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Tectonic Controls on Eocene Deltaic Architecture, Jaca Basin, Spanish Pyrenees

Volume 1

Jamie Moss, MESci

2005

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Thesis submitted for the degree of Doctor of Philosophy

Department of Earth Sciences

Durham University

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Declaration

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Jamie Moss
November 2005

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Abstract

Tectonic Controls on Eocene Deltaic Architecture, Jaca Basin, Spanish Pyrenees

Jamie Moss

The Jaca Basin lies to the south of the Pyrenean mountain chain, in Spain, and was formed by the Late Cretaceous and Tertiary convergence between the Iberian and European tectonic plates. During the Bartonian (Middle Eocene), sediment flux from the uplifting Pyrenees was deposited in this basin as the Belsué-Atarés Fm. deltaic system. At the same time, southward propagation of deformation from the orogen created a number of emergent thrusts and thrust-related anticlines along the margins of the basin and within the basin itself. The effect that the growth of these kilometre-scale structures had on the coeval marine depositional systems is the focus of this work.

Although the effects that uplifting intrabasinal structures have on fluvial systems and the effects that basin margin structures have on marine systems are well covered in the literature, the influence of intrabasinal compressive structures on coeval marine sedimentation has been largely neglected.

By undertaking detailed facies, palaeocurrent and compositional analysis of the Belsué-Atarés Fm. deltaics across the Jaca Basin, it has been found that local tectonics had the strongest control on the marine sedimentation. The structurally defined basin margins largely acted as barriers to external depositional systems, causing large parts of the basin to be dominated by marl deposition. However, a total of four structurally controlled low points through the northern and southern basin margins allowed the entry of large volumes of Pyrenean axial zone sediments, beginning at 41.5 Ma. These were composed of silts, sands and pebbles, and formed the axial deltaic system. Once in the basin, a total of ten, kilometre-scale, growing thrust-related anticlines acted as barriers to the progradation of the axial system, causing facies associations to vertically aggrade behind each structure. At 37.5 Ma, after 4 Myr of vertical aggradation, a basin-wide fall in relative sea-level allowed the facies associations to rapidly prograde, breaching the crests of each of the barrier anticlines.

The principal controls on the distribution of facies associations through time (sequence development) in the Jaca Basin were therefore local tectonic ones, with relative sea-level being secondary. This finding calls into question the work of the few existing studies into marine intrabasinal growth structures, which tended to use passive margin sequence stratigraphic concepts i.e. assume that relative sea-level was the primary control on sequences. The development of new techniques, such as numerical modelling, is needed before these types of complex geological situations can be fully understood. The results of this work will be of great relevance to basin dynamics and fold kinematics studies, and for hydrocarbon exploration in thrust-top basin settings.

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Acknowledgements

Particular thanks are extended to my supervisors Stuart Jones and Moyra Wilson, without whom this project would not have been possible. Both spent a significant amount of very valuable time in the field area, and had the unenviable task of reading the first draft of every single word in this thesis. The important contribution of trace fossil identification from the late Roland Goldring is also gratefully acknowledged. My examiners, Gary Nichols and Brian Turner, are thanked for their time and for their many valuable and supportive comments.

The Department of Earth Sciences, Durham University, the International Association of Sedimentologists (IAS) and the American Association of Petroleum Geologists (AAPG) are all sincerely thanked for generously funding this project.

Thanks are also extended to the multitudes of people who have kept me on the right side of sanity throughout a testing but rewarding four years. Names are not going to be named, but you all know who you are. The climbers of the Durham University Mountaineering Club (DUMC) deserve a special mention for providing an unending supply of inspiration and weekend exploits.

Lastly, special thanks are extended to my parents, who have supported my academic career in many ways over the years. Without their support, the undertaking of this work would not have been possible.

Jamie Moss

Lincoln, February 2006

Chapter 1:

Introduction and Methods

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1. Introduction and Methods

Contents

1. Introduction and Methods

1.1 Introduction

The Jaca Basin is one of several thrust-top basins that lie to the south of the Pyrenean mountain chain. This mountain belt forms the border between France and Spain and was produced by the Late Cretaceous and Tertiary convergence of the Iberian and European tectonic plates. The resulting doubly vergent orogenic wedge down-warped the lithosphere, creating the south Pyrenean foreland basin in Iberia – which the Jaca Basin was initially part of. Southward propagation of Pyrenean thrusts into the foreland led to structural compartmentalisation of the basin, and the creation of a series of thrust-top basins. As one of these, the Jaca Basin experienced southwards displacement on top of the Guarga thrust sheet, ongoing subsidence with the growth of the Pyrenean orogen, and an increasing flux of detrital sediments from the eroding uplifted areas.

During the Eocene, the incoming detrital material was deposited in the Jaca Basin as a prograding deltaic system. However, sediment supply rates began to exceed the subsidence rate, and non-marine conditions prevailed from the Oligocene onwards. Throughout the marine and non-marine phases of the basin, ongoing south-directed thrust activity created a series of emergent thrusts and thrust-related anticlines along the margins of the basin and within the basin itself. The effect that these growing structures had on the basinal depositional systems during its marine infill phase is the primary focus of this work.

This chapter introduces the reasons for studying the tectonic controls on marine sedimentation in the Jaca Basin (section **1.2**), the aims of this work (section **1.3**), the way this research was carried out (section **1.4**), and how the results are presented in this thesis (section **1.5**).

1.2 Context of study

It is well documented in the literature that growing compressive tectonic structures may have a profound affect on fluvial systems, diverting drainage and preventing the entry of rivers into depositional basins (Jolley *et al.*, 1990; Burbank *et al.*, 1996; Simpson, 2004; Jones, 2004; Ghassemi, 2005). It is also well documented that ongoing tectonic activity within the margins of a marine basin can give rise to cyclic activity within the basinal depositional system (Marzo & Anadón, 1988; Boorsma, 1992; López-Blanco, 1993; Dorsey *et al.*, 1995; Burns *et al.*, 1997; López-Blanco *et al.*, 2000; Marzo & Steel, 2000; Benvenuti, 2003; Sohn & Son, 2004; Clevis *et al.*, 2004). However, very few studies have attempted to deduce the effects that growing *intrabasinal* compressive structures may have on *marine* depositional systems. However, if the above-mentioned systems are anything to go by, then it is likely that the influence on the coeval marine sedimentation could be very great.

The few known studies into the controls that intrabasinal compressive growth structures may exert on shallow marine systems have come from other south Pyrenean thrust-top basins (De Boer *et al.*, 1991; Dreyer *et al.*, 1999; López-Blanco *et al.*, 2003), or from particular areas of the Jaca Basin (Millán *et al.*, 1994; Castelltort *et al.*, 2003). Many of these studies attempted to place the syntectonic strata into a conventional passive margin type sequence stratigraphic framework (Van Wagoner *et al.*, 1988). However, if local tectonic factors actually have the greatest controlling effect on sequence development, and not relative sea-level, then the validity of this approach may be called into question. This work will investigate whether sequence stratigraphic concepts may be used when studying the growth strata of the Jaca Basin.

The understanding of tectonic controls on shallow marine sedimentation, which this work aims to achieve, will be of great relevance to studies into compressional basin dynamics or the kinematics of growth structures, and could be of particular importance for hydrocarbon exploration in these types of settings.

1.3 Aims of study

The aims of this study may be summarised as:

- To investigate the effects that compressive intrabasinal growth structures may have on the activity of a coeval, shallow marine depositional system.
- To deduce the role of active, structurally defined basin margins in determining the style of sedimentation in a marine thrust-top basin.
- To assess the relative importance of tectonic controls and relative-sea level changes in determining sequence development in the infill of a marine thrust-top basin, and hence assess the applicability of passive margin sequence stratigraphic concepts.

1.4 Methods

This section describes how the research presented in this thesis was undertaken – from the collection of field data (section **1.4.1**), through to data processing and presentation (section **1.4.2**).

1.4.1 Fieldwork

This work focuses on the marine syntectonic strata of the Jaca Basin, which are composed of the sand dominated Belsué-Atarés Fm. and the marl dominated Árguis Fm. Overlying these units are the non-marine Lower Campodarbe Fm. and Middle Campodarbe Fm. (Jolley, 1987). During the course of this work, the superb geological map of Puigdefàbregas (1975) has been a great help in finding where each of these formations outcrop within the basin (**Fig. 1.1**; note that, throughout this thesis, the most important figures appear unbound in Appendix I and are denoted by being **underlined** in the text). This map also depicts the important intrabasinal structures, and so the exposures likely to be most useful to examine in order to fulfil the aims of this project could be quickly targeted for more detailed field study.

A total of 18 weeks of fieldwork were undertaken over four separate field seasons, between October 2001 and September 2003. During this time, 33 sections through the Belsué-Atarés Fm. were logged, covering a total sediment thickness of more than 16 km. The vertical logging scale used was 1 cm = 4 m, meaning that the thinnest recordable bed was 20 cm thick. Where exposure allowed, the logs covered some or all of the thickness of the underlying Árguis Fm., in some cases right down to the uppermost Guara Fm., and also extended up into the Lower / Middle Campodarbe Fm. Sections logged were distributed across the 100 km long by 30 km wide basin, but tended to be concentrated around the intrabasinal tectonic structures. **Fig. 1.1** shows the locations of each of the logged sections, and indicates which geographic feature each was named after. Where there are gaps of greater than 10 km between adjacent logs, exposure was found to be very poor and worthwhile sections were unattainable.

For each bed, the logging involved recording: thickness, lithology, nature of lower and upper surfaces, grain size and trends, sedimentary structures, clast content, fossil content, and trace fossils. The orientations of as many palaeocurrent indicators as possible were recorded, along with regular strike and dip readings. All facies were photographed, including their characteristic sedimentary structures and trace fossils.

Where a fossil or trace fossil could not be identified, it was collected or photographed for later analysis. Where possible, the composition of particular beds, especially conglomerates, was noted, and up to seven samples from fine–medium sandstone beds were collected per section for later analysis. The start and end position of each log, and the position of any formation boundaries contained with it, were accurately recorded using a GPS unit.

Because of the fairly one-dimensional insight that graphical logging affords, where possible, the logged outcrops were viewed and photographed from neighbouring hillsides, enabling some understanding of the three-dimensional architecture to be gained. The extremely rough nature of the terrain meant that laterally 'walking out' beds was only rarely possible.

1.4.2 Processing of field data

After from the field, all graphic logs were drawn up at the original field scale, and are presented in the second volume of this thesis (Vol.2, p.45). From these, summary logs at one-tenth of the original scale were created, and are also presented in the second volume of this thesis (Vol.2, p.5). The symbols key for both these scales of logs is given in the second thesis volume as well (Vol.2, p.1). From the summary logs, and with constraints from pre-existing mapping (Puigdefàbregas, 1975) and dating (Hogan & Burbank, 1996; Pueyo *et al.*, 2002), correlation panels were constructed. These are presented in Appendix I of this volume, and discussed throughout the main text.

