. Identify fracture systems related to the folding and thrusting and to set this in the context of the major fold and thrust stages.
2. To identify the fracture system related to the soft sediment deformation and compaction and
3. To compare these to the fractures found in the Quarry.
4. Finally, a fracture frequency analysis has been performed to evaluate the extent and potential of the fracture system on fluid communication.

4.2 The Ainsa Quarry

This locality is located south of Ainsa, (UTM: 65340E/98819N). The length of the complete section of the abandoned quarry is approximately 500 m and it is 15 m high (Fig.4.4)

The turbidites in the Ainsa quarry form part of the San Vincent formation. The individual beds are a few centimetres to one metre or more thick and there is a gradual fining upward unit in each succession. Graded and massive beds are predominant. The mud layers which separate each succession with an erosional surface can be traced laterally for couple of metres. The sandstone bodies show characteristic channel configuration. The sand layers are deposited on top of each other forming a multi-story stacking pattern while some of the beds are amalgamated. Some parts of the section reveal conglomerate beds together with the mud and sand beds. Abundant trace fossils can be found within the rocks. The rocks at some parts of the section are horizontally and vertically bioturbated. Flute and groove casts indicate palaeocurrent directions from SE to NW. Water escape structures are also present. Mud clasts can be observed within sandstones. Folds and faults were not found to occur within the beds. However, the beds are generally gently inclined towards the south and the sandstones are fractured.

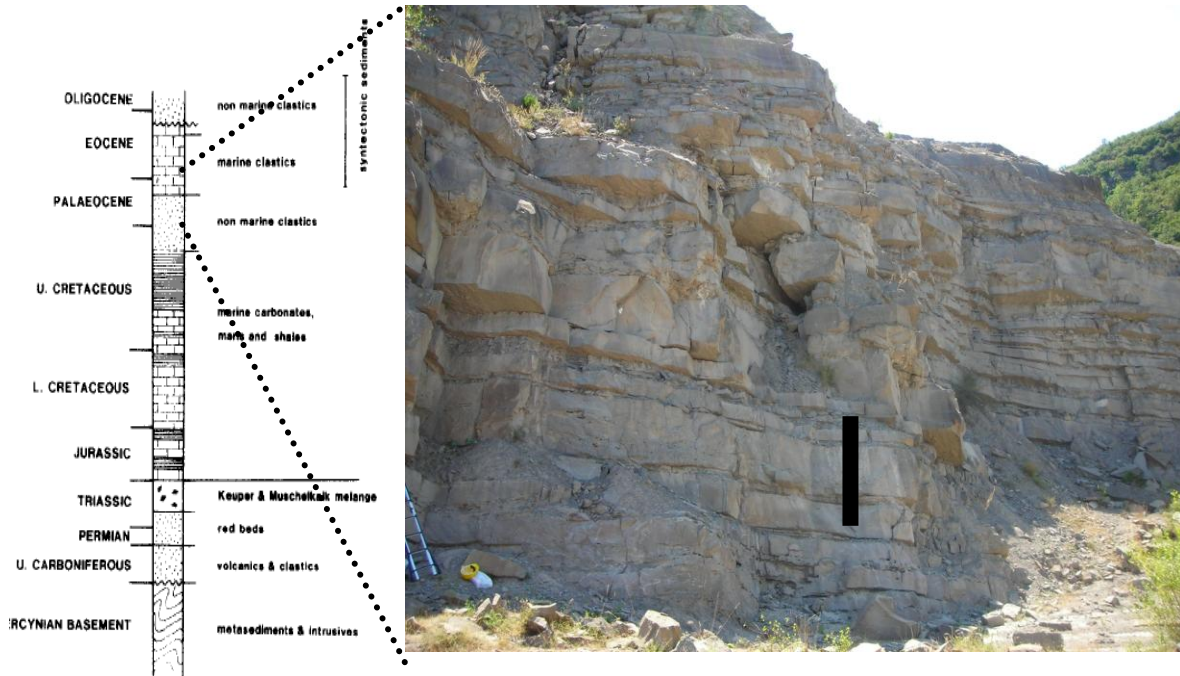
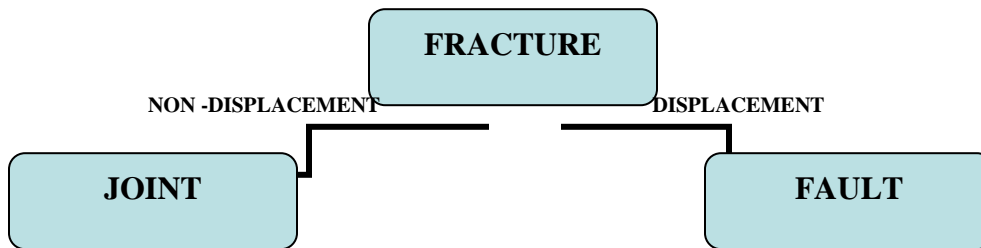


FIGURE 4.4 Eocene marine clastics (turbidites) exposed at the Ainsa Quarry. Black vertical line is indicating the three beds from which fracture logs have been prepared.



Geologically fractures encompass faults and joints (Nystuen, 1989). The partition between faults and joints has been recently been linked to the scale of displacement across the fracture (Ramsay and Huber, 1987; Gabrielsen, 1990). Therefore, a structure which has been defined as a fault under the microscope can be referred to as a joint when observed in a rock exposure. To avoid these drawbacks, the following definitions have been advanced by Gabrielsen (1990): “A fracture is a planar or curvilinear discontinuity

in a rock body caused by strain. A fault is a fracture along which displacement parallel to the fracture surface has taken place, whereas a joint is a fracture in which no such displacement can be detected”

Fracture characterization within study area

Although the strata present at the Ainsa Quarry are less strongly deformed, fractures are quite common and which have been studied from three selected sandstone beds of the exposed section of this locality (Figure 4.4). The Los Comune area is more intensely deformed into folds and thrusts with the joints being influenced by the major folds in the area apart from those generated by burial and uplift. (The fracture analysis of the Los Comune fracture system has been presented under, *minor structures associated with folds* in the next sections). Several fracture populations can be observed in both localities (Ainsa Quarry and the Los Comunes). A simple approach to classify these populations based on fracture geometry, orientation extension and fracture fill has been applied for a qualitative and quantitative analysis. Below the characteristics of the fracture populations in the three beds at the Ainsa Quarry have been presented (Fig4.7);

Fracture Mineral fill- joints are filled with calcite to various extents may be open, sealed or partly sealed.

Fracture Penetration - joints show various manner of penetration within beds, fractures may cut through the entire bed or may be restricted within the bed.

Geometry – the fractures may be are straight, curved, wiggly or en echelon.

Orientation – Classification of all the population at Ainsa based on the field orientation, have yielded five populations; these populations are denoted Q a to Q e (population Q1 to Q 5 ; Fig4.4b)).

4.2.1 Fracture analysis at Ainsa Quarry

Five distinct populations were measured at Ainsa Quarry. Their measurements are shown in the figure 4.4b below.

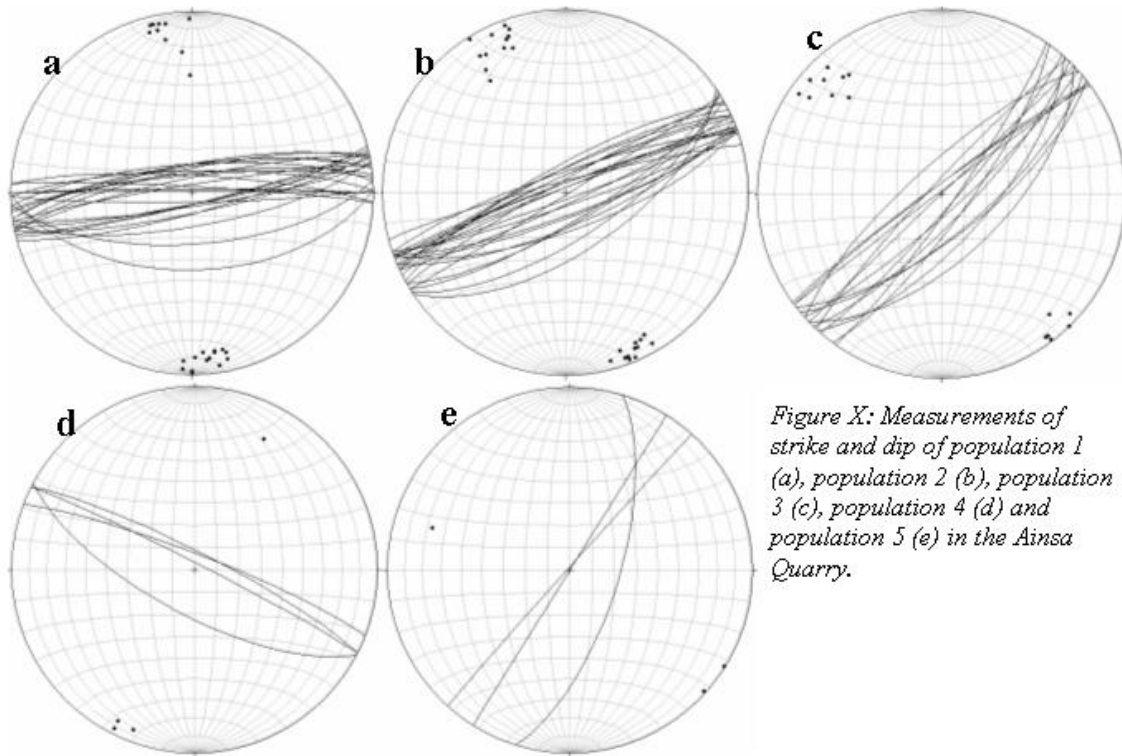


Figure X: Measurements of strike and dip of population 1 (a), population 2 (b), population 3 (c), population 4 (d) and population 5 (e) in the Ainsa Quarry.

FIGURE 4.4b Stereonets. Showing measurements of strikes and dips of the five populations at Ainsa Quarry(a) to (e) These are populations Q1 to Q5 respectively discussed in text.

Characteristics of fracture population Q1 (N-264E)

Population Q1 fracture are characteristically intraformational, sub-vertical to vertical. They are calcite filled mode I tensile fractures. They are eleven populations I fractures in bed 1, seven in bed 2 and three in bed 3. One of these fracture populations originate from the upper bedding surface and terminate within the bed, one originate from the lower bedding surface and terminate within the bed, thirteen fractures are completely enclosed within the bed and one fracture cuts through the bed. The average strike direction of this population is N-264 E.



FIGURE 4.5 Vertical and intraformational mode I fractures in a sandstone bed in the Ainsa Quarry

Characteristics of fracture population Q2 (N-240 E)

This fracture population is mostly strata bound, calcite filled and closed. They are mode I tensile fractures which are sub normal to normal to the bedding. The populations show the following penetration characteristics; six fractures originate from the lower bedding and terminate in the bed, three originate from above and terminate within the bed. Thirteen fractures are within the bed. One fracture cuts through the bed. The average strike direction is N 229 degrees

Characteristics of fracture population Q3 (N-229 E)

These are mode I tensile fractures there are strata bound and steeply dipping. Thirteen of these fractures are intraformational. One shows an echelon geometry while thirteen are formed within the bed. They are mostly calcite filled and have straight geometry with a few wiggly forms. The population has an average strike of N-229 E)

Characteristics of fracture population Q 4 (N-295E)

These population belong to mode I tensile fractures which are cutting through many layers and calcite precipitation is common. They are sub-normal to bedding, with both straight and wiggly forms common. This population strike is N-295E

Characteristics of fracture population Q5 (N-222 E)

The fractures of these population are mode II fractures. They show strike slip movement (dextral strike-slip) the average strike direction is N-222E



FIGURE 4.6 Fault plane showing dextral strike slip movement as observed from the slickenside lineation.

Preliminary conclusion of fractures at Ainsa Quarry

A total of five populations have been studied in this area and can be classified as follows Q1, Q2, & Q3 = populations related to burial, Q4 = population related to uplift and Q5 = population related to tectonics

Joint spacing

Joint spacing in sedimentary rocks is for the most part a function of the following: 1) *Bed thickness* 2) *Lithology* and 3) the “*intensity of deformation*”(Harris et al., 1960, Hobs 1967, Huang & Angelier, 1989 and Narr & Suppe 1991). The thickness of the incompetent

layers above and below have an influence on the joint spacing in the incompetent layers
(Hobbs, 1967).

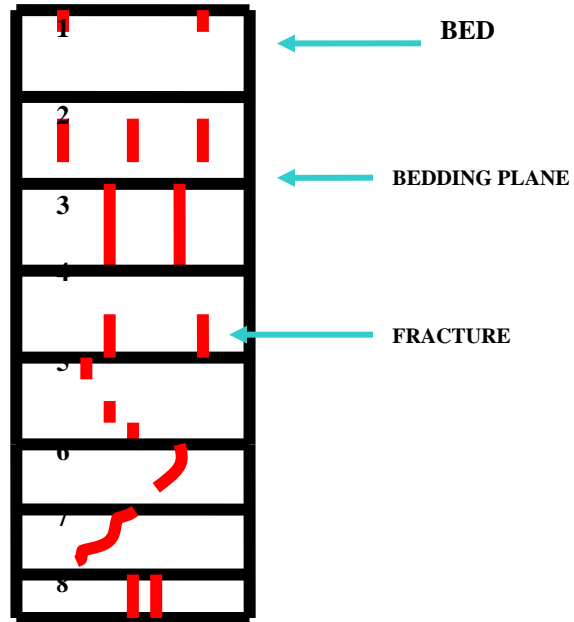


FIGURE 4.7 schematic representations of bedding, fracture geometry and penetration within beds in the study area.

TABLE 2 A summary of fracture fill for the population (calcite-cemented and non cemented fractures) and the number of open and closed fractures for the sandstones beds 1, 2 and 3 at the Ainsa Quarry.

Bed/Fracture	Open	Closed	Calcite cement	No cement
1	6	33	34	5
2	12	9	11	10
3	0	17	17	0

A statistical summary of the types of fractures for the three sandstone beds at the Ainsa quarry is shown in table 2 and figure 4.8 is a pie chart of same has been generated. Both are showing the number of open, closed, cemented and non-cemented fractures.