Beyond the logs, all of the palaeocurrent data collected was collated, corrected for tectonic dip, and plotted. The rose diagram plots of this data appear at the appropriate heights on the graphic logs and summary logs, and on maps throughout the main text. The sandstone samples were thin-sectioned and their compositions analysed by point-counting the various grain types under a microscope. The results were plotted graphically and appear throughout the main text of the thesis. Any previously unknown fossils or trace fossils were identified with the help of relevant experts, and are referred to at the appropriate points in the main text.

1.5 Layout of the thesis

For the purposes of writing this thesis, the basin was divided into six sectors. Each is described as a separate chapter (**Fig. 1.2**; chapters 4 – 9), in which all of the relevant sedimentological, palaeocurrent, composition and correlation data is presented and interpreted. Each sector focuses on the effects that one or more growth structures had on the marine sedimentation – the names of these structures, and other important features of the basin, are given in **Fig. 1.3**.

The titles and subject matters of each of the subsequent chapters of this thesis are as follows:

- **Chapter 2: The Geological History of the Pyrenees** – a review of the present knowledge on the formation of the Pyrenees and the development of the Jaca Basin.
- **Chapter 3: Facies and Facies Associations** – a description and interpretation of the lithofacies and facies associations that were observed in the syntectonic marine strata of the Jaca Basin.
- **Chapter 4: Far NE Jaca Basin** – the area to the west of the basin bounding Boltaña anticline.
- **Chapter 5: NE Jaca Basin** – the area around the Santa Orosia input point and the Río Basa growth anticline.
- **Chapter 6: Northern Jaca Basin** – the area around the Binacua growth anticline.
- **Chapter 7: Western Jaca Basin** – the area around the Martes input point and the western end of the External Sierras.
- **Chapter 8: SE Jaca Basin** – the area around the Nocito and Rodellar palaeovalleys and the Balces, Alcanadre, Nocito and Gabardiella growth anticlines, at the eastern end of the External Sierras.
- **Chapter 9: Southern Jaca Basin** – the area around the Lúsera, Pico del Águila and Bentué de Rasal growth anticlines of the central External Sierras.
- **Chapter 10: Discussion and Conclusions** – brings together the work on the separate sectors of the basin to determine the key findings of this study, and describes their implications for a number of areas of geological research.

Throughout the thesis, at the end of every chapter, a brief introduction to the following chapter is given. So, the next chapter, Chapter 2, gives a detailed account of the formation and structure of the Pyrenean mountain belt, and a summary of the major tectonic events. The structure, history and stratigraphy of Jaca Basin are also described.

Chapter 2:
The Geological History of the Pyrenees

2. The Geological History of the Pyrenees

Contents

2. The Geological History of the Pyrenees

2.1 Introduction

The Pyrenean orogeny lasted for 60 Myr and involved a complex series of tectonic and stratigraphic events, generally interrelated, and at all scales. Many of these had some bearing on the development of the Jaca Basin and the Belsué-Atarés Fm. found therein – which together are the focus of this project. Thus, before the Belsué-Atarés Fm. and the Jaca Basin can be understood, the development of the Pyrenees must first be studied.

This Chapter begins by briefly outlining the pre-Pyrenean history of Iberia, which had a considerable bearing on the Pyrenean orogeny (section **2.2**). The next section describes the Pyrenean orogeny itself (section **2.3**). After that, the current knowledge of the development and in-filling of the Jaca Basin is described (section **2.4**). Next, the development of the Aínsa Basin, which lay adjacent to the Jaca Basin and was an important source of sediment, is outlined (section **2.5**). The final section summarises the most important aspects of the development of the Pyrenees for this project (section **2.6**).

2.2 Iberia from the Devonian to the Tertiary

Although this project is only concerned with sedimentation during the formation of Pyrenees as part of the Tertiary Alpine orogeny, it is important to understand the pre-Alpine nature of Iberia. This is because the Alpine event reutilised many existing structures in the pre-Alpine basement, and as such the older structures ultimately acted as controls on the Tertiary sedimentation. Many of these structures were formed during an earlier orogenic episode, the Carboniferous Variscan orogeny, or during a subsequent period of rifting that culminated in the Early Cretaceous. The pre-Alpine stratigraphy is also important as various levels were exhumed, eroded and re-sedimented during the Pyrenean orogeny, and some units acted as detachments for the Pyrenean thrusts.

2.2.1 Variscan orogeny

During most of the Devonian, prior to the Variscan orogeny, Iberia formed part of the northern shelf of the northward-drifting Gondwanan supercontinent (García-Alcalde *et al.*, 2002; **Fig. 2.1**). However, by the Late Devonian, Gondwana had begun to collide with the continents of Laurentia and Baltica (**Fig. 2.2**). The result of this was the Variscan orogeny, which continued until the Late Carboniferous and, ultimately, the creation of the immense supercontinent of Pangea (Ábalos *et al.*, 2002). Today, the fold belt formed by the Variscan orogeny is 3000 km long by 800 km wide, and stretches across central and western Europe. It is made up of a number of tectonostratigraphic terranes, bounded by transcurrent faults or sutures, and each with their own specific stratigraphic, petrographic and structural characteristics (Matte, 1991).

Although Variscan basement rocks outcrop across Iberia (**Fig. 2.3**), in the Pyrenees area they are mainly confined to the Pyrenean axial zone, and as such has undergone a degree of Alpine overprinting. However, all of the penetrative ductile structures seen there, and the metamorphic and igneous rocks, date from the Variscan orogeny and not the Alpine event. Thus, it is still possible to reconstruct the Variscan structures. Despite this, the exact nature of the Variscan orogeny remains controversial. Models ranging from dominant crustal shortening (e.g. Matte, 1976) through to extension only (e.g. Vissers, 1992) have been proposed. The most recent explanations suggest that the overall tectonic regime was transpressive, with crustal shortening being followed by dextral wrench-dominated transpression (e.g. Gleizes *et al.*, 1998).

During the Variscan orogeny, the Variscan rocks that now crop-out in the Pyrenees area experienced a polyphase structural evolution, with contemporaneous magmatism and low pressure–high temperature metamorphism. The Pyrenean Variscan folds take the unusual form of broad domes and pinched synclines, with axes that trend WNW–ESE. The associated metamorphic rocks include orthogneisses and migmatic schists, whilst the igneous rocks are mainly sheeted granitoid batholiths and stocks. In the latter stages of the orogeny, deformation became progressively localised along narrow shear zones (mylonite belts), and ultimately all Variscan structures were rotated towards NW–SE trends.

2.2.2 Post-Variscan extension

The Permian and Triassic rocks of Spain record the change from the Variscan compressive regime to overall extension, the break-up of Pangea, and the westward expansion of the Tethys Ocean (**Fig. 2.4**). During the Permian, rift systems already developed in the Norwegian–Greenland Sea to the north of Iberia, and the Tethys to the east, propagated southwards and westwards respectively, into Iberia. This resulted in the

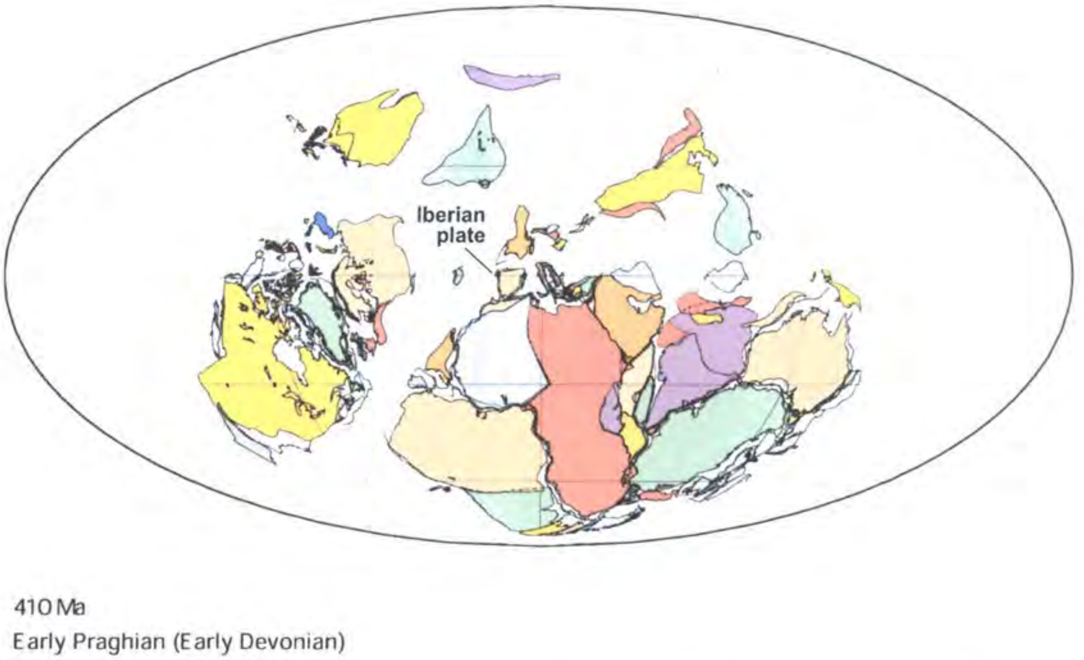


Fig. 2.1. A plate tectonic reconstruction for the Early Devonian, showing the Iberian plate lying on the northern shelf of Gondwanan supercontinent.
(From http://www.ig.utexas.edu/research/projects/plates/)

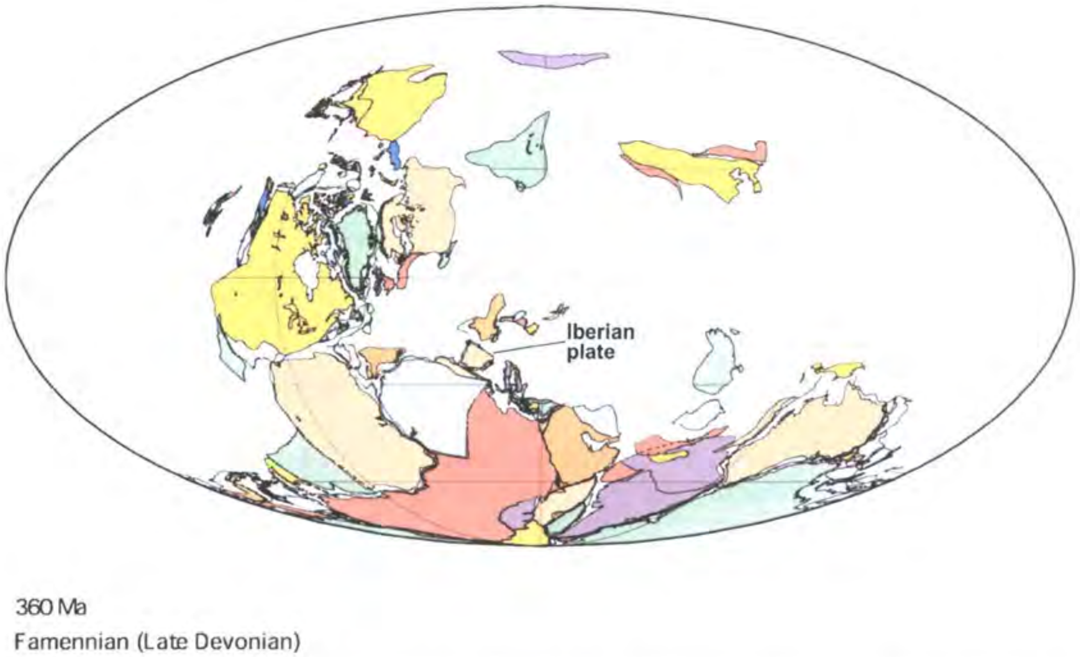


Fig. 2.2. A plate tectonic reconstruction for the Late Devonian, showing the collision between Iberia, Laurentia and Baltica – the cause of the Variscan orogeny.
(From http://www.ig.utexas.edu/research/projects/plates/)

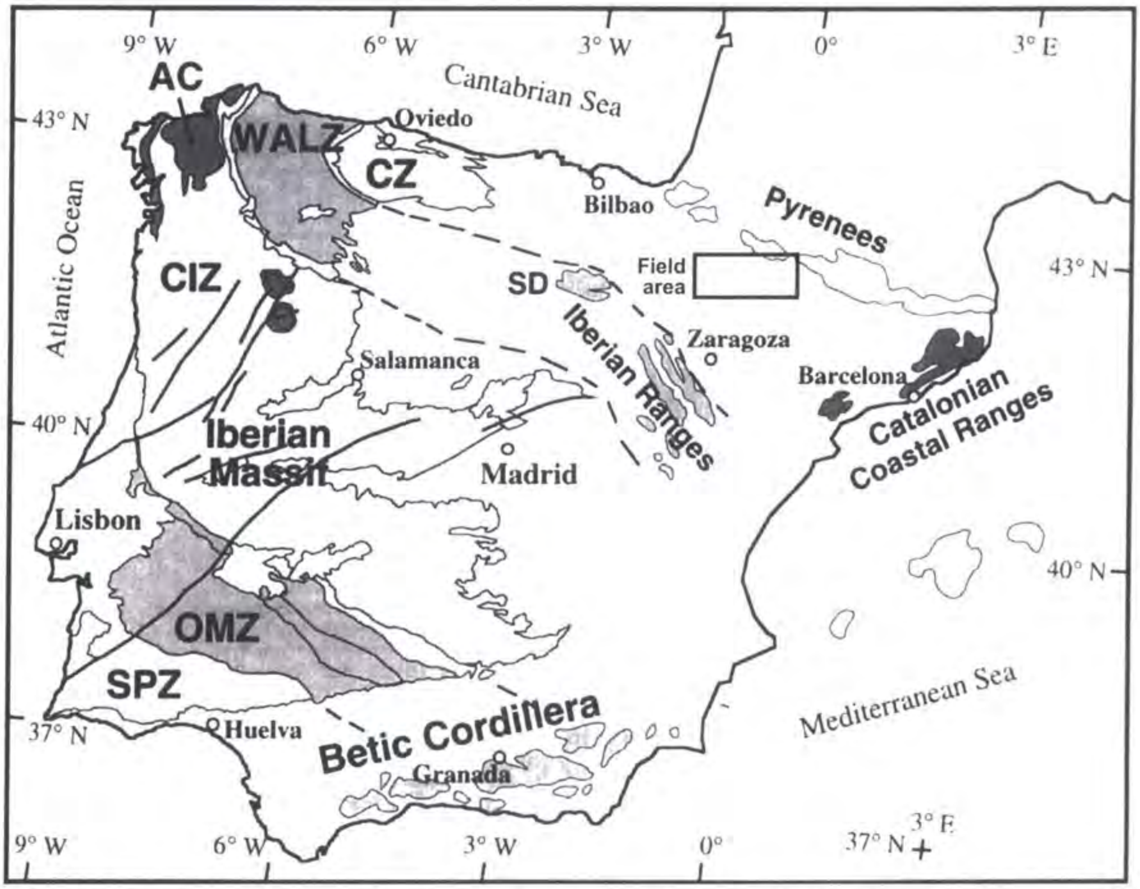


Fig. 2.3. Geological map of the Iberian Peninsula, showing the locations of the principle Variscan massifs, and the field area for this project. The zones into which the Iberian massif has traditionally been subdivided are: CIZ, Central Iberian Zone; CZ, Cantabrian Zone; OMZ, Ossa Morena Zone; SPZ, South Portuguese Zone; WALZ, West Asturian–Leonese Zone. (From Ábalos *et al.*, 2002.)

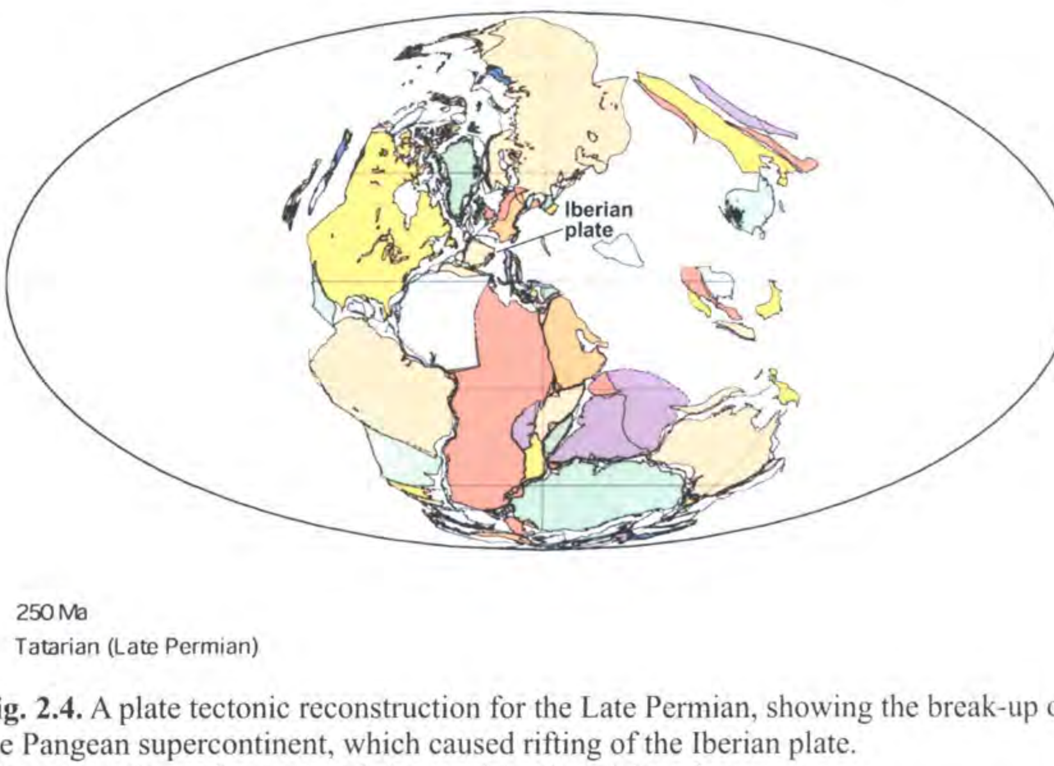


Fig. 2.4. A plate tectonic reconstruction for the Late Permian, showing the break-up of the Pangean supercontinent, which caused rifting of the Iberian plate. (From http://www.ig.utexas.edu/research/projects/plates/)

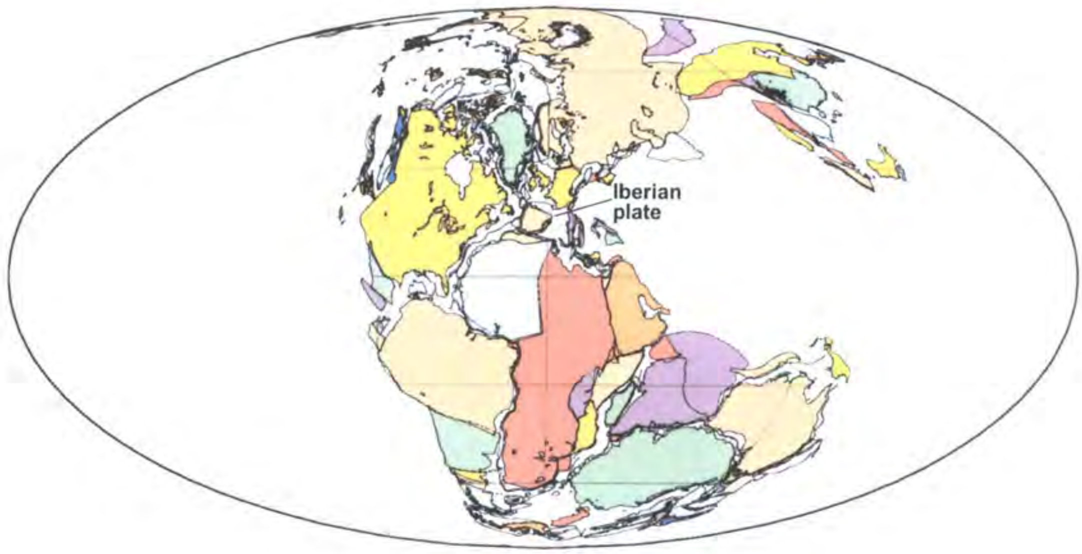
Iberian Variscan foldbelt being dissected by a series of major strike-slip faults. After this phase of rifting, thermally controlled post-rift subsidence allowed the Tethys to advance westwards. By the Middle Triassic, all of the rifted areas around Iberia, and much of the Iberian plate itself, had been drowned. The resulting marine basin was filled with shallow-water sediments and thick evaporites.

During the Jurassic, the Iberian plate lay at a low latitude in the northern hemisphere (Aurell *et al.*, 2002). To its north lay the large European plate, across a trough representing the early rifting of the Bay of Biscay (**Fig. 2.5**). To the NW, between Iberia and the Laurentia–Greenland plate, lay an epicontinental rift-formed sea that would go on to become the Atlantic Ocean. To the south, a narrow oceanic trough connected the Tethys to the proto-Atlantic, separating Iberia from Africa. Iberia itself was predominantly occupied by intracratonic basins that formed shallow epicontinental seas, with only the Variscan massifs remaining emergent.