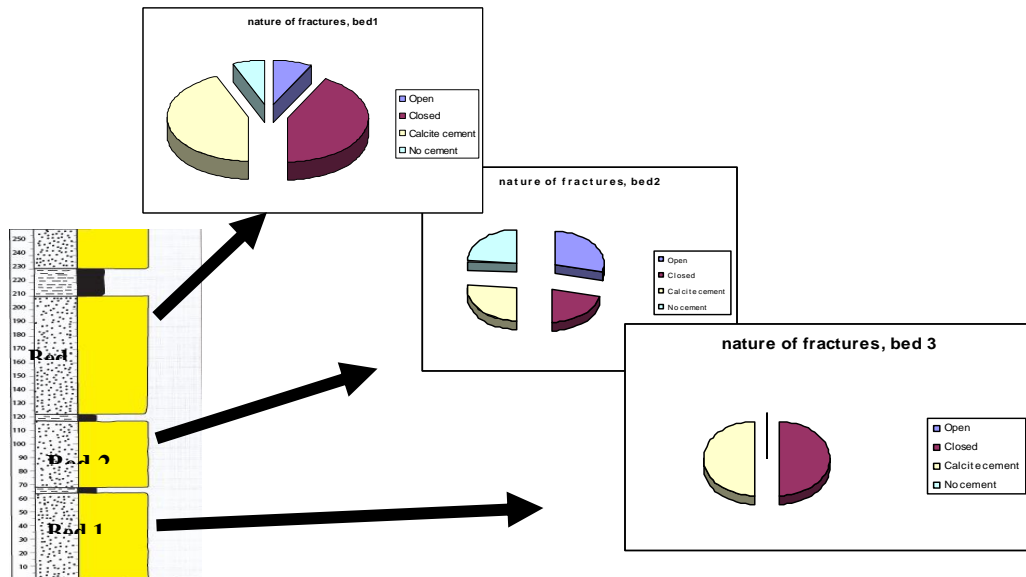


FIGURE 4.8 Pie charts showing the proportions of the nature of fractures (open, closed, calcite filled and non-calcite filled) within the three beds studied at the Ainsa quarry.

Fracture frequency for the Ainsa Quarry

Fracture frequency for the beds studied at the Ainsa quarry has been made from the number of fractures measured per metre

Bed	Population 1	Population 2	Population 3	Population 4	Population 5
BED 1	11	6	9	3	1
BED 2	9	7	4	3	3
BED 3	3	12	2		
Fracture Frequency					
BED 1	0.50	0.27	0.41	0.14	0.05
BED 2	0.62	0.48	0.28	0.21	0.21
BED 3	0.18	0.73	0.12	0.00	0.00

4.3 The Los Comunes area

The Los Comune area is located about 15 km NE of Ainsa (Figs. 4.1, 4.8). This part of the studied area is located at the eastern margin of the Ainsa foreland basin and consists mainly westward-prograding outer-shelf/slope facies of Eocene age (Mutti et al.,1988; Travé *et. al.* 1998). The structural elements studied at Los Comunes area are;

1. The Los Molinos fold and thrust system
2. Major faults
3. Major folds
4. Fracture systems

4.3.1 The Los Molinos fold and thrust system

The Los Molinos thrust constitute a major thrust and fold zone which is located at the front of the Cortiella nappe. Movement of this nappe occurred during the early Eocene

(Fig.4.2; Travé *et al.*1998). According to Mutti *et al.*, (1988) the frontal part of this thrust system (including the Los Molinos thrust) remained active during the mid-Eocene. This thrust zone is located on the foot wall of the Atiart thrust (Fig. 4.1). Lithology is mudstone intercalated with thinly bedded sandstone. It can be followed from a very good exposure in a *road section* at UTM: 7459E/9825N. From this point, the thrust branches to the NE and along the foot of a valley to another good exposure *the escarpment*. From here its trace turns southwards to a gully which cut through a hill (Fig.4.9). The main structures within the Los Molinos thrust and fold system are contractional faults, this can be studied in great detail at the road section and the gully.

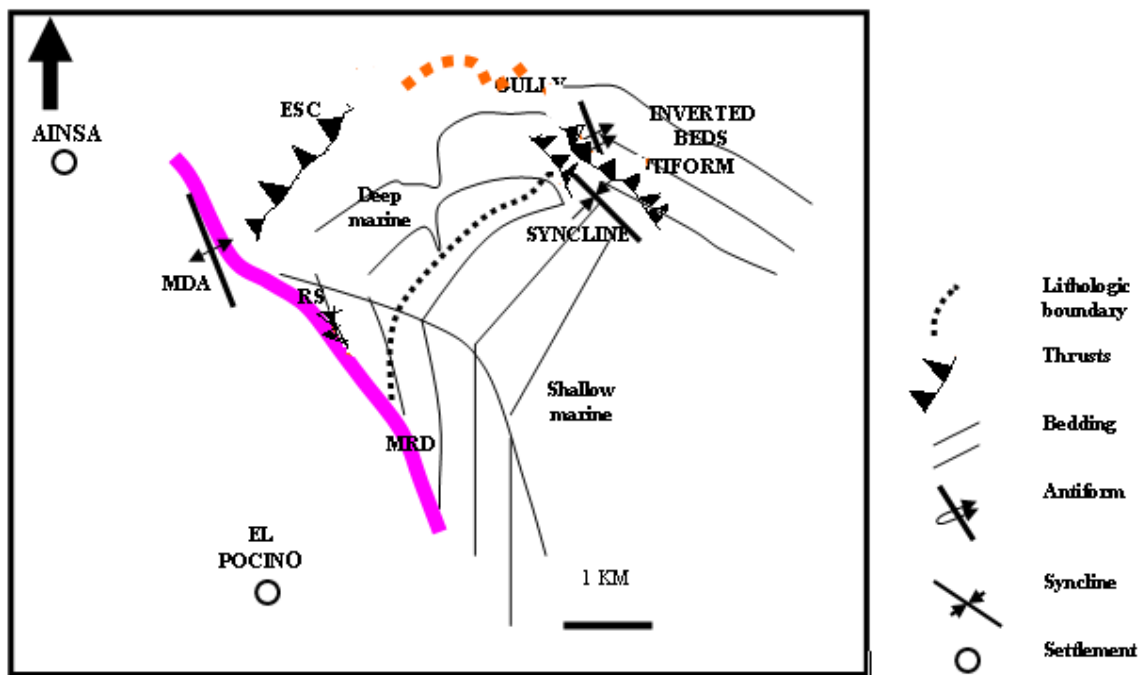


FIGURE 4.9 Sketch map of Los Comune area taken from figure 3.2. The locations of the sub localities where data were acquired are shown as follows; **MRD** - main road, **ESC** – escarpment, **RS** - road section, **MDA** – Mediano anticline, Yellow dash line - Trace of thrust faults. Note the position of the gully relative to the Los Comune synform and antiform.

CONTRACTIONAL FAULTS

Within the Los Comune area the fold and thrust system has affected rocks of different lithologies. Contractual faults patterns linked to the thrusts and fold deformation in this area are basically of two contrasting types; the low-angle thrust which is well developed in the road section and the high-angle thrust found in the gully east of the road section (Fig. 4.10)

Road section (Road No: HU=V6442)

The road section is located along road number HU-V6442 from El Pocino to Ainsa (Fig.9.9; UTM 7459E/9825N). A very good exposure ca 70 m long exposure and approximately 5-10 m high vertical section oriented (N-S) parallel to the road has been studied (Figs. 49 and 4.10). The stratigraphic units affected and their age can be referred from the introductory part of this section. Together with the main faults, other associated structures of importance were identified and have been described

These structures are;

- Subordinate-faults
- Folds
- Duplexes

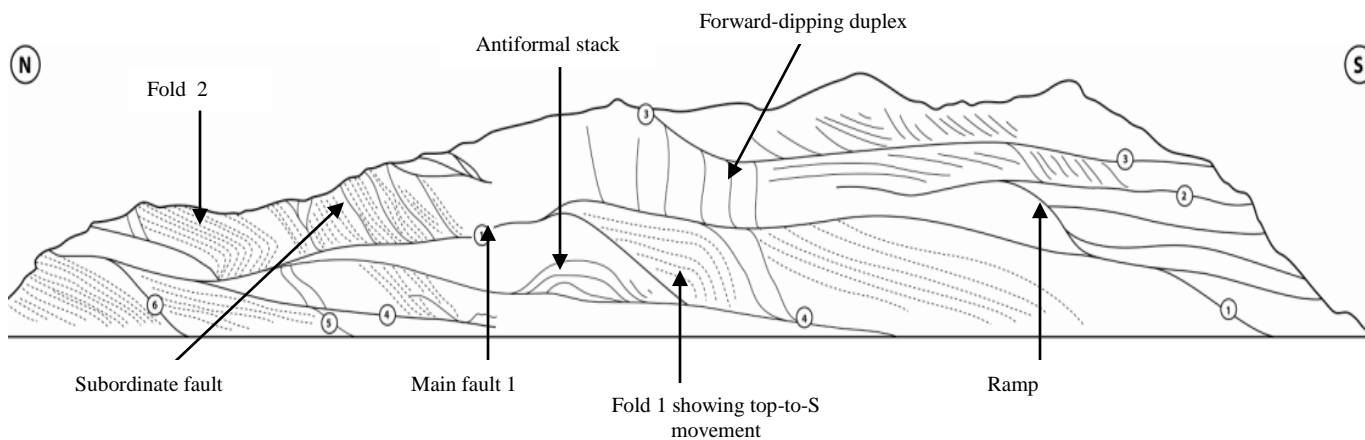


FIGURE 4.10 Los Molinos thrust. Sketch of outcrop showing the fault zone, with the main and minor faults including associated structures. Note the main transport direction (field sketch by Gabrielsen, 2008).

Main faults

The road cut is characterised by the occurrence of calcite-filled main thrust-fault planes. Four shallowly dipping master thrust faults planes were identified in the road section (Figs 4.10). The lithology affected is mudstone intercalated with thinly bedded sandstone of Eocene age. The main faults are characteristically sub parallel and their intersection with the lower surfaces is at low angle (Figs. 4.10 & 4.11). When traced along strike, they become gently dipping to the south. Another feature of importance is the development of ramp geometry although not very prominent. The ramps are affiliated with the main faults by connecting the floor and the roof fault levels.

Subordinate faults

More steeply inclined faults are associated with the master faults and can be observed in the road section. These fault planes are calcite-filled with predominant dip of 55 degrees to the south. They are characteristically joining the main faults above (roof) and merge with those below (sole thrust). The other faults planes of this category have also been folded together with the strata (Fig.4.12)

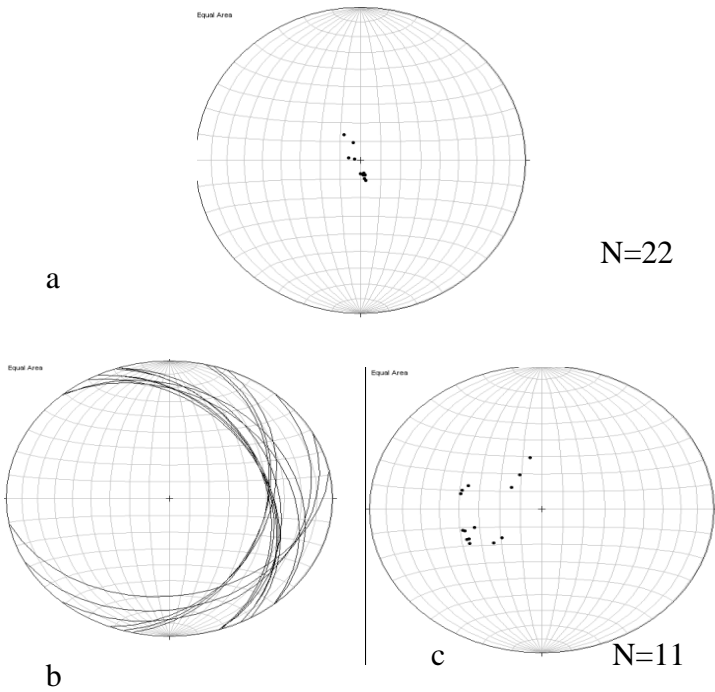
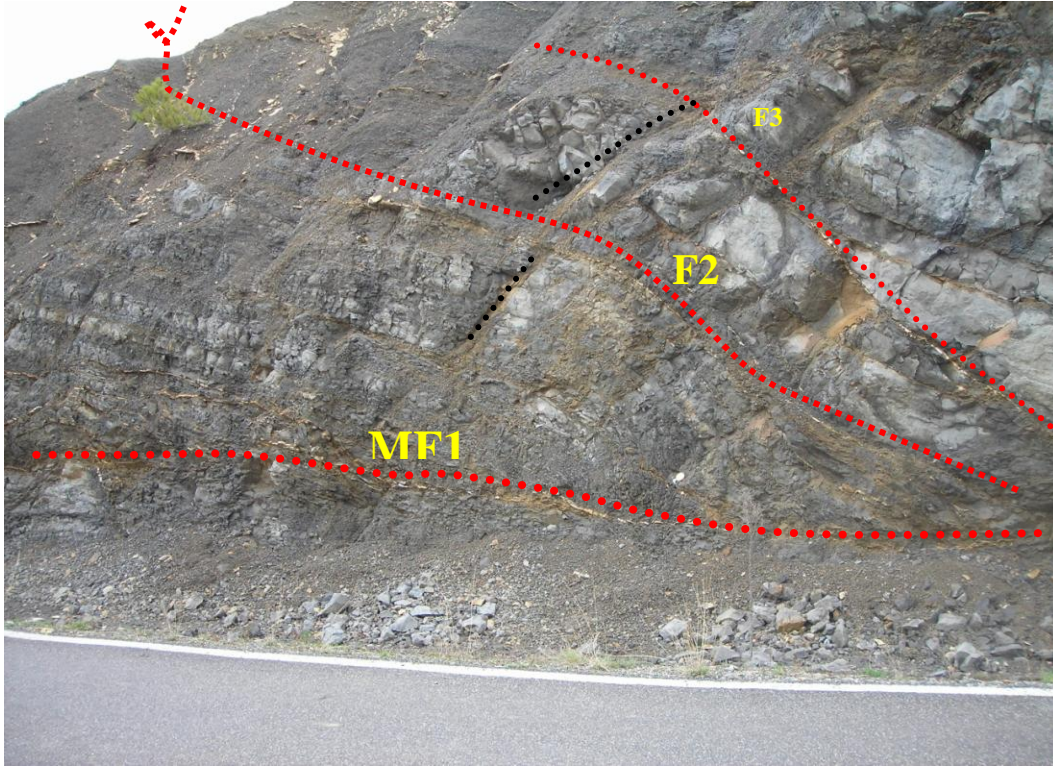
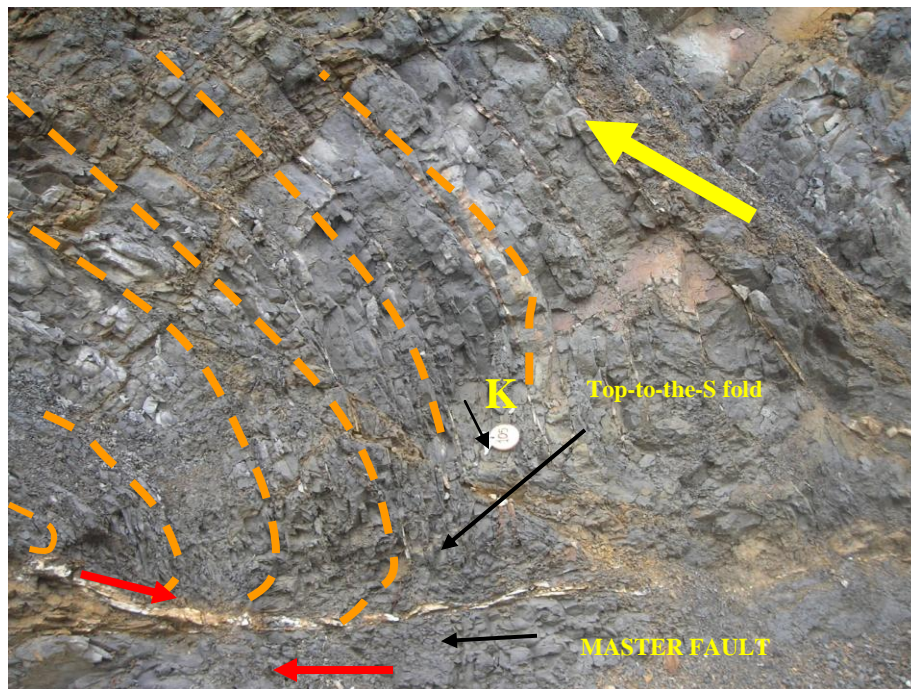


FIGURE 4.11 Above is overview of the road section showing: a master fault (MF1) and shear surfaces **K**= Key holder for scale. Detail of section with the key holder is shown in figure 4.12 To the left are stereoplots plunges of lineations (a) fault plane (b) poles (c) for master faults at road section..

Folds

In the road section, some of the tectonic lenses encompass isolated folds two of which can be studied in the road section. They are small asymmetric fold with wave lengths of about $\frac{1}{2}$ m with amplitude of approximately 1 m. They have recumbent form and located within the main thrust surfaces. The lower limb, of fold one in close contact with the master fault has been sheared. The folds are compressed and continuously rotated during transport by their bounding upper and younger fault surfaces. Minor fault planes are also involved in the folding, these are older fault. A new generation of fault planes which are not folded indicating a second phase of thrusting can be studied in the road section. Lithologic units found within the folds slope mudstone intercalated with thinly bedded sandstones all of Eocene age (Figs.4.12).



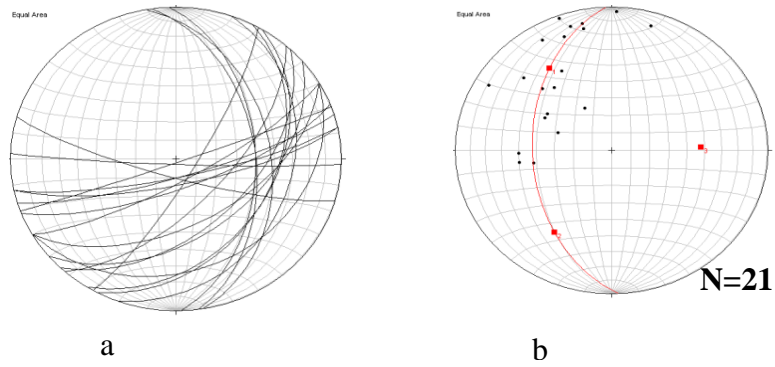


FIGURE 4.12 Road section showing the development folds within the deep marine deposits of the hanging wall of the master fault at the road section. K=Key holder for scale .Planes (a) and best fit (b) of bedding of fold at road section. Note the top-to-the-south fold in the hanging wall of the master thrust. Yellow arrow for North direction

Horses and Duplexes

Duplexes can be studied at the road section. Good system of imbricate lense-shaped to sigmoidal horses seen enclosed within the steep faults with the horses linking the roof and the sole thrusts with top-to-the-S transport or foreland stepping configuration. Individual horses can be observed to stack on top of each other resulting in a small metre-scale antiformal stack which can be observed around the centre of the road-section. Lithologies involved are mudstone intercalated with thinly bedded sandstones.

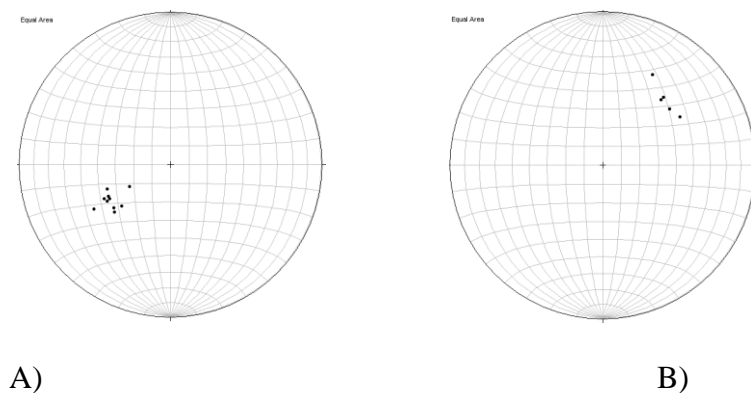


FIGURE 4.13 Poles a) and lineation b) for the master faults at the duplex structure.

The escarpment

An exposure located at the foot of an escarpment about 30 m east of the road section (Fig.4.9 UTM: 274613E/469827N to 274780E/469832) The erosion gullies in the escarpment offers a three dimensional view of the thrust observed at the road section (Fig.4.12). The section of about 100 m long and approximately 15 high with a major gully crossing the escarpment. The major features measured within this sub-locality are the master faults and lineation which are well exposed along sections cut by erosion (Fig.4.15) The fault planes dip gently towards the E. Imbricate thrust faults dominate the deformation of the strata with top-to-the-SW transport as can be seen in the stereoplots (Fig.4.14).

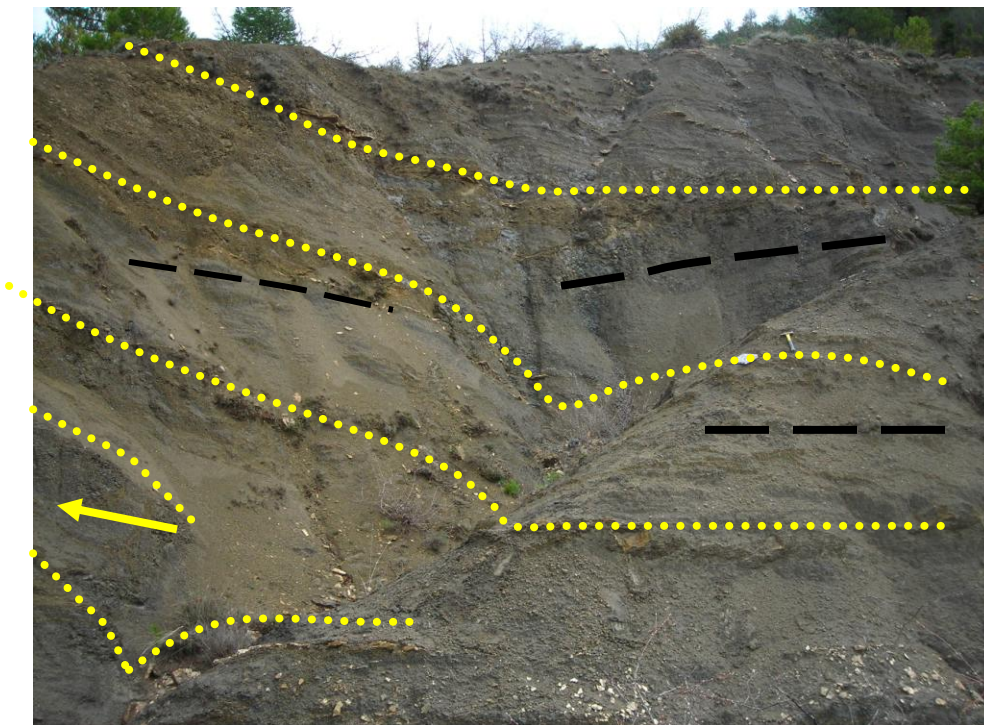
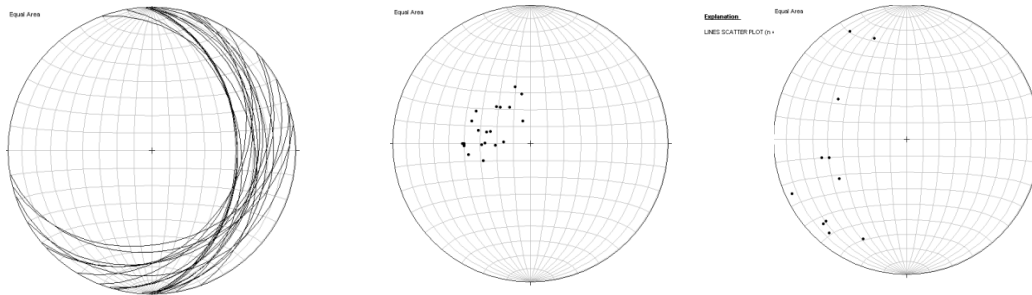


FIGURE 4.14 Three dimensional view of escarpment dissected by erosion. Note the calcite filled shear veins (Yellow Lines) cutting through the mud which has been previously folded. Note the array of overlapping thrusts (Yellow dotted lines). Yellow arrow for the north direction.



a



b

c

d

FIGURE 4.15 Escarpment a) master fault exposed within a gully at the foot of the escarpment within the mud layer b) planes c) poles and d) lineations for the master fault at the escarpment. Yellow arrow, for north direction.

4.3.2 Major faults (*The Gully*)

The gully is located about 3.5 km east of the road section. (Figs.4.9, 4.19; UTM: 27509E/469839N, 27519E/46984N, 27515E/469842N, and 275116E/469840). It offers approximately 100 m long and 15 m high exposure with an approximate N-S orientation (Fig.4.16). The lithologies within the gully are mudstone and turbiditic sandstone (slope facies) and shallow marine carbonates. A marker sandstone bed occurs at this locality; it

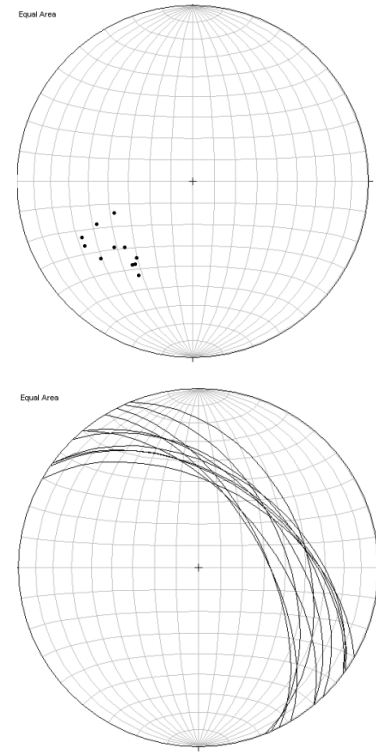
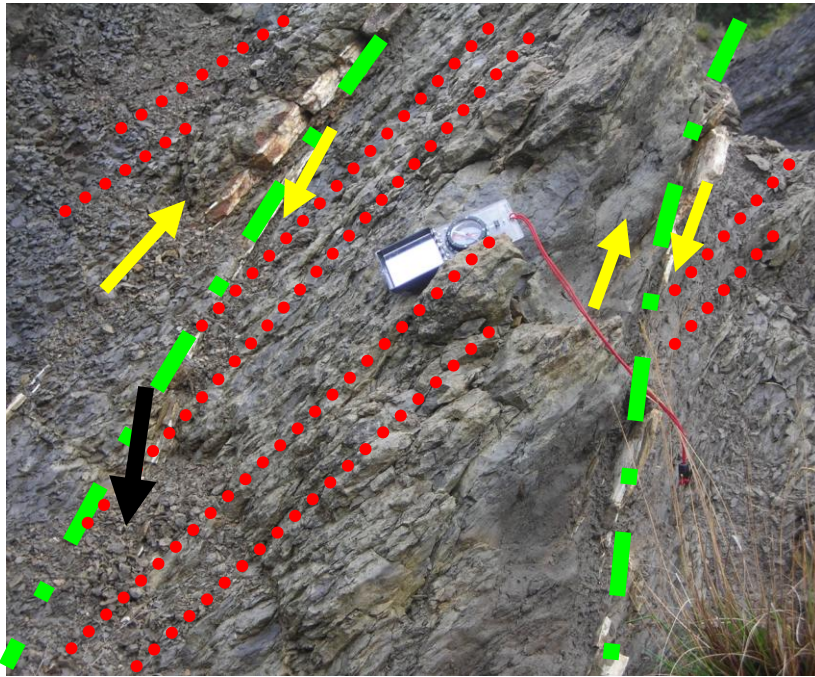
strikes E-W with a maximum dip of 70 degrees. Some segment are vertical and within the this same vicinity some are overturned and assumes a NW-SE strike with an average dip of 65° (Figs. 4.13 & 4.16). The fault system affecting the strata here is characteristically high-angle and can generally be subdivided into major and subordinate faults

Major faults

The major faults in the gully area are characterised by a number of major calcite filled fault planes. They are continuous and inclined at relatively steep angles with dominant dip of about 60° to the E and westward directed with concave upwards geometry. Its sense displacement has been well preserved within the incompetent mudstone beds that have been affected (Figs.4.16and 4.18). The hangingwall blocks have been displaced up the fault plane relative to the footwall blocks the Los Comune syncline. The measurement of the fault plane is shown in figure 4.17b



FIGURE 4.16 High-angle reverse faults found in the gully. Note the convex upwards geometry of the incompetent mudstone as it has been forced upwards at the contact with more competent limestone beds of the foot wall to the right of photograph. Section viewed from the N-W.