Iberia remained positioned between the European and African plates throughout the Cretaceous period (Martín-Chivelet *et al.*, 2002; **Fig. 2.6**). During this time period, the Bay of Biscay opened between Iberian and Europe (Olivet, 1996; Osete *et al.*, 2000), and oceanic spreading was initiated in the North Atlantic (Ziegler, 1988). The creation of the hot and buoyant Mid-Atlantic Ridge displaced much water out of the ocean basin and onto the continents, causing the greatest marine transgression since Early Palaeozoic times. When sea-levels were at their highest, the only parts of Iberia remaining emergent were the Variscan massifs. Finally, in the Late Cretaceous, oblique convergence between Africa and Europe began (e.g. Reicherter & Pletsch, 2000), signalling the onset of the Alpine orogeny (**Fig. 2.7**).

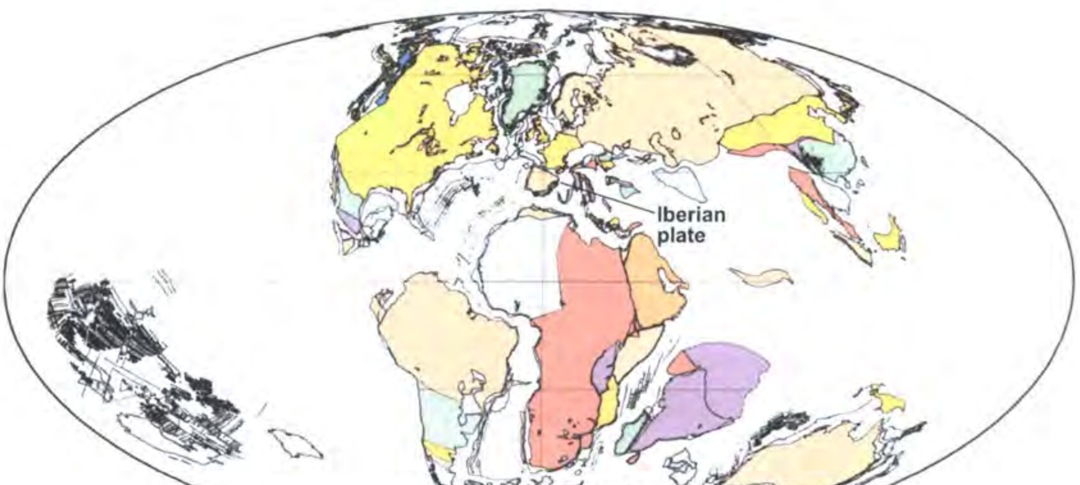
2.2.3 The Alpine orogeny

The Alpine orogeny occurred because of Tertiary convergence between the European and African plates, with Iberia trapped in between (Capote *et al.*, 2002; **Fig. 2.8**). Roest & Srivastava, (1991) used the Atlantic magnetic anomalies to reconstruct the precise relative plate motions during this time period (**Fig. 2.9**). Prior to the Alpine orogeny, the Iberian plate was free to move relative to its larger neighbours. However, when north–south-directed convergent motions between Europe and Africa began in the Late Cretaceous (84 Ma), Iberia became joined onto the African plate. In the Middle Eocene (42 Ma), the southern margin of the Iberian plate (the Azores–Gibraltar fracture zone) became active, allowing Iberia to move independently once more. This continued



170 Ma
Bajocian (Middle Jurassic)

Fig. 2.5. A plate tectonic reconstruction for the Middle Jurassic, showing the Iberian plate in close proximity to the European and African plates, prior to the initiation of rifting in the Atlantic. (From http://www.ig.utexas.edu/research/projects/plates/)



100 Ma
Late Albian (Early Cretaceous)

Fig. 2.6. A plate tectonic reconstruction for the Early Cretaceous, showing the Iberian plate laying between the European and African plates, at a time when the Atlantic Ocean was forming. (From http://www.ig.utexas.edu/research/projects/plates/)

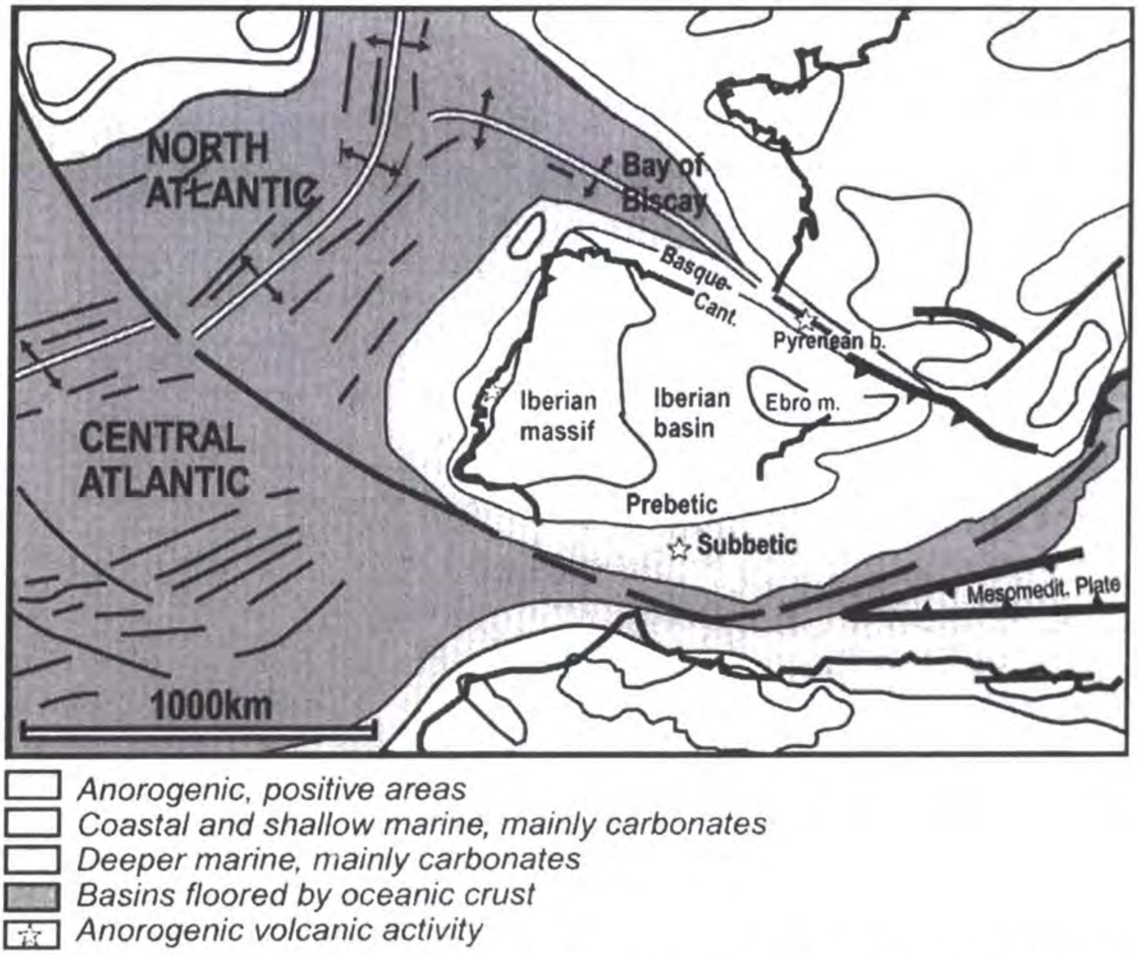


Fig. 2.7. Palaeogeographic reconstruction of Iberia during the Late Cretaceous, showing the main tectonosedimentary domains at a time when convergence between the European, Iberian and African plates was just beginning. (From Martín-Chivelet *et al.*, 2002.)

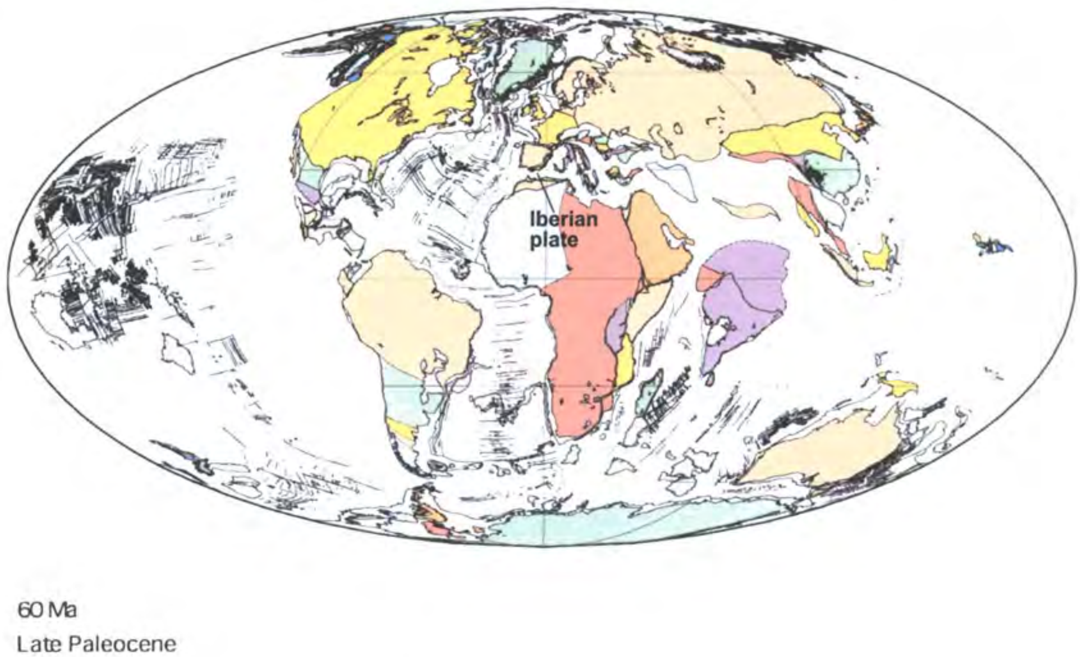


Fig. 2.8. A plate tectonic reconstruction for the Late Palaeocene, when convergence between the European, Iberian and African plates was causing the Alpine orogeny and the creation of the Pyrenees. (From http://www.ig.utexas.edu/research/projects/plates/)