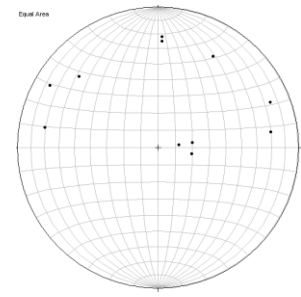
a)

b)

FIGURE 4.17 Reverse faults. Two main faults planes (green dotted lines) cutting through the axial plane cleavage showing reverse slip movement within an overturned syncline in the Los Molinos area (a) and planes and poles for the fault plane (b1 and b2) See Figure 3.14 above for location of the above fault zone. Black arrow for North direction

Sub-ordinate fault

Within the vicinity of the gully, a subordinate fault zone can be studied it is located in close proximity, further W and to the SE of the location of main reverse faults discussed in the previous section for tens of metres. (UTM275191E/469840 to 274861E/4698281N). The trend of these faults can be traced in most places to coincide with small topographic lows where mudstone is sandwiched between nearly vertical limestone beds. This part corresponds to the Los Comune syncline and the antiform fault zone (Figs.4.16). The surrounding strata are characterized by fibrous slickenside lineations with striae which reveals dominant plunge of about 65 degrees indicating dip-slip movement (Fig.4.18). These constitute the subordinate faults which occur in both the carbonates mudstones and sands of this area.



a)

b)

FIGURE 3.18 View of the Los Comunes subordinate fault system. Calcite slickenside lineation in limestone and mustone beds the slip fibers showing steps indicating vertical and upward displacement of the missing beds. (dip-slip movement).(a) and Poles for the slickenside lineation found in proximity to the gully area (b)

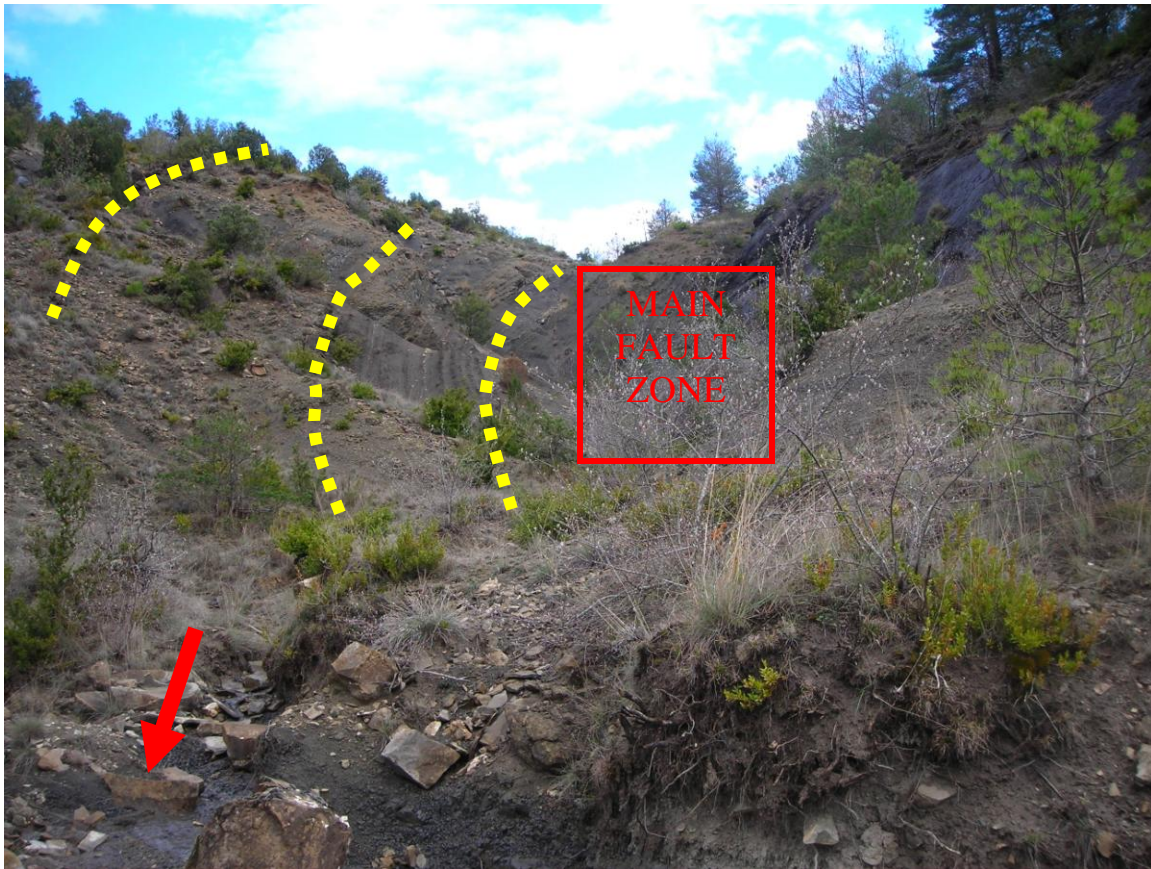


FIGURE 4.19 Location of one of the best preserved fault planes within the gully (Red square see figure 3.14 for detail) Folded and overturned strata to the top left (Yellow dotted lines indicate mud stone intercalated with thin sandstone beds and turbiditic sandstone). Red arrow for north direction.

Preliminary conclusion of contractional faults

In the road section, there are recognised two phases of thrusting associated with the Los Molinos fold-thrust zone. This conclusion is based on the transport directions of the folds and steps in fibrous calcite in the road section, the escarpment (top-to-the-S and SW) and steep faults in the gully (top-to-SW). A comparison of the main fault system in the road section and the gully is worthwhile. The main similarity is that they are all thrust faults. However, the main faults in the road section dip at a low angle approaching horizontality while those in the gully are steeply dipping. The top-to-S low-angle thrusts, post dates the sediments at the road section (slope facies) and predate the top-to S-W thrust system in the escarpment and the top-to- SW steep faults at the gully.

4.3.3 Major folds (Los Comunes syncline and antiform)

The Los Comunes fold system is the dominant structure of the study area. It occupies an area east of the main road (no HU-V6442) from El Pocino to Ainsa. This area comprise a complex relationship between two major folds denoted the Los Comune syncline and the Los Comune antiform. The SW part of this structure host the Los Comune Syncline and the NE part the Antiform (Figs.3.1 and 3.8).

The Los Comune sycline

Good outcrops in this structure are found in the area; UTM: 274789E/469781N, 274808E/469778N. The lithologies affected by the folding are mudstones and shallow marine carbonates of Lower to middle Ypresian age. The fold axes trend N-S and can be traced from El Pocino all through the road section to the N and around the gully and to the SE over a steep hill to a field (Figs. 4.1 and 4.8).. The structure is an open asymmetric syncline with amplitude of approximately 100 m and wavelength of about 400 m. The fold is characterized by gently inclined SW-limb, which strikes approximately N-S and dip 22 degrees east. There is a significant change in the strike and dip of these beds as they are traced northward. At the N- end of the structure the beds strike NE-SW with an overall dip of 65 degrees to the SE, defining the hinge of the structure. The hinge of the syncline, coincides with the main fault zone in the gully (already described, Fig.4.13). The orientation of the bedding is shown in figure 4.20. The fold axis is NW-SE trending with a plunge to the SE.

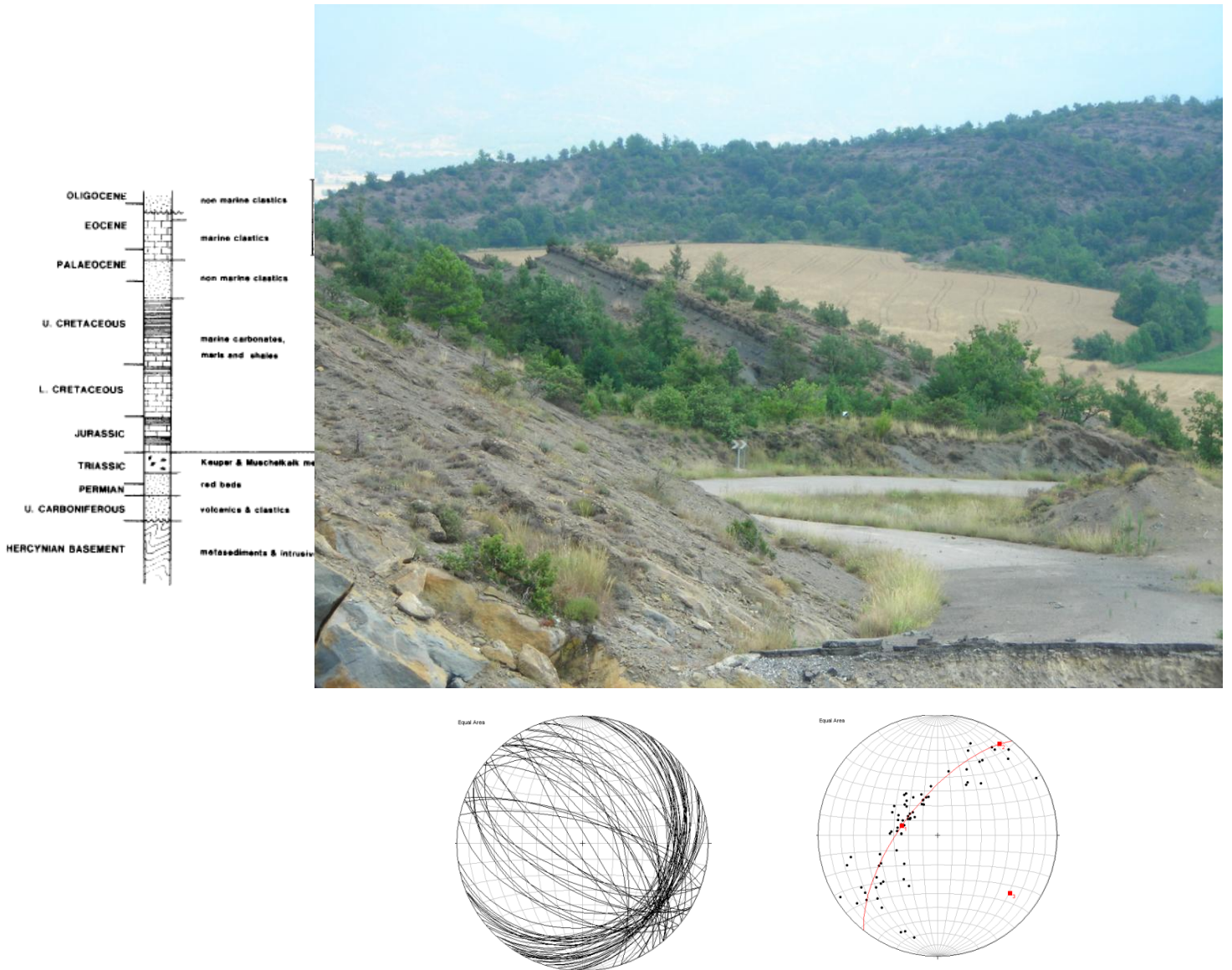


FIGURE 4. 20 The Los Comune syncline. An overview of the Los Comune syncline (above) and plots of the bedding. Note the Nw-Se trend of the fold axis and its SE plunge.

The Los Comune Antiform

Good out crops of this structure have been studied around the gully. The lithology and the setting are same as the gully and have been presented in this section (Fig.4.1). This structure is located to the east, beyond the hinge region of the Los Comune Synform. Of particular importance for the interpretation of this structure an overturned turbiditic bed which is tilted to the east with an over all dip of 65 degrees. This marker bed is medium sand body of medium to coarse grained with irregular base and well developed sole markings. The Bourma BCE sequence has been well preserved within this bed. These sedimentary structures have been the bases of establishing the overturned configuration of this structure among other evidences (Fig. 4.21 and 4.22). The major faults in the gully mark the boundary between this structure and the Los Comune syncline (Fig.4.8).

In conclusion of this section it is important to note that, about the steep fault in the gully, the Los Comune syncline is at the foot wall while the Los Comune antiform defines the hanging wall rock mass.



FIGURE 4. 21 Photograph of sub vertical to Vertical medium size turbidite sand bed at the vicinity of the Los Molinos fault zone and the antiform.



FIGURE 4. 22 Same turbidite sandstone bed beyond the inflexion point is overturned showing erosive base and well developed sole marks.



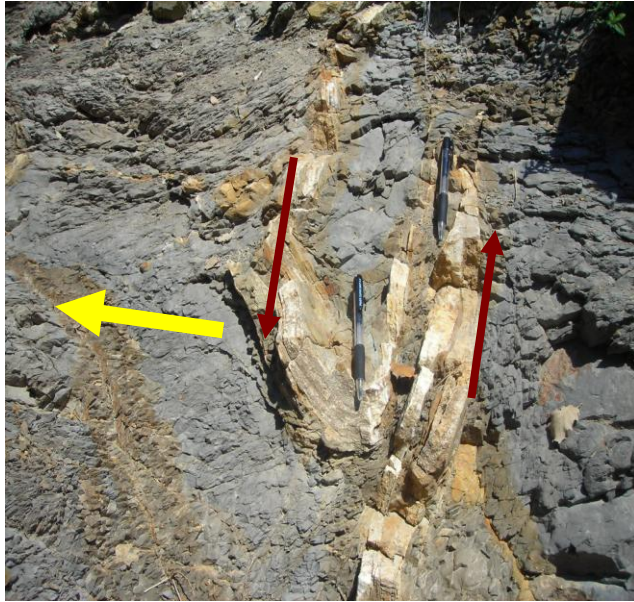
FIGURE 4.23 Los Comune antiform. Showing view of the relation between antiform and the main fault zone.

Secondary structures formed during flexural-slip folding

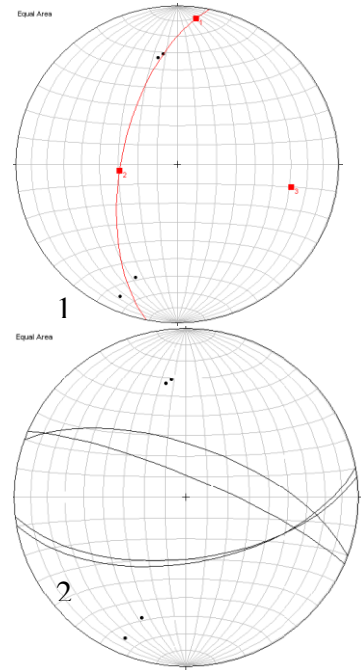
Within the Los Comune area the rocks around the folds presents excellent outcrops for the detail study of secondary structures associated with folding. An important feature which has been studied in association with the major fold are parasitic folds which is located within the overturned beds. The limb of the Los Comune syncline provide outcrops suitable for this study.

Parasitic fold

This secondary feature was found within the strata of the overturned limb of the syncline. It is a small structure exposed in a small stream channel. (UTM: 275308E /4698186N) It is a calcite filled sole thrust that has been folded into a tight asymmetrical fold within a mud bed (Fig.4.24). It has a wavelength of approximately 4 cm and an amplitude of 5 cm. Its orientation is NW-SE. (Axis is approximately parallel to that of the antiform). It can be used to interpret fold patterns; the axial trace of the major folds could be traced based on the shift of the asymmetry of the drag fold from S to Z or from Z to S geometry. The antiformal versus synformal nature of the fold could be interpreted based on the the sense of layer parallel slip reflected by the drag fold within the limbs of the major fold.



a)



b)

FIGURE 4.24 S-shape drag fold resulting from counter clockwise internal rotation found in mud within the overturned beds (fault zone). Note left handed shear (red arrows) and the two axes at the locations of the pencils (a) and Poles and best fit for the parasitic fold (Yellow arrow =North direction and pencil for scale)

4.3.3.1 Fracture analysis at Los Comunes

Introduction

It is has been noted that fractures have diverse origins and they commonly develop when the stress exceeds the tensile strenght of the rock. The generation of stresses leading to the formation of joints found in rocks may be related to one or a combination of the following factors; uplift and unroofing of rocks, compaction of the sedimentary layers and regional deformation of rocks (Hancock,1994).

In this section fractures measured at the road section and on the bedding surfaces of the Los Comune have been discussed. Only a brief account of the road section has been presented; two fractures populations have been measured at the road section for comparison with those of the Ainsa Quarry (Populations L6 and L7). Input for the fracture analysis of the Los Comune area is based on data obtained from bedding surfaces of the syncline (UTM: 274789E/4697808N to 274808E/44697780N).

ROAD SECTION

The fracture population related to burial and uplift are well exposed at the road section. The fractures are commonly steeply dipping and intraformational. Fractures which originate at the upper bedding plane and terminate within the bed are common.

Fracture characterization – Los Comunes

This part of the study area is located in the frontal part of the Pyrenean thrust and fold belt. The area is located approximately 15 km east of Ainsa. It is made up of deepmarine muds overlain by shallow marine mixed carbonate siliciclastics all of Eocene age. The area has been fractured in various ways and detailed studies of the fractures in this area have been made. The fracture populations measured are populations L6, L7, L8, L9, L10 and L11 discussed below;

Population L6 – This population is calcite filled and occurs normal to sub normal to bedding. They are mode I tensile fractures. They are intraformational and mainly closed fractures. The average orientation is N-210 (Fig.4.25)

Population L7 - These populations are mode I tensile fractures. They are intraformational with steep dips their average orientations N-140. Fracture frequency for this population is

very low. They are open fractures and show evidence of fluid weathering (Figs.4.25 and 5.3)

Population L8 This population is fracture cleavage and related to the Los Comunes antiform cleavage. The average strike is N-319.

Population set L9

This is one of the major fracture populations in the area. Their average strike is approximately N-S and occur as single fractures in most of their length. There is a high degree of fluctuation of frequency of these population, high frequencies are noticed around the hinge area of the fold.

Population set L10 This population is calcite filled and generally straight. Open fractures of this population predominate. The average strike is N-250

Population set L11 These populations are shear fractures with an average strike of N-130°. The fractures are commonly calcite filled with only a few of them which are not (60 to 80°). They generally have steep dips. The proportion of open fractures to close ones is high.

Preliminary conclusion of Los Comunes area

This area has the following fractures

L6– mode I related to burial intraformational mineralized, sub-normal to bedding

L7 – related to uplift there open unmineralized

L8 – mode II related to tectonics, there are fracture cleavage

L9 – tensile mode I related to N-S compression

L10– mode II conjugate shear fractures related to tectonic NE-SW compression

L11- mode II conjugate shear fractures related to tectonic NE-SW compression

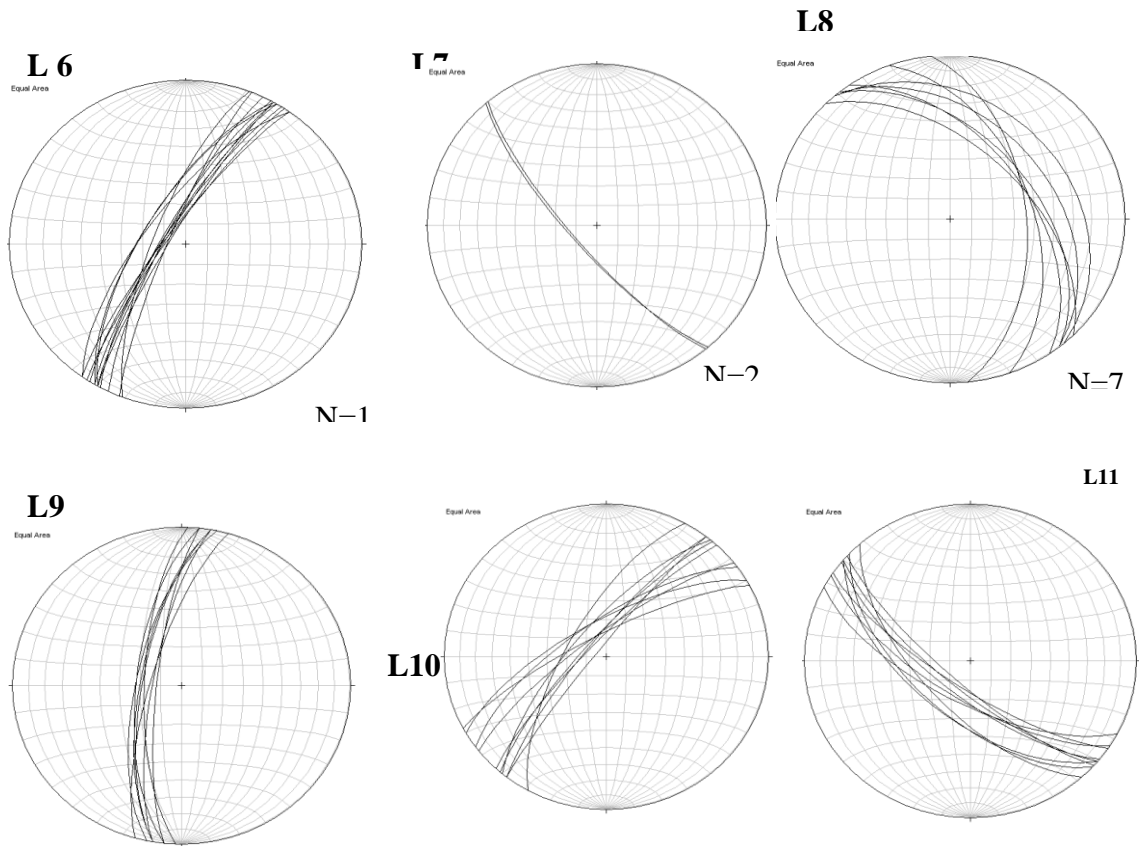


FIGURE 4.25 Open fractures at the Los Comunes area. Note their normal orientation to bedding



FIGURE 4.46 Vertical and intraformational fracture from the road section at Los Comunes area (Compare with fig.4.5).

Field data were collected from the hillside with very good rock exposures were joints on rock surfaces can be suitably measured around the Los Comunes syncline.

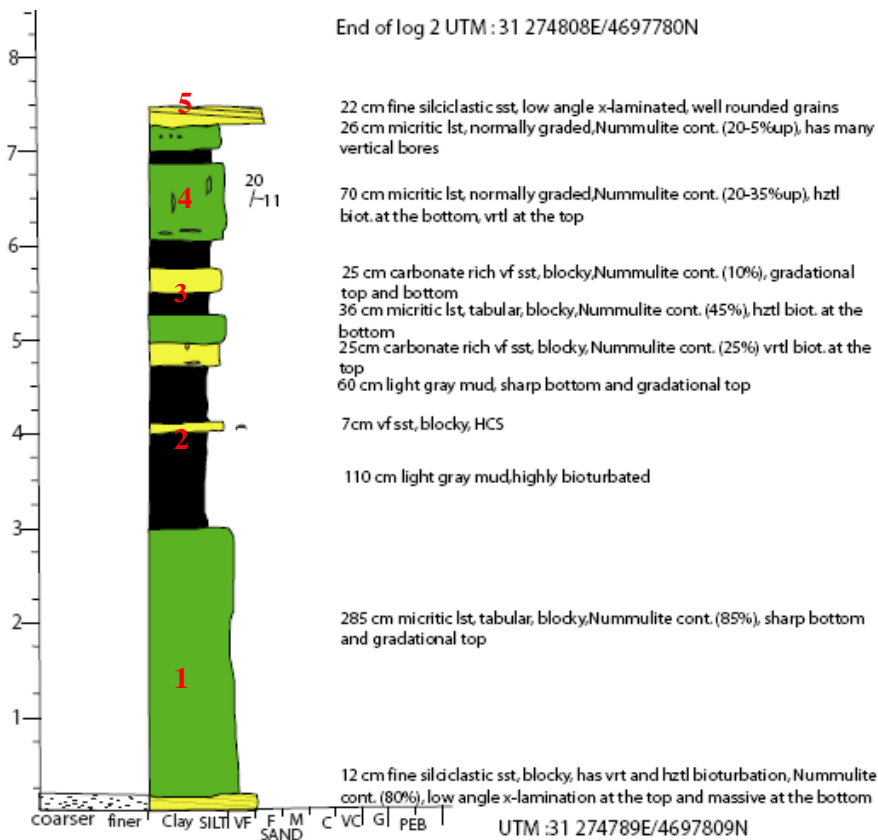


FIGURE 4.27 Log of locality 1 within the main structure where fractures on bedding surfaces have been measured. Note the five beds (Bed1-5), their thicknesses and lithology used for fracture frequency analysis. Note the variability of the beds in terms of thickness, lithology and relative positioning. (Woyessa, 2008)

A section of about 120 m long and 9 m high perpendicular to the main road can be studied in detail (Figs 4.27). The beds show a variable strike from SSW-NNE to SW-NE. Lithology is deep marine overlain by shallow marine mixed carbonates silici-clastics platform deposits of Eocene age. Joints are restricted to the competent layers. Five beds have been selected for the purpose of fracture analysis. A description of these beds is presented below;

Bed 1 is 285 cm thick micritic limestone with about 85% nummelitic content. Bed 2 is very fine grained carbonate rich sandstone, blocky and has hummocky cross bedding. Bed 3 is 25 cm thick carbonate rich very fine grained sandstone which is blocky and contain about 10% nummelites. Bed 4 is micritic limestone with about 35% nummelitic content and 70 cm thick. Bed 5 is 22 cm fine grained silisiclastic sandstone. (Fig.3.19). For each of the five beds, the distance perpendicular to the joints surface was measured and the number of joints per unit length was calculated.

TABLE Number of joints counted per unit length for five beds at Los Comunes

BED	THICKNESS(M)	Population L9 No of fractues	Population L10 No of fractures	Population L11 No of fractures
1	9.7	8	4	3
2	0.92	9	9	11
3	2.04	9	9	11
4	5.34	9	3	0
5	1.25	11	4	11

TABLE Fracture frequency of the corresponding fractures above

BED	THICKNESS(M)	Population L9	Population L10	Population L11
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		Fracture frequency	Fracture frequency	Fracture frequency
1	9.7	0.82	0.4	0.5
2	0.92	9.8	7.4	10
3	2.04	5.4	1.6	2.15
4	5.34	1.7	1.1	0
5	1.25	8.66	3.33	10

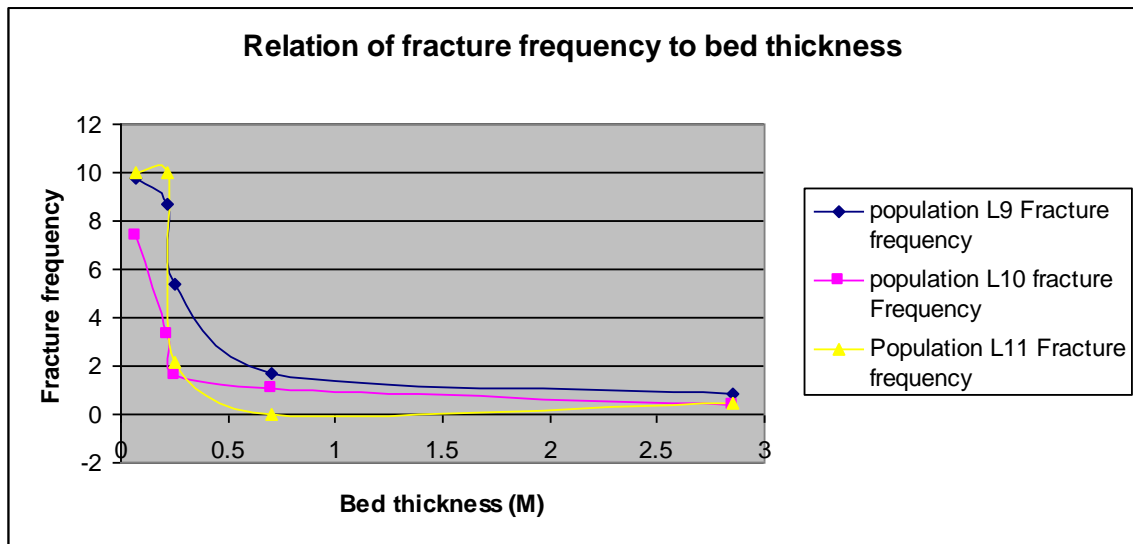


FIGURE 4.28 Relationship between fracture frequency and bed thickness for five beds of different thickness at Los Comunes.

The above results show that joint spacing is a function of bed thickness. The fracture frequency is inversely proportional to bed thickness. The thicker the bed the greater the joint spacing and vice versa. This result is in line with what is in the literature (Shaocheg et al. 1998; Hancock, 1994).

Communication

The figure 5.3 is showing open fracture with evidence of fluid migration. This observation points to good communication within the open fracture system in the Los Comunes area.