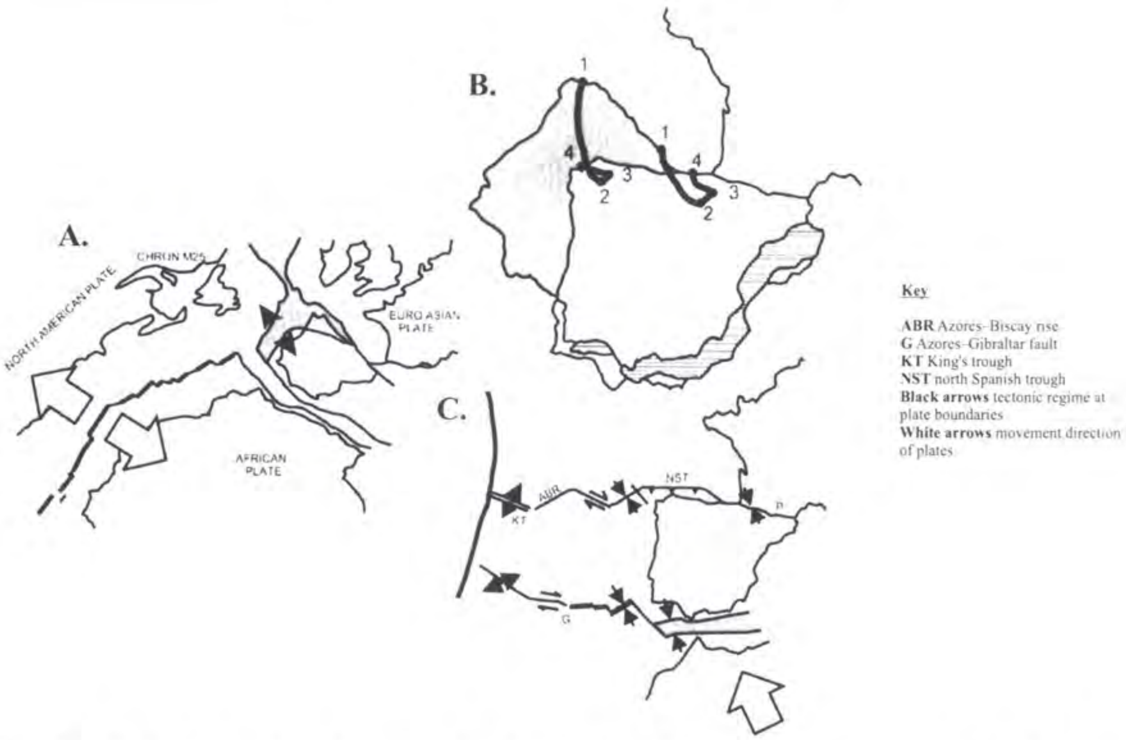


Fig. 2.9. Relative motions between the Iberian, North American, European and African plates leading up to the Alpine convergence. **A**. Plate positions and motions during the Late Jurassic, with active spreading in the North Atlantic. **B**. Iberian motion and rotation, with respect to the European plate, from the Late Jurassic to the Early Miocene. **C**. Active plate margins during the Alpine convergence. (From Capote *et al.*, 2002.)

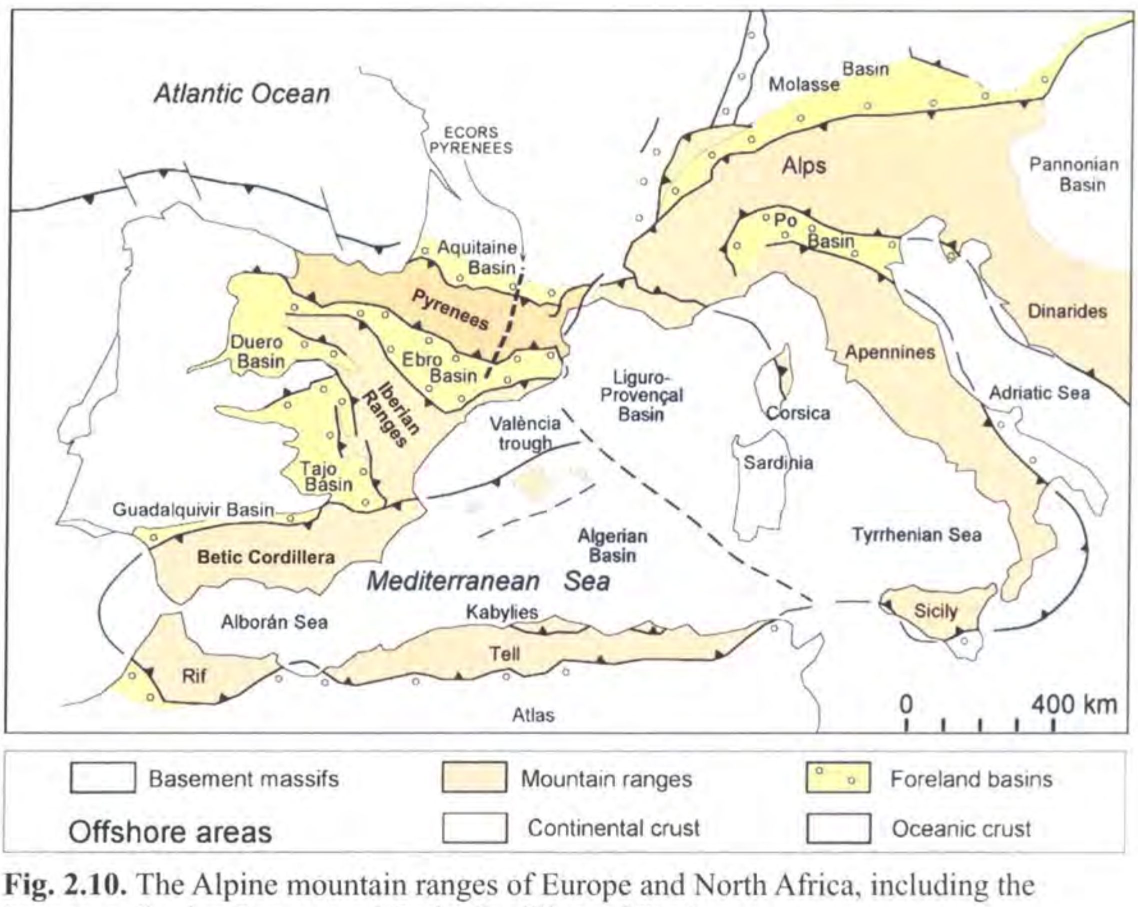


Fig. 2.10. The Alpine mountain ranges of Europe and North Africa, including the Pyrenees, Iberian Ranges and Betic Cordillera of Iberia.

until the Late Oligocene (24 Ma), when Iberia joined with Europe, giving the present day plate configuration.

The north–south-directed convergence between Europe and Africa inverted the pre-existing Mesozoic rift basins in Iberia, and created the Alpine mountain ranges of the Pyrenees and the Betic Cordillera (**Fig. 2.10**). At the end of the Palaeocene (around 55 Ma), the compressive stress that Iberia was under resulted in the reactivation of Variscan faults in the interior of the plate, creating the Iberian Ranges and the Central Range mountain belts. Modern earthquake activity indicates that this compressive regime is ongoing today.

2.3 The Pyrenees

The Tertiary N–S convergence between Europe, Africa and Iberia, caused the development of the Pyrenees between Europe and Iberia, and the Betic Cordillera range between Iberia and Africa (**Fig. 2.11**; Alonso-Zarza *et al.*, 2002). The convergence between Iberia and Europe was, however, oblique rather than perpendicular (**Fig. 2.9**), meaning that the Pyrenean orogeny and associated palaeogeographical changes were diachronous, beginning in the east and propagating westwards.

The Pyrenees is a doubly vergent mountain belt, i.e. thrusts propagated both north and south from the Pyrenean axial zone, onto both colliding plates (**Fig. 2.12**). Similarly, foreland basins were developed on both sides of the axial zone – the Aquitanian Basin to the north, and the Ebro Basin to the south. The Jaca Basin, the focus of this study, lays to the south of the Pyrenean axial zone, yet north of the Ebro Basin, behind the thrust front.

This section explains the structure of the Pyrenees, both deep and shallow, and the geodynamic evolution of the range, in order to put the Jaca Basin in its correct structural and stratigraphic context.

2.3.1 Deep structure of the Pyrenees

The lithospheric structure of the Pyrenees is perhaps the best constrained of any orogen in the world, due to the quality and quantity of geophysical work on the range. The model of the deep structure of the Pyrenees that best fits the geophysical data is one in which the orogenic double wedge involves only upper crustal rocks (**Fig. 2.12**). The crust would therefore be decoupled, with the lower crust (below the upper crustal

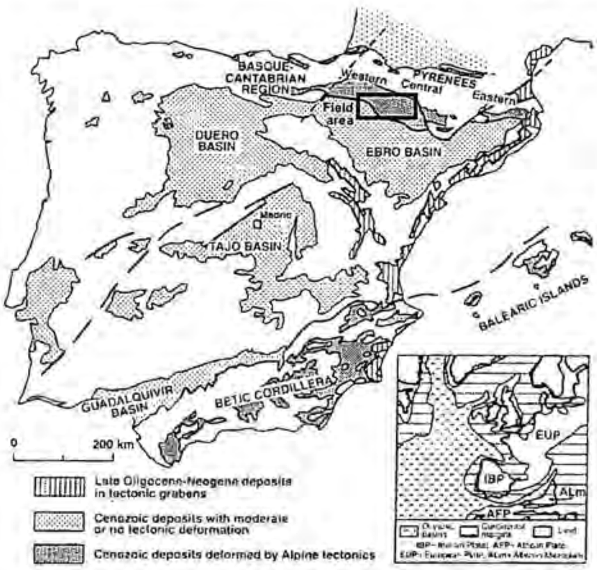


Fig. 2.11. Map of Cenozoic outcrops of Iberian, showing the location of the field area for this project. Inset: Palaeocene palaeogeography of the north Atlantic domain. (From Alonso-Zarza *et al.*, 2002.)

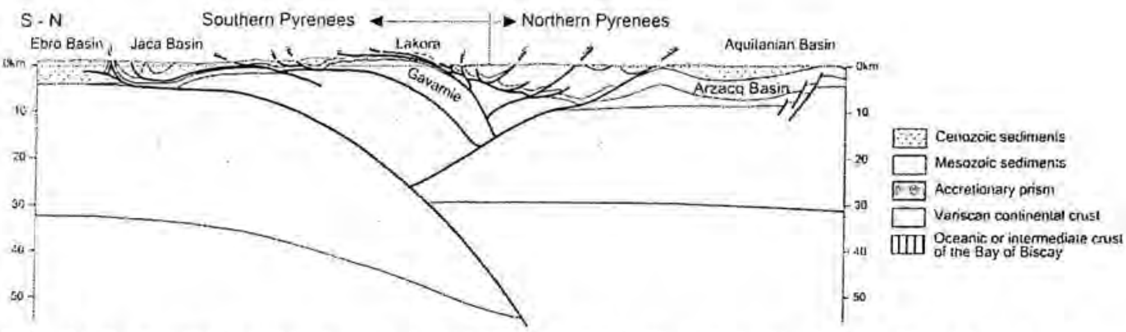


Fig. 2.12. Crustal cross-section across the west-central Pyrenees. Location shown on **Fig. 2.15**. (From Capote *et al.*, 2002.)