Chapter 5 Discussion

5.0 Introduction

Two main areas have been the focus of this study. There are the less tectonically deformed Ainsa Quarry located south of Ainsa Town and the more deformed Los Comune area to N-E of Ainsa (Fig.4.1). These areas are crucial in the evaluation of the influence of the Alpine tectonics across the western oblique ramp of the south central Pyrenean unit (SCPU). According to Dreyer et al., (1999) the Ainsa basin started its development during the Cuisian-Lutetian due to flexural subsidence of the area adjacent to the active south Pyrenean central thrust sheet. A thick deep marine slope succession (the San Vicente Formation) was formed within this part of the study area (transitional foredeep) underlain by a deeply buried sole thrust (Muñoz et al., 1994, 1998). These part of the study area defines the boundary between the Tremp-Graus and the Ainsa basin (Dreyer et al., 1999). The boundary is characterized by a change from the southward thrust displacement of the eastern Tremp-Gruas basin to a south-westward thrust displacement of the of the western Ainsa basin.(Nijman and Nio, 1975; Munoz et al 1994, Teixell 1996). This boundary zone accommodated the Lower to Middle Lutenian slope deposits in close interaction with active thrusting (Mutti et al.1988; Muñoz et al., 1994). During the Middle Lutenian and Bartonian, antiformal stacking of the thrust sheet occurred within the eastern part of the Ainsa basin, mean while the sole thrust of the Ainsa basin broke surface in several locations accounting for the high topography

(Dreyer et al., 1999). A major thrust system extends from the master thrusts beneath the greater nappes associated with the regional-scale south to south-west imbricate thrusts and related fold system. The Mediano anticline is one of the prominent expressions of the thrust top phase which vans to the south characterized by gentle dip corresponding to the location of Ainsa Quarry (Puigdefabregas et al., 1991; Barnolas and Teixell, 1994). The Los Comune area located within close proximity of the thrust front, have been deformed into folds and faults and characterized by elevated topography and steep dips.

5.1 Fracture populations in study area

Eleven distinct populations of fractures have been identified in the study area; they are presented below with their basic characteristics;

5.1.1 Populaatios within the Ainsa basin

- 1). Population **Q1**, these are sub vertical to vertical open intraformational mode I fractures related to shallow burial
- 2). Population **Q2**, they are mode I tensile fractures which are strata bound and approximately normal to bedding.
- 3). Population **Q3**, are mineralized mode I fractures which are steeply dipping and strata bound and related to deep burial.
- 4). Population **Q4**, are steeply dipping open unmineralized mode I tensile fractures which are cutting through many beds.
- 5). Population **Q5**, these are mode II fractures related to strike slip movement this is recorded from the dextral strike slip movement of ht fault plane in figure.

5.1.2 Populations within Los Comunes area

- 6). Population **L6** they are mode I fractures, calcite filled and normal to bedding .
- 7). Population **L7** population consist of open model fractures with steeply dipping and un mineralized.

- 8). Population **L8** these are mode II fractures which are related to cleavage these fractures are characteristically cutting through many beds.
- 9). Population **L9** these are steeply dipping mode I extensional fractures strike is approximately N-S multiple bed fractures.
- 10) Population **L10** these are calcite filled shear fractures related to folding
- 11) Population **L11** these are calcite filled shear fractures related to folding

By analyzing the fracture systems, I intend

- 1).to evaluate the distribution of the different fracture sets
- 2). to determine the structural environment for their initiation and development
- 3). to determine the relation between the Los Comune folds and thrusts and
- 4). to set the fracture systems into the context of the structural history of the study area

Fracture distribution and relation to tectonic development

The problem of fracture distribution and their relation to tectonic development is addressed firstly by categorizing the identified fracture populations according to their total geological environment of formation which corresponds to the types of deformation environments ((Davis and Reynolds, 1996; Gabrielsen et al., 1998). Then there are further discussed in the context of the two contrasting geological settings; from the less deformed, Ainsa Quarry to more deformed Los Comune area.

Sediments deposited in a shallow marine environment, on the surface, undergo burial with continued sedimentation and become lithified and turn to sedimentary rocks. The distribution of joints within this sedimentary rocks has a link to tectonic development of

the sedimentary basin during and after deposition. The simulation of the necessary conditions for the formation of joints in nature has been demonstrated experimentally (Handcock, 1985, Price, 1966, Paterson 1978). Results of “triaxial” compressive test performed in a brittle isotropic rock, when loaded to failure shows that; the fractures developed are symmetrically oriented with respect to the three principal stresses ($\sigma'_1 > \sigma'_2 > \sigma'_3$; compressive stress positive); and the effective stress (σ') being the total stress minus the fluid pressure or $\sigma' = (\sigma'_1 - \sigma'_3) - P$ (fluid pressure). The type of fractures that will be generated will relate to the value of the minimum compressive stress (σ'_3) and the stress difference ($\sigma'_1 - \sigma'_3$) relative to the tensile strength of the rock. Three main fracture classes are recognized by assuming the generalized failure envelope with an angle of internal friction (ϕ). From this, the principal stress axes can be determined. It is well known that the tension fractures are generated perpendicular to the minimum stress plane (σ'_3) containing ($\sigma'_1 - \sigma'_3$). The shear or conjugate fractures enclose an acute bisector which is parallel to (σ'_1) or the maximum stress axis (Fig.5.5 Hancock,1985)

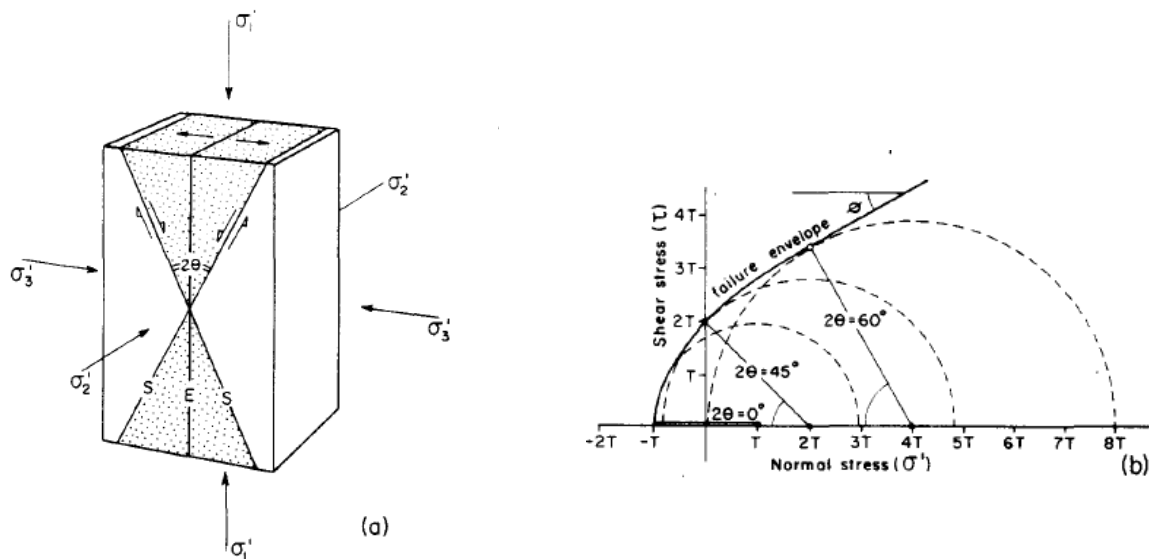


FIGURE 5.1 (a) The relation between the between effective principal stresses ($\sigma'_1 > \sigma'_2 > \sigma'_3$), extensional or tensile fracture (E) and conjugate shear fractures (S) (b) Composite failure envelope with Mohr circles constructed for $2\theta = 0, 45 \text{ \& } 60^\circ$ Where T= tensile strength and ϕ =angle of internal friction (Handcock1985)

Table 5.1 Classes of brittle fractures (Handcock1985)

Class	Failure mode. Etheridge (1983)	$(\sigma_1 - \sigma_3)$	Dihedral angle (2θ)
Extension fracture	Tensile failure	$<4T$	0°
Hybrid shear fracture	Extensional shear failure	$4T-8T$	$1-60^\circ$
Shear fracture	Compressional shear failure	$>8T$	$>60^\circ$

Fracture populations in the Ainsa Quarry and Los Comune

Five fracture populations identified in the Ainsa Quarry are populations Q1 to Q5. These populations are both mode I (tensile fractures) and mode II fracture (shear fractures) and are related to burial and uplift. The steeply dipping fractures linked to burial are two types; fractures which are open and intraformational, are generated at relatively shallow depths and fractures which are intraformational and mineralized, are tensile fractures linked with moderate to deeper burial. The mode II shear fractures at the Ainsa Quarry are related to strike slip deformation characterized by the development of fibrous calcite slickenside lineation on the fault plane. In contrast, six fracture populations (L6, L7, L8, L9, L10 & L11) have been identified in Los Comune area and related to burial, uplift and tectonic deformation (see description of the populations above). These fracture populations are discussed below in the context of their mode, orientation, mineralization geometry and environment of generation.

5.2 Fracture population at Ainsa Quarry

5.2.1 Fractures related to burial and uplift

The Ainsa Quarry is composed essentially of deep marine turbiditic sandstones. The fracturing of the sandstones is related to burial and uplift. An approximately 5000 meters of upper Eocene sediment are deposited in U-shaped arc within the Ainsa basin (developed laterally to an active south Pyrenean central thrust sheet) in a regressive setting with lower slope marls and turbidite sandstones (The San Vicente Formation) overlain by a thick succession of continental and deltaic deposits of the Tremp-Graus 'piggy-back' basin (Ninjan and Nio, 1975, Ori and Friend 1984, Puigdefabregas, et al,1991, Ninjan, 1998, Dreyer, et al 1999,). Vertical compression due to burial under this sedimentary pile is able to generate differential stress great enough to initiate fracturing. The fracturing of the rocks are enhanced by compaction of this huge overburden.

The fracture populations have been placed at approximate positions in the burial/uplift curve to visualize the likely environments of the fracturing within Ainsa Quarry.

The fracture formed as a result of burial and uplift respond to vertical and horizontal stresses at intervals during this development. The effective vertical stress is given as

$$\sigma_1 = \rho gh$$

where'

- σ_1 = effective vertical stress
- ρ = density of overlying column
- g = gravitational constant
- h = depth

Burial and uplift

Extension or tensile fractures are formed normal to the direction of σ_3 at the instance of failure as shown in figure 5.1 above. Fractures related to burial and uplift are basically

tensile. These class of joints are mode I and normally propagated perpendicular to the direction of opening of the crack (Fig .5.1)

Burial stage

The fractures which are generated by loading and are steeply dipping tensile may be initiated at shallow depths (Fig.5.1 population 1,2,3,& 6 ;Davis and Reynolds, 1996; Gabrielsen et al., 1998.) where they will not be mineralized or at greater depths where they can be mineralized.

Uplift stage

Meanwhile uplift accompanied by unroofing result in a significant buildup of internal tensile stresses that may be larger than the tensile strength of the rock. Tensile fractures will then form effortlessly (Fig5.1).

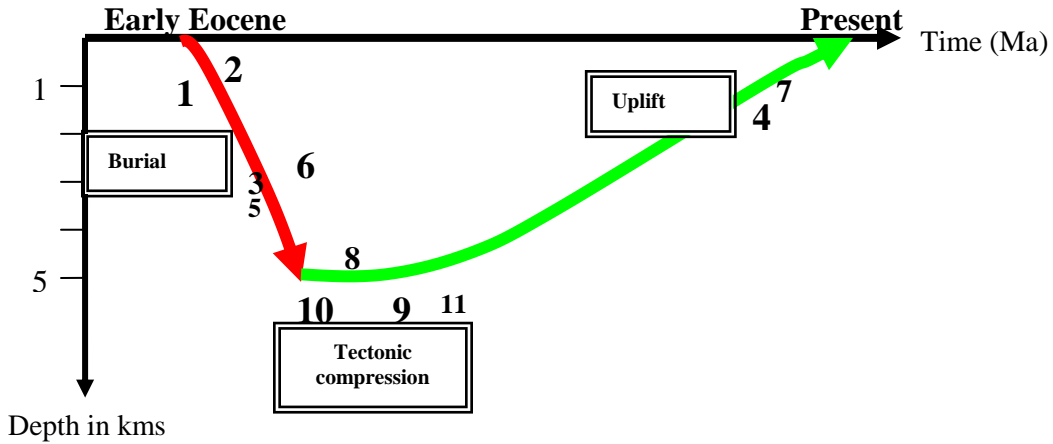


FIGURE 5.2 schematic relations of the geological processes and the types of fracture populations generated in the study area. The red curve corresponds to burial and the green one to tectonic compression and uplift. Figures 1, 2, 4, 3, 5, 6 and 7 are fracture population generated during burial and uplift. Figures 10, 9, and 11 are populations generated due to tectonic compression.

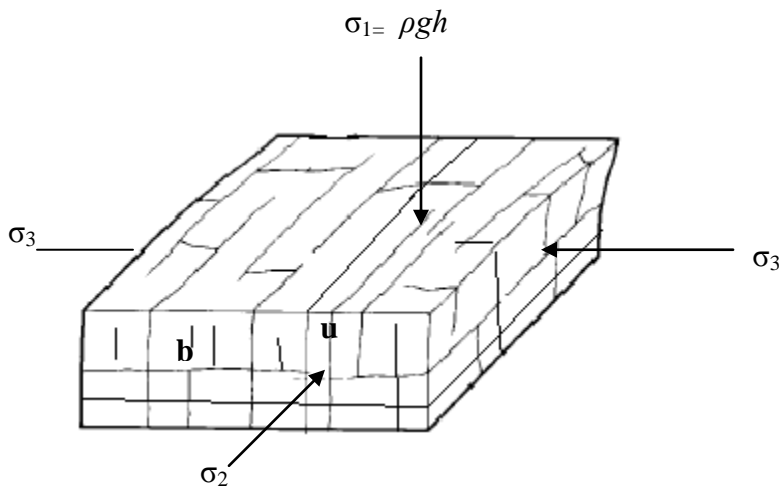


FIGURE 5.3 Generation of extension fractures due to burial and uplift at the Ainsa Quarry. Fractures related to burial (b) and uplift(u). Note the development of the tensile fracture U perpendicular to the plane of the minimum stress axis, σ_1 and parallel to the plane of σ_1 and σ_2 . Also note that the fractures related to uplift are crossing several beds (Angelier, 1994)



FIGURE 5.3 open fractures generated due to uplift at Los Comunes

5.2.2 Fractures related to tectonic compression

Fracture population Q5 with strike-slip component at Ainsa Quarry with N 217E orientation show dextral strike slip movement. This is quite evident from the steps in fibrous calcite on the fault plane as shown in Fig. 4.6. The initiation of strike-slip takes place with the intermediate principal stress axis, σ_2 is vertically oriented with the maximum, σ_1 and the minimum stress, σ_3 axes in the horizontal. The plane of the maximum stress is oblique (30°) to the plane of the fault or fracture and not parallel as in the case of tensile fractures and the minimum stress axis is perpendicular to σ_1 .

5.3 Los Comunes area

The lithology at this site is deep marine mudstones inter bedded with thin stringers of sandstones overlain by shallow marine mixed carbonate siliciclastic deformed by thrusts and folds. The fracture populations identified within the strata encompasses six population categories including fracture populations assumed to be related to burial and uplift as well as to tectonic shortening.