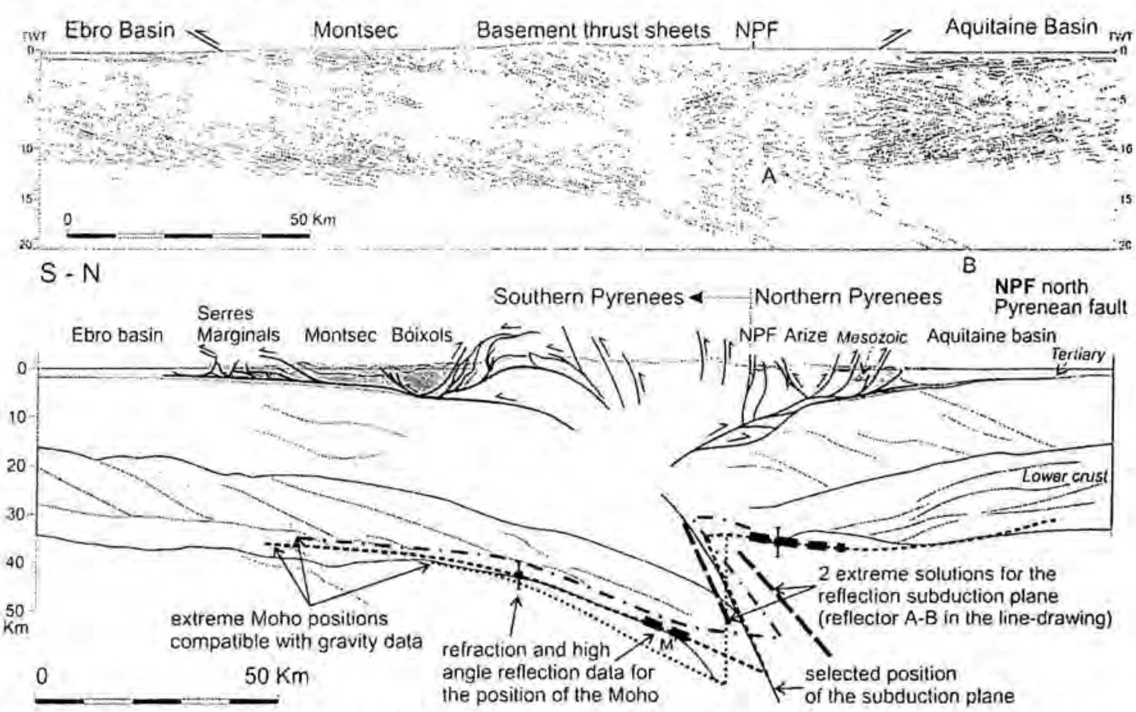


Fig. 2.13. Geophysical data along the ECORS Pyrenees profile. Top: seismic reflection time section (after Choukroune *et al.*, 1989; Berástegui *et al.*, 1993). Bottom: interpreted crustal structure along the ECORS profile, including constraints from high-angle reflection and refraction data, and gravity studies. Location of ECORS profile is shown on **Fig. 2.15**. (From Capote *et al.*, 2002.)

double wedge) being subducted together with the lithospheric mantle. This model explains the surprising and important absence of post-Variscan metamorphic rocks or lower crustal rocks in the Pyrenean axial zone. The model is backed-up by interpretations of the ECORS seismic profile that was shot across the range (**Fig. 2.13**; Choukroune *et al.*, 1989), and by magnetotelluric and seismic tomography surveys that have detected subducted Iberian lower crust at 80–100 km depth (Pous *et al.*, 1995; Souriau & Granet, 1995; Ledo *et al.*, 2000). Subduction of the lower crust is also consistent with observed conductivity anomalies (Glover *et al.*, 2000), a three-dimensional density model of the deep Pyrenean structure (Vacher & Souriau, 2001), and recent numerical modelling (Beaumont *et al.*, 2000).

The nature of the Alpine orogeny in the Pyrenees was strongly controlled by the geometry of the pre-existing structures originating in the earlier Variscan orogeny and the Early Cretaceous extensional period. The geometry of these older structures can be estimated by creating balanced restored cross-sections across the Pyrenees (**Fig. 2.14**). This process has shown that the pre-existing structures were generally north-dipping and listric, and developed over a layered lower crust. Basement structures of this geometry have been observed in the undeformed parts of the crust on the ECORS seismic profile, and in the Aquitaine foreland to the north of the axial zone (Boillot & Malod, 1988; Marillier *et al.*, 1988).

Balanced restored cross-sections can also be used to estimate the total amount of crustal shortening across an orogen. Along the Pyrenean ECORS seismic line, values of 147 km (Muñoz, 1992) to 165 km (Beaumont *et al.*, 2000) have been calculated. These figures are in agreement with work on the kinematics of the Iberian plate, which showed that shortening in the central Pyrenees could not be less than 150 km (Olivet, 1996). Convergence lasted for around 60 Ma in the central Pyrenees, and so the shortening occurred at an average rate of 2.5 mm/yr. To the east and west of the central Pyrenees, the net amount of shortening decreases to around 100 km, but due only to a shorter period of convergence, rather than a slower shortening rate (Vergés *et al.*, 1995).

2.3.2 Shallow structure of the Pyrenees

The development of the Pyrenees was strongly controlled by the reactivation of structures formed during the Variscan orogeny and the inversion of the Triassic–Cretaceous rift systems. The differences in these inherited structures across the Pyrenean area explains the strong variations in structural style seen both along and

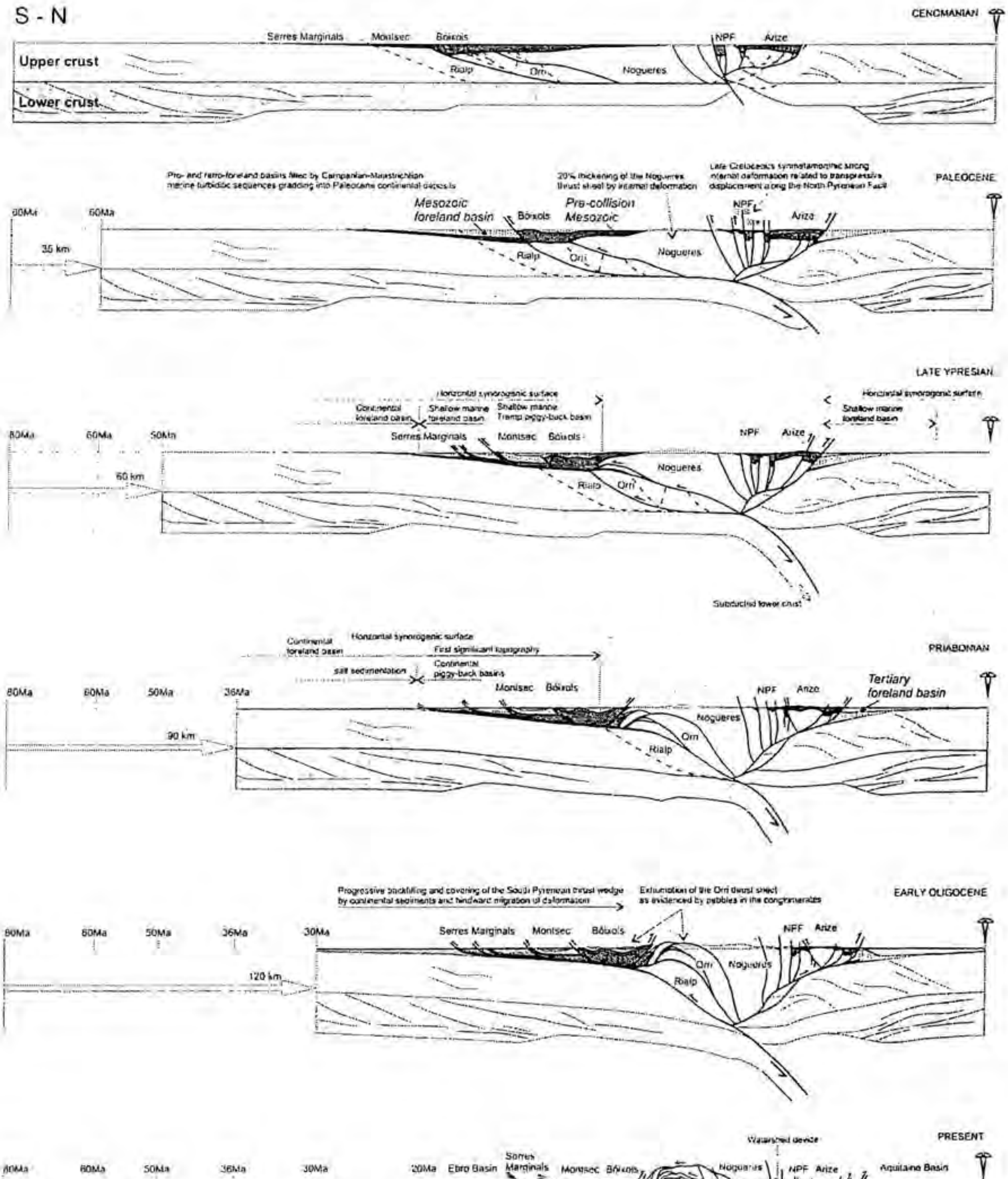


Fig. 2.14. Balanced, partially restored and fully restored cross-sections of the Iberian crust along the ECORS profile, from the present day back to the Cenomanian (Late Cretaceous). The Cenomanian cross-section shows the geometry of the inherited Early Cretaceous extensional system and the north Pyrenean strike-slip fault zone. Note also the significant uplift that has occurred since the Early Oligocene. Location of ECORS profile is shown on **Fig. 2.15**. (From Beaumont *et al.*, 2000.)

across the strike of the orogen (e.g. Muñoz *et al.*, 1986). Because of this, the Pyrenees is best considered in two separate halves: the Aragonese–Catalan Pyrenees in the east, and the Basque–Cantabrian Pyrenees to the west (**Fig. 2.15**). The boundary between these two corresponds to an inverted Early Cretaceous transfer zone (the Pamplona fault). The Aragonese–Catalan Pyrenees can be subdivided, on the basis of further along-strike structural differences, into three sectors: eastern, central and west-central (Capote *et al.*, 2002). The Jaca Basin, which is the principal focus of this study, falls into the eastern half of the west-central sector of the Pyrenees; the Aínsa Basin and Tremp–Graus Basin, which are also of importance to this work, fall into the central sector. The structural differences between these two areas had important consequences for the sedimentation that occurred in them, and so are discussed below in detail.

The axial zone of the central Pyrenees area consists of three main basement units – the Nogueres, Orri and Rialp thrust sheets – arranged into an antiformal stack (**Fig. 2.16A**; Muñoz, 1992). To the south, and structurally above the basement thrusts, are three sedimentary cover thrust sheets. From north to south, they are the Bóixols, the Montsec, and the Serres Marginals thrust sheets, and are collectively referred to as the south Pyrenean central unit or SPCU (**Fig. 2.17**; Séguret, 1972). Each is detached over Late Triassic evaporites, and seismic and well data indicate that they were thrust southwards onto the autochthonous rocks of the Ebro foreland basin (Teixell & Muñoz, 2000). The Montsec thrust sheet forms a broad syncline that supports the thrust-top Tremp–Graus Basin, and continues to the NW into the Cotiella thrust sheet, where it is thrust on top of the Eocene turbidites of the Aínsa Basin (Muñoz *et al.*, 1994). The frontal thrust in this area – the Serres Marginals – forms a range of hills known as the Marginal Sierras (*Sierras Marginals*).

The boundary between the central and west-central sectors of the Pyrenees is a N–S- to NW–SE-oriented fold and thrust system at the western end of the SPCU (**Fig. 2.17**). Associated with this system are two, kilometre-scale folds – the Mediano anticline and Boltaña anticline. These major structures define the eastern and western margins of the Aínsa Basin, respectively. They developed during Middle to Late Eocene times (Poblet *et al.*, 1998), and experienced nearly 40° of clockwise rotation during the south-directed emplacement of the SPCU (Pueyo, 2000).

In contrast to the central Pyrenees, the basement thrust sheets of the west-central area form a piggyback imbricate stack that has been thrust under the cover units, which are also deformed into an imbricate stack (**Fig. 2.16B**; Teixell, 1996). These cover units crop-out immediately adjacent to the axial zone, in the Internal Sierras (*Sierras*

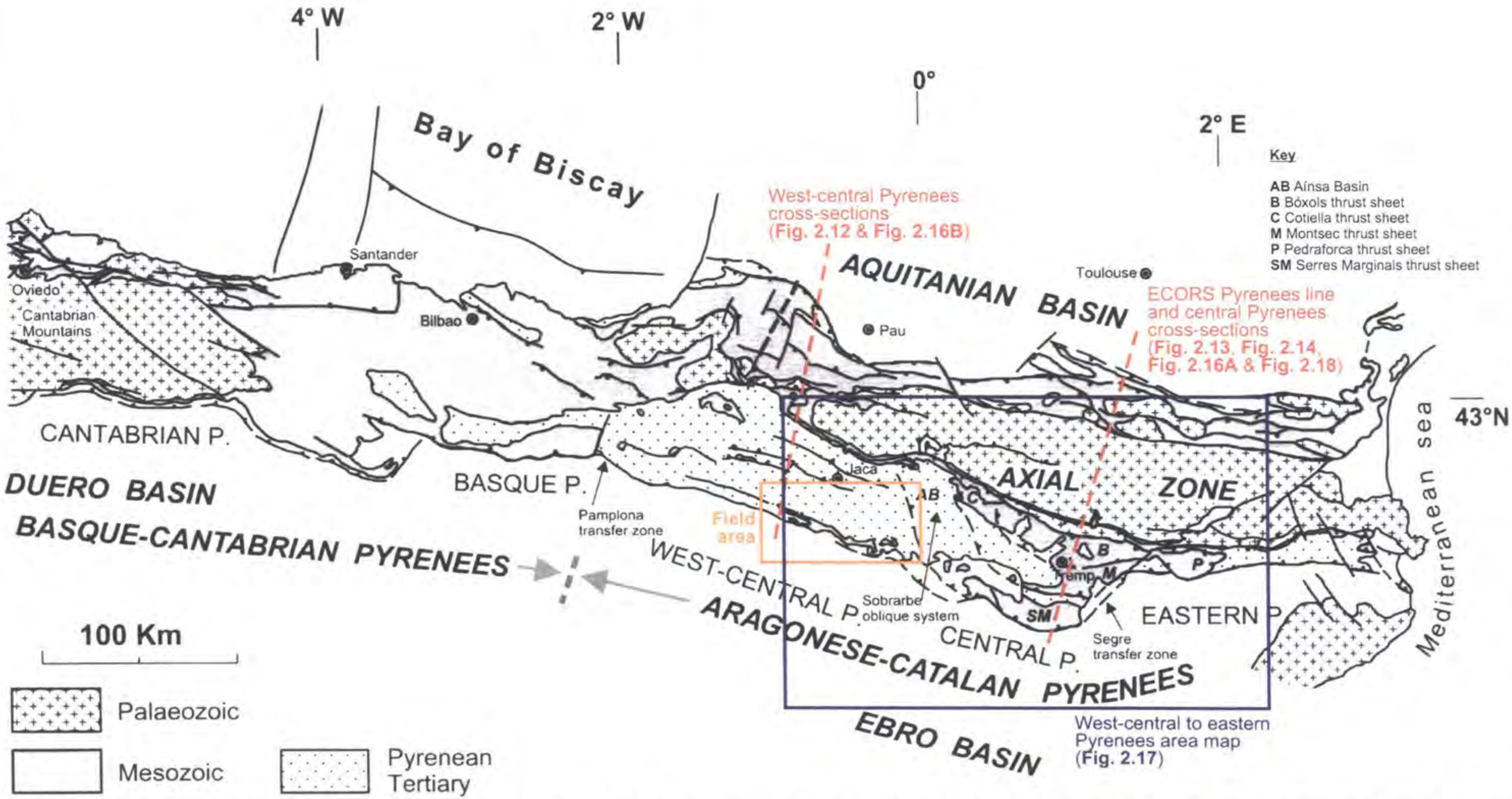


Fig. 2.15. Structural map of the Pyrenees. The locations of the west-central Pyrenees cross-sections (**Fig. 2.12** & **Fig. 2.16B**), the ECORS Pyrenees line and central Pyrenees cross-sections (**Fig. 2.13**, **Fig. 2.14**, **Fig. 2.16A** & **Fig. 2.18**), the map of the west-central to eastern Pyrenees area (**Fig. 2.17**) and the field area for this project are indicated. (From Capote *et al*., 2002.)

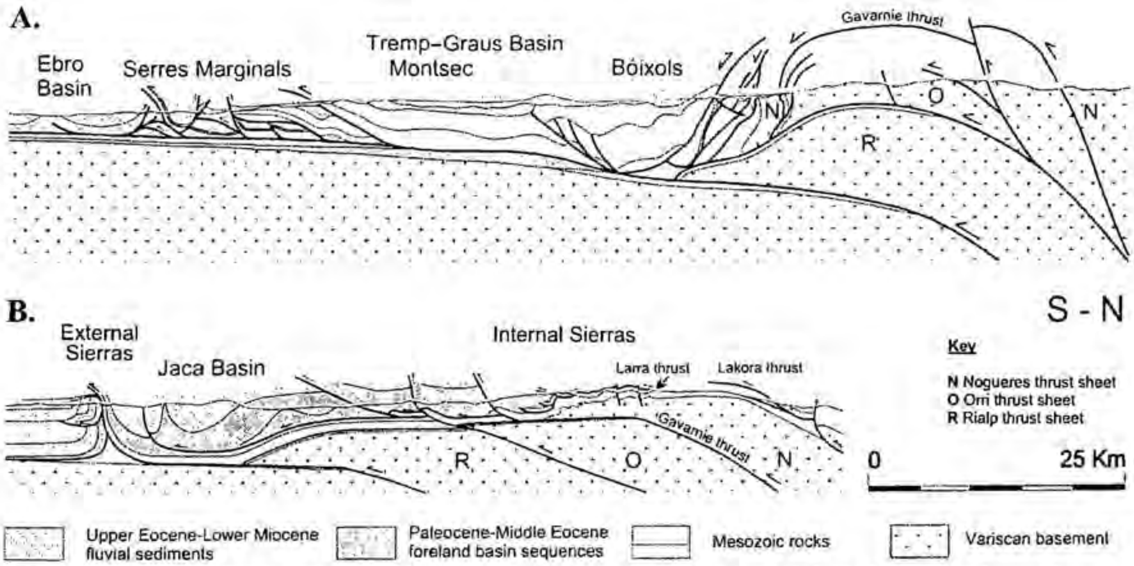


Fig. 2.16. Cross-sections illustrating the differences in structural style and exhumation along the strike of the Pyrenean orogen. The locations of both cross-sections are shown on **Fig. 2.15**. **A**. Through the central Pyrenees, along the ECORS profile. **B**. Through the west-central Pyrenees. (From Capote *et al.*, 2002.)

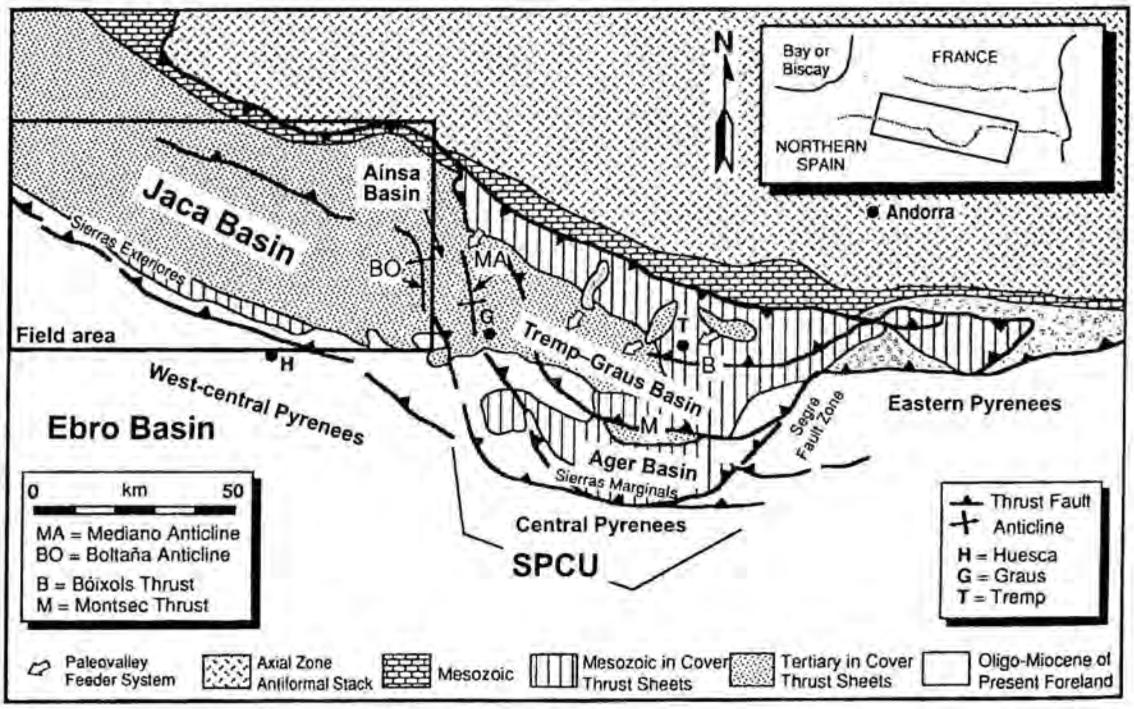


Fig. 2.17. Geological map of the southern Pyrenees showing the location of the SPCU thrust sheet, the frontal thrusts (Sierras Exteriores and Sierras Marginals), the sediment-ary basins (Ebro, Jaca, Aínsa, Tremp–Graus and Ager), some of the major structures that divide them (Boltaña and Mediano anticlines), and the location of the field area for this project. The location of this map is shown on **Fig. 2.15**. (From Bentham *et al.*, 1992.)