5.3.1 Populations related to uplift and burial

Within this locality, two populations (L 6 and L7) are related to burial and uplift

Population L6 steeply dipping mode I, calcite filled and intraformational. The average orientation is N210E this population is assumed to be relation to uplift.

Population L7 is open with no mineralization and cut several beds. The average strike of this population is N140 and assumed to be generated during uplift.

Comparison of fractures related to burial and uplift in the Quarry and Los Comunes

Populations Q1, Q2 and Q3 at the Ainsa Quarry are related to population L6 at the Los Comunes area firstly because they are all mode I, normal to sub-normal to the beddings, they are all intraformational, they are all mineralized their orientation is more or less similar (Populations Q1, Q2 and Q3 have the respective orientations N265E, N246E and N229E and population L6 is striking N210E).

Fracture population Q4 of the Ainsa Quarry is related to fracture population L7 from Los Comunes; they are all non mineralized open mode I fractures. They are all steeply dipping and cut through several beds. The orientation of Q4 is N295 and that of L6 is N140E

The similarity between populations Q1- Q3 and L6 stems from the similarity in the burial conditions during their generation. Similarly populations Q4 and Q7 have been subjected

to more or less same conditions during uplift. Implying that both the turbidites at Aisa Quarry and the carbonate siliciclastics have undergone burial and had been exhumed.

5.3.2 Fractures related to tectonic compression

Tectonic stresses may affect the entire crust and related fractures can be generated in rocks at shallow depths as well as in the deeply buried rocks. Some fractures formed under this condition are considered to be response to first-order plate stresses (Gabrielsen et al., 1998). Four fracture populations are related to tectonic compression within the Los Comunes they are L8, L9, L10 and L11. Fracture population L8 is axial plane cleavage

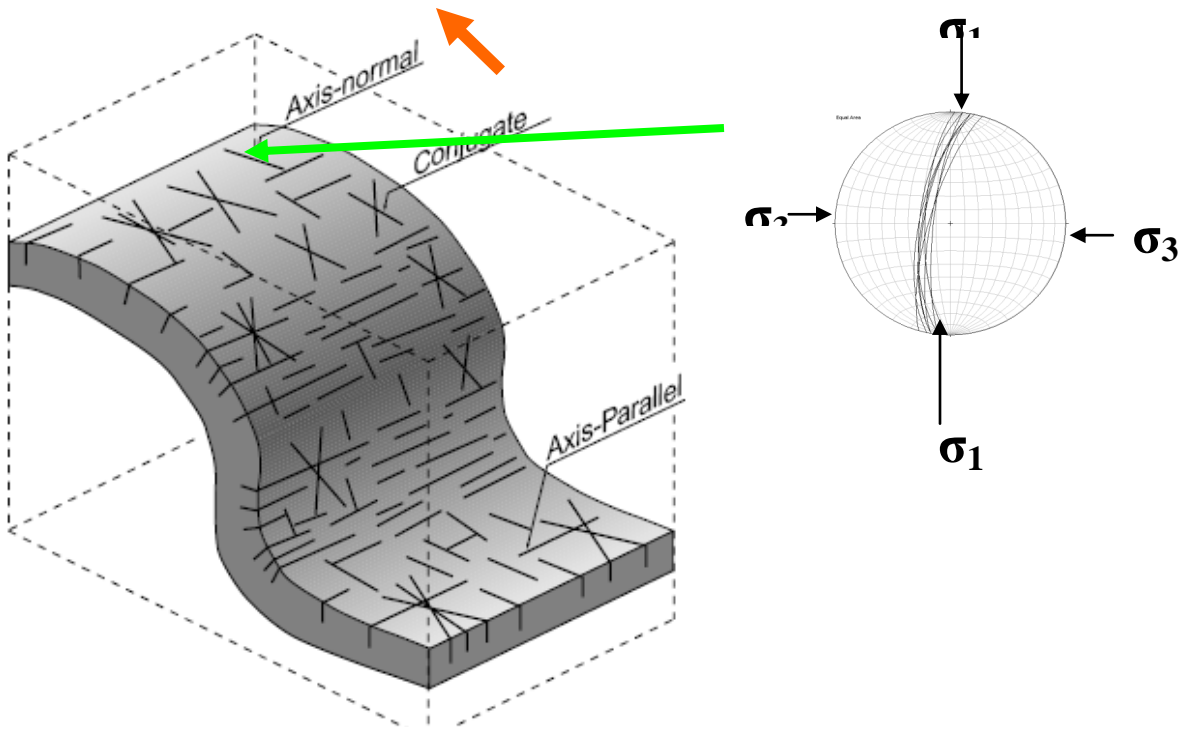


FIGURE 5.4 Relation of fractures to folds. Green arrow is pointing to the tensile fracture which are N-S oriented as shown in the stereonet for population L 9 (Fisher, 2000) Orange arrow for north direction (Fisher, 2000)

According to Van der pluijm (2003) rock cleavage are planes of weakness generated at depth which are subject to fracturing when the rock is uplifted. The cleavage planes in the study are associated with folding see (fig 5.5). Their orientation is NNW-SSE and cut through several beddings.

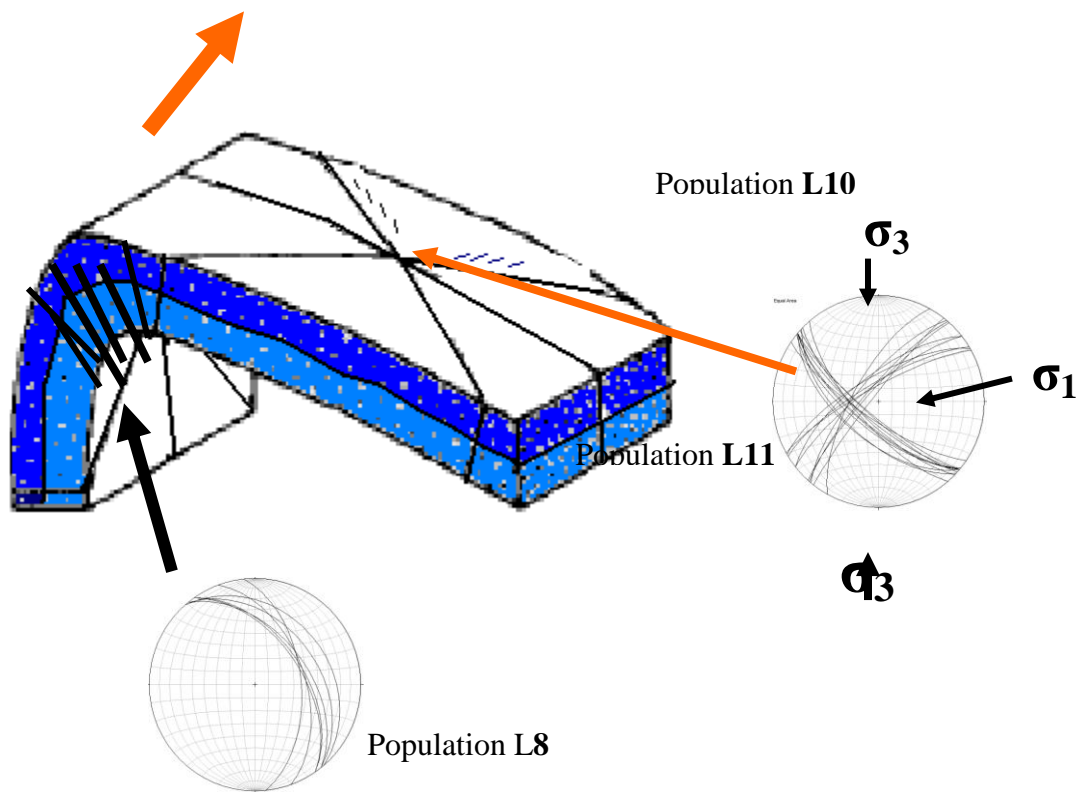


FIGURE 5.5 Relation of the conjugate shear fractures and cleavage to folds in the Los Comunes. Note the top-to-the SW maximum stress field which generated the conjugate fracture system in Los Comunes. Short red arrow for north direction. (*Modified after Hancock (1985).*)

Populations L10 and L11 are oriented NW-SE and SW-NE respectively considering the magnitude of the dihedral angle, 2θ (which is above 60°), these fractures comprise a conjugate set. The orientations of the principal stress axes can be inferred from these conjugate fractures since the attitude of the acute bisector of the conjugate set gives the σ_1 axes and that of the obtuse yields the σ_3 and the point of intersection between the sets yields σ_2 from these indicates the top-to-the-south west transport direction at the time of formation of the fractures

5.4 Relation between Los Comunes folds and thrusts

The Los Comunes area is located at the frontal part of the Pyrenean thrust fold (Fig3.1 and 3.8). The main lithology within this area comprises of less competent deep marine mudstones overlain by the more competent shallow marine mixed carbonate-siliciclastics of Eocene age. These part of the study area have been deformed to a number of fold and thrust systems. The structural complexity of the area points out from its relative position to the main fold and nappes, the Mediano anticline and the Cortiella and the Atiart thrusts systems respectively. Local changes in the stress fields during the evolution of this part of the basin may have had considerable influence..

Recent studies have demonstrated the occurrence of different structural styles in fold-fault deformations. The fold-fault relations for simple structures are reliant on the mechanisms of deformation. Three main fold-fault relations can be used to explain the majority of simple structural geometries in fold and thrust belts. There are fault-bend folds, fault propagation folds and detachment folds. The above models have been described by Suppe (1983, 1985); Mitra and fisher (1992). Also find illustration of the models in the terminology section (Figure1.4).

Mapping around Los Comune has revealed a number of structural elements of deformation which are; 1). *the Los Molinos fold and thrust system* 2). *the Los Comunes major faults* 3). *the Los Comunes folds*

The *Los Molinos fold and thrust* which constitute a major thrust and fold zone located at the foot wall of the of the Cortiella and Atiart thrusts is well represented in an approximately N-S trending road section and an E-W escarpment in close proximity in Los Comunes (Figs. 4.8 and 4.9). The thrust had affected deep marine mudstones intercalated with thinly bedded sandstones. The main structures in the road section are; thrust folds, low-angle and high angle thrust faults and duplexes. The major fault planes around the southern part of road section show gentle dips towards the south. The duplexes show a top-to-S transport direction indicated by southward stepping of the horses (Fig.4.10). The main thrusts in the escarpment shows mainly top-to-the- S-W transport as indicated by the calcite slickenside lineations found within the fault planes exposed at the gully (Figs3.12).

The major faults, an approximately 7 m wide reverse fault zone is located between the Los Comune folds. The main fault plains are steeply dipping with overall angles of dip of about 60 degrees to the E. The hanging wall antiformal block has migrated up-dip to the W relative to the foot wall, the Los Comune syncline. Eastwards dipping slickenside lineation characterized by fibrous calcite with dip angles ranging between 60 and 65 degrees can be found within area for tens of meters (Figs. 4, 17 and 4.18). In conclusion, two major fault systems exist in the vicinity of Los Comune encompassing the low angle and high angle contractional faults

Los Comune major folds.

The major structures of the Los Comunes area encompass a syncline (the Los Comunes syncline) and an anticline (the Los Comunes antiform) above the major detachment described in the previous section, a spatial and genetic relationship between these features is clear. The folds constitute the hanging wall of the major thrust which in turn is truncated by a reverse fault (Fig. 4.17). The footwall fold represents a recumbent isoclinal fold with a NW-SE trending fold axis. The upper limb of the hanging wall antiform is overturned around a NNE-SSW trending fold axes (Figs.4.16, 4.17 and 5.8) with major strata dipping to the E (approximately 65°). Here, turbiditic sandstones are situated with sedimentological right-way-up stratum overturned, this is documented by the occurrence of sole markings at the present top of the bed (Figs 4.21 and 4.22). There are also small parasitic folds related to the major folds mentioned above probably generated due to internal rotation of the fold limb (Fig.4.24)

5.4.1 The development of the Los Comunes fold-fault system

The aim of this section is to evaluate the genetic relation of the Los Comunes major folds and faults. The link between the folds and the faults in the Los Comunes requires that the field relationship of the Los Comunes syncline, the Los Comune antiform and the major

faults be established. These have been achieved by mapping and constructing a cross section for the Los Comunes fold-fault area (Fig.5.8) It is observed that the fault-propagation-fold model fits reasonably with the geometry of the Los Comunes fold-fault structure, whereas the fault-bent fold and the detachment fold models shows considerable departures.

Model for the development of fault propagation fold

Stages of development of fault propagation fold are shown in Figure 5.6 below. The determinant of progressive evolution of the fault propagation fold is an advancing fault tip. From the flat-lying pre-tectonic sequence of sedimentary rocks (A) the thrust initiates and the fault tip branch upwards at the sole thrust. (B). as the thrusting progresses, the fault tip migrates upwards until the final stage of deformation (C-D). At each stage of development the hanging wall strata glide along a lower flat and up a ramp and become replaced upward by an asymmetric fold which is overturned in the direction of transport (fault propagation-fold). Above the fault tip in the hanging wall, a complementary fault propagation fold (*an overturned anticline*) may be developed

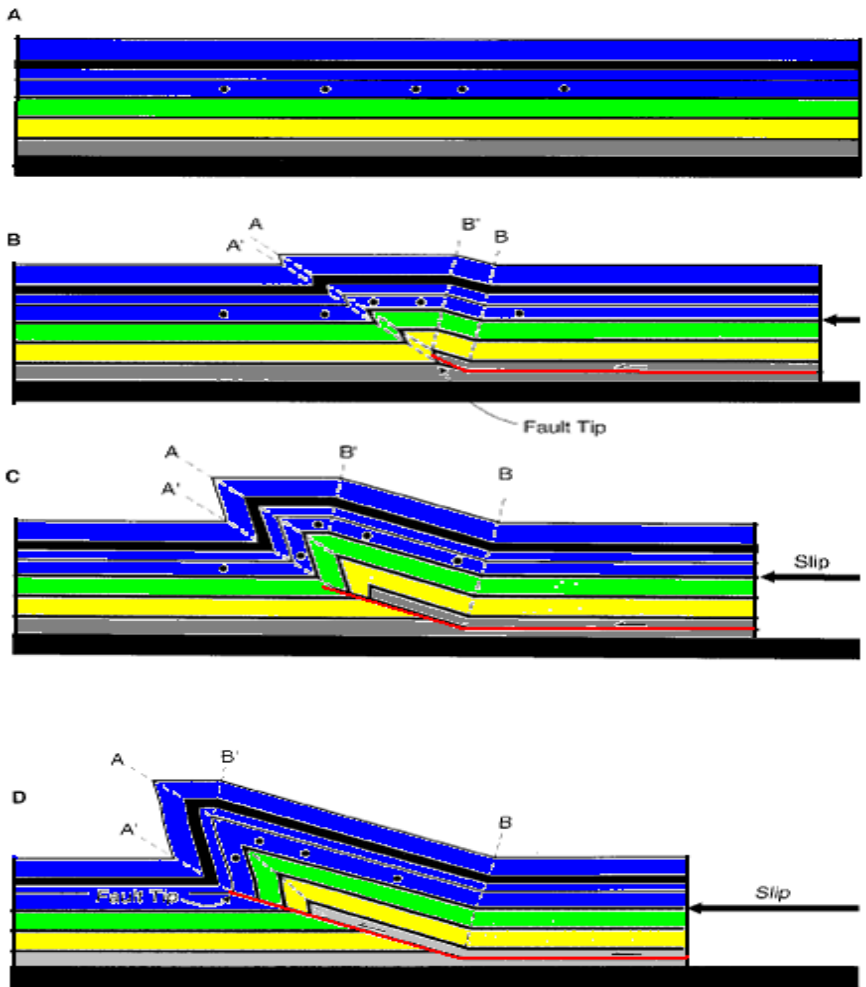


FIGURE 5.6 Progressive evolution of fault propagation geometry showing its development from stage A to D. The gliding horizon is grey the thrust is red line. The transport direction is from right to left (modified from Davis and Reynolds, 1996).

As the thrust advances the unbroken fold just beyond the fault tip must be overtaken by the fault.

Comparison between fault propagation model and constructed section

From the constructed cross section, (Figs.5.7 and 5.8), the Los Comunes syncline and the Los Comunes antiform is constrained. Their compatibility is demonstrated by matching the components of the model to those of the constructed section starting from east to west (from the overturned bed of the model (Fig. 5.8)) The easterly dipping overturned beds in the lower part of model corresponds to the turbiditic overturned sandstone bed with an easterly steep dip of the Los Comunes antiform. (marker sandstone bed of the Los Comunes antiform). The deepest part of present erosional level of the model has reached the thrust tip which corresponds to the lowest reaches of the constructed section of the fault zone (the gully Figs.5.8) Note that the fault angle in the constructed section has been increased at the contact with the more competent limestone beds. To the left of the model, is top-to-south thrust corresponding to the *Los Molinos thrust*. This thrust probably initiated the first folding in the area to form the Los Comunes syncline. At the road section there is evidence that this area had undergone compression by the development of contraction related structures. Most prominent are the duplexes. These has been adapted to the model (Fig 5.7) and interpreted in context of the fault-fold relation of the Los Comunes and that the earlier folding event must have served as thrust-propagated fold system (the Los Molinos thrust system)

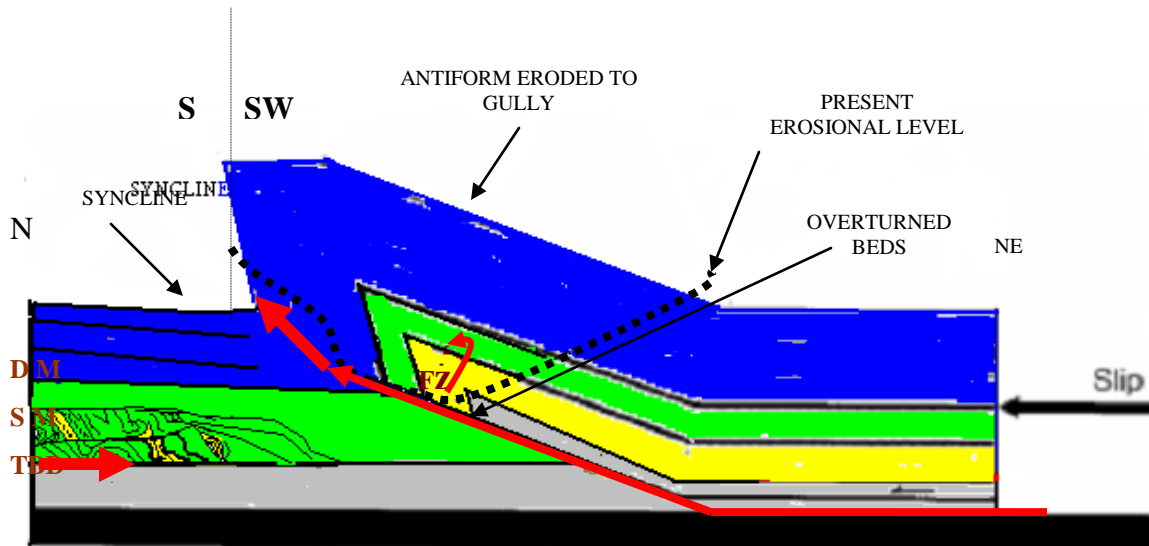


FIGURE 5.7 Fault propagation. Stage D taken from figure X2 for comparison with the constructed section (Fig. XS) for the Los Comunes major folds. Note that DM – deep marine, SM – shallow marine and TBD – turbidite sandstone Also note the top-to-the S thrust to the left of model. (Modified from Davis and Reynolds, 1996)

The kinematics for the fold and thrust system of Los Comunes is compatible with the fault propagation fold model. It can be concluded that the fold-fault relation for the Los Comunes area is double folding and one fault. There is the initial phase of folding with the top-to-the south transport direction and the second phase of folding was initiated with top-to-the-southwest transport direction.

5.5 The general structure of the study area

The general outline of the study area has been made by relating the structure of the Los Comunes area from the east through the Mediano anticline to the Ainsa Quarry to the west. The present structural disposition of the study area shows a transition from the mildly deformed western part to an increasingly intensely deformed eastern part across the Mediano anticline (Fig.5.8) The eastern part is characterized by thrust and folds, duplexes and other deformational structures. As a result of its proximity to the frontal part of the Pyrenean thrust belt, the influence of the top-to-the-southwest thrusting during

the Middle Lutetian and Bartonian has created considerable relief in the northeast (Dreyer et al., 1999) this part coincides with Los Comunes area (Fig. 5.7).

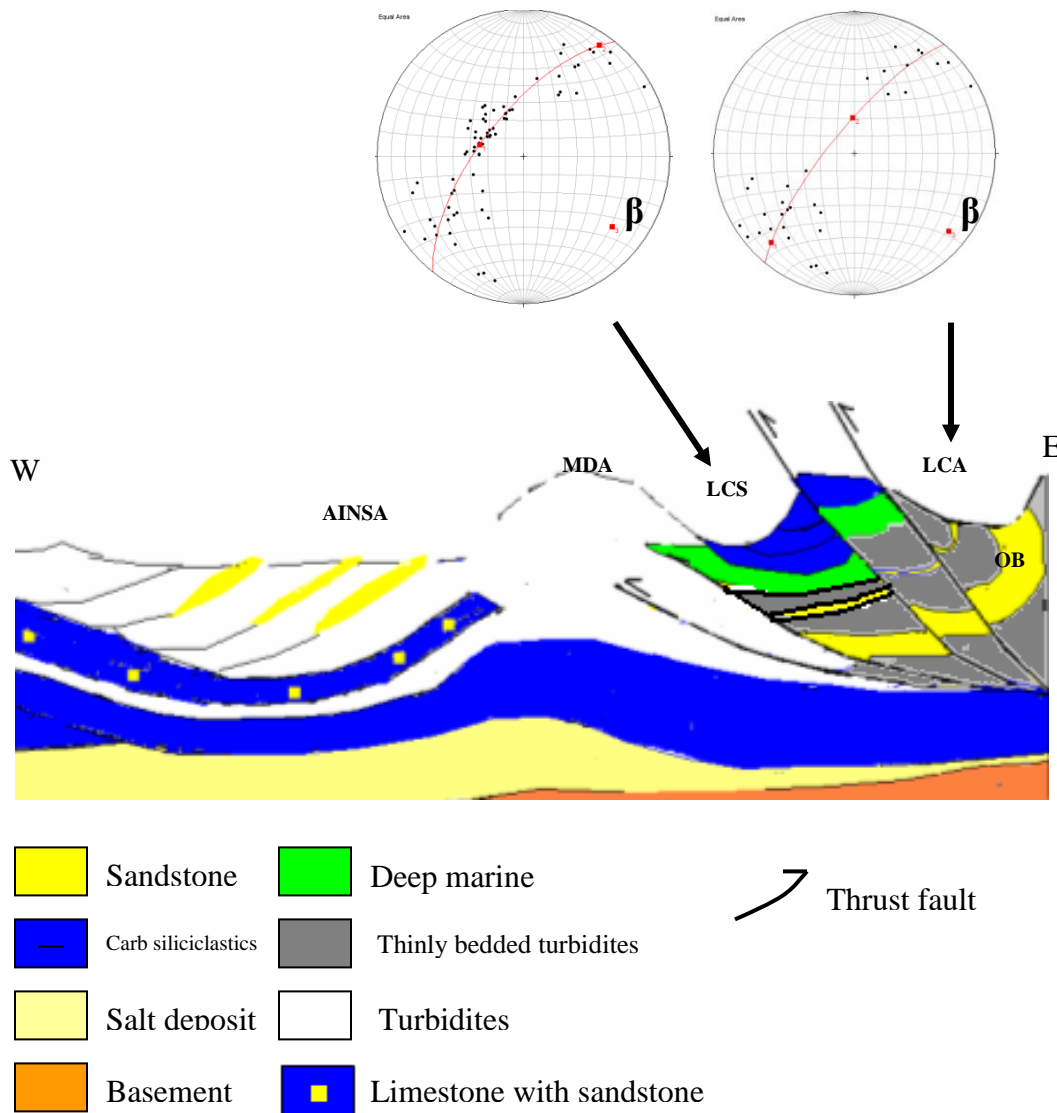


FIGURE 5.8 General structural section across the study area not to scale (see Figs. 4.1. & 4.8 for location) showing the thrust related structures of the Los Comunes area to the east; **LCS** = Los Comunes syncline, **LCA** = Los Comunes Antiform, **OB** = overturned bed, **MDA** = Mediano anticline and **LM** = Los Molinos thrust. Note the topographic variation from E to W. The stereo plots for the main folds have been shown with NW-SE orientation of fold axes

Chapter 6 Conclusions

The main theme of this thesis has been to evaluate the relation between structures generated by burial, uplift and contraction of the eastern part of the Ainsa basin. The structures within the study area have been accessed in two distinct locations including the mildly deformed deep marine turbidites exposed at the Ainsa Quarry and the more intensely deformed Los Comunes area.

Fracture populations in the study area were classified according to their initiation mechanism. In this context measures have been taken to identify and separate between fracture population initiated as a result of burial and uplift and tectonic contraction (Figure 6.1)

It is concluded that fracture populations Q1, Q2, Q3, Q5 and L6 were formed due to burial. These fracture populations are mode I, unmineralized, affect only one bed and are oriented normal to bedding and intraformational. These fractures were initiated in a normal stress situation, with $\sigma_1 = \sigma_{\text{vertical}} = \rho$. In this context, tensile fractures are initiated perpendicular to the plane of the minimum stress axis and parallel to that of the maximum principal stress. It is not likely that fractures become mineral-filled until the rocks have been buried to a minimum depth.

The fracture populations Q4 and L7 were most probably generated through uplift and unloading. These are open unmineralized mode I fractures, with steep dips that commonly cut through several beds.

Two systems of contraction, both involving folding and thrusting are identified in the study area.

The earliest stage involved top-to-the south transport and the folds were mainly fault-propagation-folds. Fracture populations L8 and L9 are related to this stage. Population L8 consists of mode II fractures and typically cut through several beds. Population L9 – fractures are oriented N180E, are mode I and are filled with calcite. The orientation of this fracture population indicate that the maximum principal stress was oriented N-S since tensile fractures open parallel to σ_1

The second stage of shortening is characterized by top-to-the SW transport. Fracture populations L10 and L11, which are conjugate mode II fractures are related to this development.

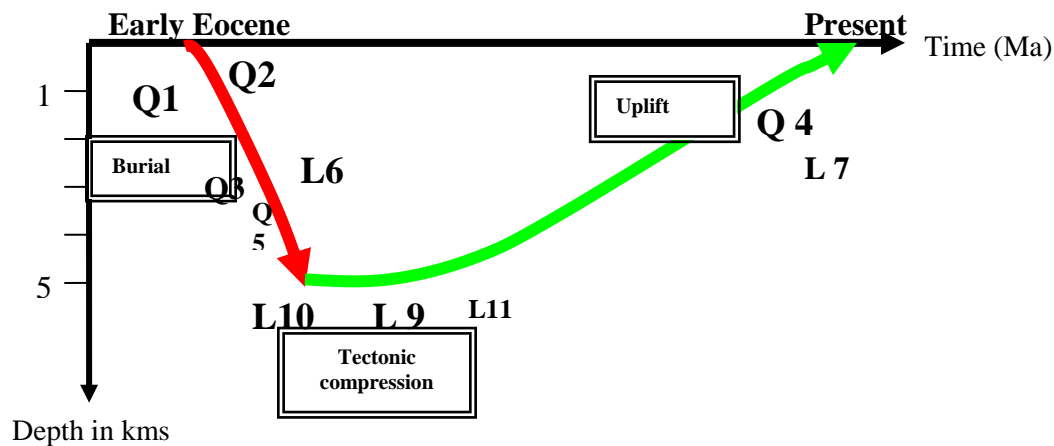


FIGURE 6.1 schematic relations of the geological processes and the types of fracture populations generated in the study area. The red curve corresponds to burial and the green one to tectonic compression and uplift.

The general picture with double folding and several generations of fracturing are in harmony with that reported in the literature by Poblet *et al.*(1992), Muñoz *et al.*(1994, 1998) and Travé *et al.*(1998).

It is also found that the development is in good harmony with the conclusions of the study by Jarsve Morisbak (pers. com) performed in a neighboring study area. It is still

realized, however, that the area contains more in structural complexity than can be solved within the framework of a master thesis.

Relative timing of geological events

- 1 Ypresian: deposition of the sediments in the subsident Ainsa basin
- 2 Formation of burial related fractures (shallow burial, unmineralized fracture set) in Ainsa Quarry and Los Comunes
- 3 Formation of burial related fractures (deep burial mineralized fracture set) in Ainsa and Los Comune
- 4 First episode of folding and development of fractures related to top-the-south maximum stress at Los Comunes area.
- 5 Middle Lutetian: second episode of folding and the generation of the fractures related to the top-to-the southwest directed maximum stress in Los Comunes
- 6 Present: uplift, erosion and generation of fractures related to uplift and unloading in Ainsa Quarry and Los Comunes

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