Interiores), and around 50 km to the south, as part of the Guarga thrust sheet, in the External Sierras (*Sierras Exteriores*). The External Sierras represent the thrust front in this area, and as such are the westward continuation of the Marginal Sierras of the central Pyrenees. The location of the thrust front is determined by the southern pinch-out of the Triassic detachment level. Laying between the Internal and External Sierras, and on top of the Guarga thrust sheet, is the broad syncline of the Jaca Basin (**Fig. 2.16B**). Its fill of Middle Eocene to Early Miocene marine and continental sediments was deposited during the southward translation of the underlying Guarga thrust sheet (Puigdefàbregas, 1975), i.e. the Jaca Basin was infilled as a thrust-top basin.

2.3.3 Geodynamic evolution of the Pyrenees

The complex geometry of the Pyrenean orogen evolved gradually over the 60-Myr-long convergence between the African, Iberian and European plates. By dating the abundant syntectonic strata that are preserved across the Pyrenees, it is possible to work out when each of the major structures formed and thrusts moved (**Fig. 2.18**; Vergés & Muñoz, 1990), and so arrive at a geological history of the range. In this section, the evolution of the Pyrenees is presented as a number of separate stages, on the basis of the dominant tectonic regime that was operating at the time.

2.3.3.1 Late Cretaceous

Convergence in the Pyrenean area began with transpression on the north Pyrenean fault in the Cenomanian age of the Late Cretaceous (Puigdefàbregas & Souquet, 1986), followed by true compression in the late Santonian (Brunet, 1986). During this initial stage of convergence, Early Cretaceous extensional structures were inverted (Bond & McClay, 1995). These reactivated structures therefore exerted a strong control on the subsequent development of the Pyrenean orogen.

2.3.3.2 Palaeocene

During the Palaeocene, convergence between Europe and Africa was occurring at a relatively low rate (Roest & Srivastava, 1991), causing the Pyrenean crust to slowly thicken. The Pyrenean area was an east–west-trending, elongate, marine embayment, with a westward connection to the palaeo-Bay of Biscay (**Fig. 2.19A**; Plaziat, 1981). To

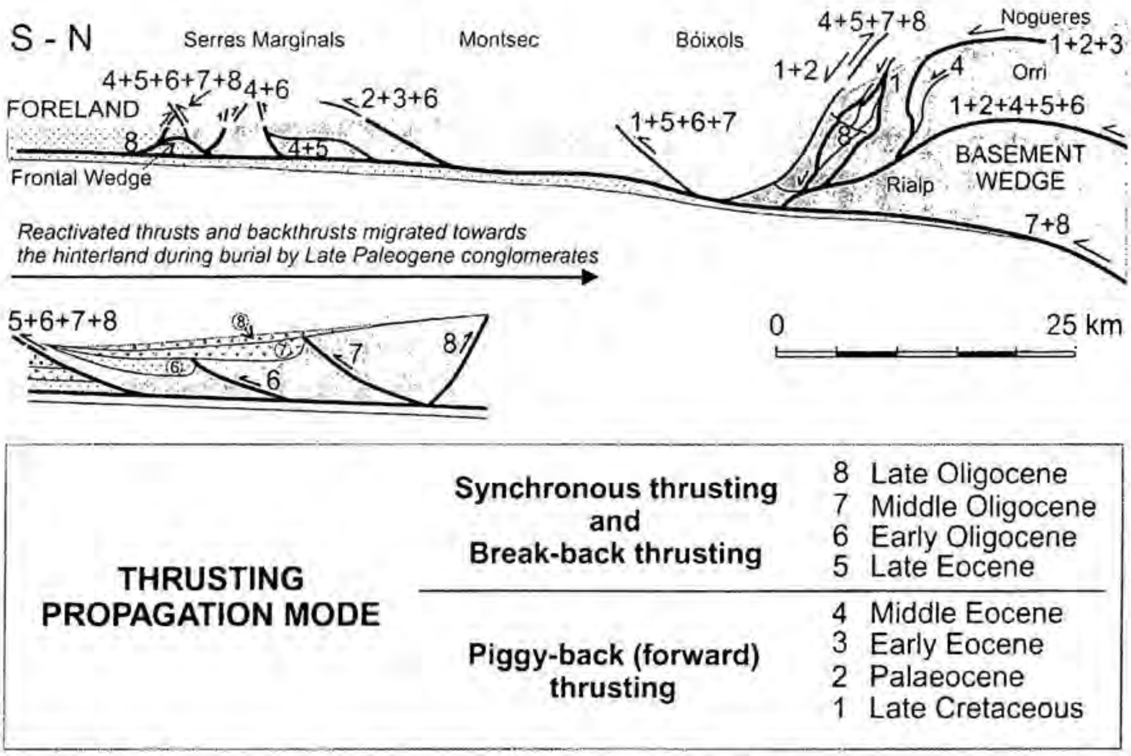


Fig. 2.18. The timings and sequence of thrust movement on the southern side of the central Pyrenees, along the line of the ECORS profile. Position of section is shown in **Fig. 2.15**. (From Capote *et al.*, 2002.)

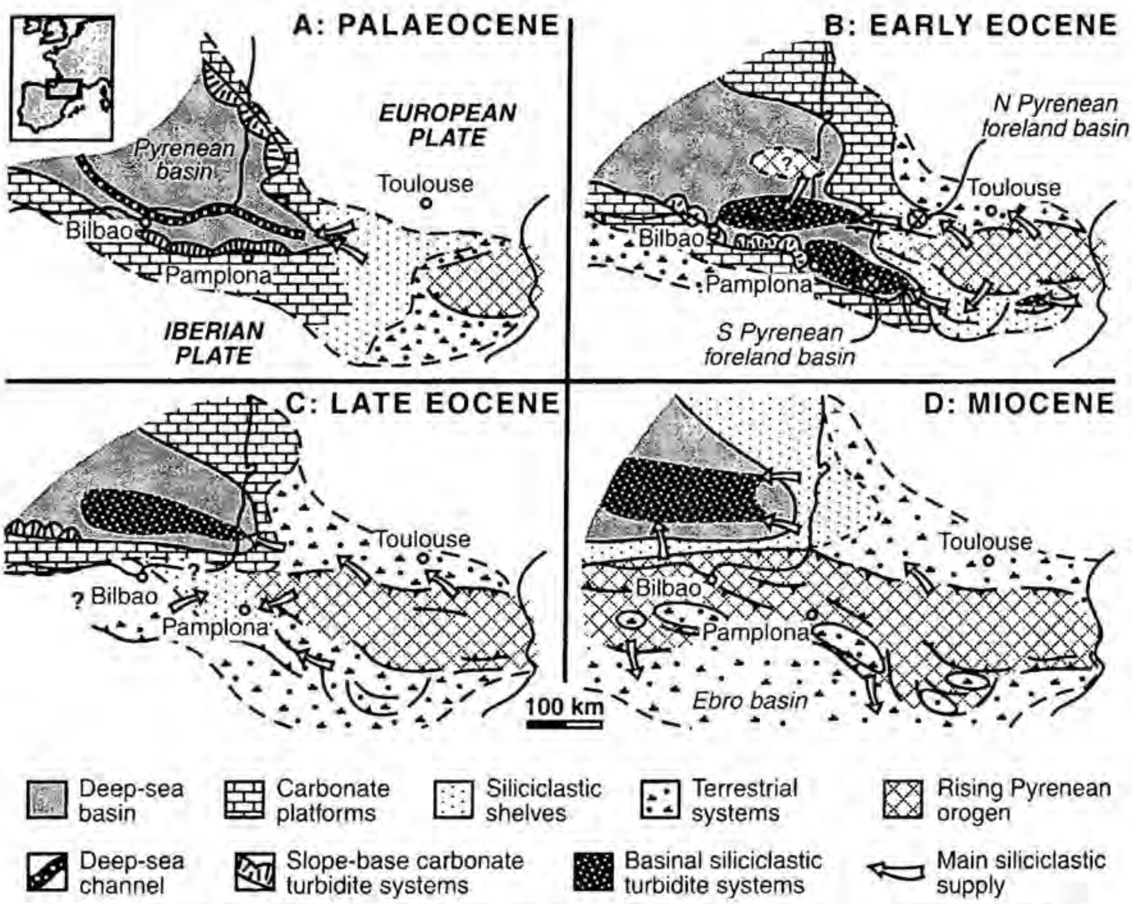


Fig. 2.19. Palaeogeographic evolution of the Pyrenean and Basque–Cantabrian region during the Tertiary Alpine orogeny. (From Alonso-Zarza *et al.*, 2002.)

the south, the Iberian plate was emergent above the sea and, importantly, remained so throughout the Pyrenean orogeny. As the convergence continued, the areas of emergence progressively expanded across the Pyrenean region.

2.3.3.3 Early–Middle Eocene

Convergence rates rapidly increased during Early–Middle Eocene times (Vergés *et al.*, 1995), inducing the emplacement of a number of thrust sheets. The south Pyrenean thrust front was able to advance rapidly along a weak detachment layer of Triassic evaporites. The resulting loading of the lithosphere, plus the effects of subduction loading (Beaumont *et al.*, 2000), caused rapid subsidence and widespread marine conditions in the south Pyrenean foreland basin (**Fig. 2.19B**; Puigdefàbregas *et al.*, 1992; Burbank *et al.*, 1992). The resulting deep marine troughs accumulated turbidite successions such as the Hecho Group of the Jaca Basin. Continued growth of the orogenic wedge led to flexural subsidence of the Iberian margin to the south, causing the turbidites to onlap progressively southwards onto the margin (Labaume *et al.*, 1985). The ongoing flexure also caused the stepped, southward retreat of shallow-water carbonate ramps growing on the Iberian margin (Barnolas & Teixell, 1994). The turbidite sediments were composed of basement-derived material from the hinterland, where a topographic relief of 1–2 km had formed (Millán *et al.*, 1995). Towards the end of this phase of the orogeny, during the late Lutetian, the Biarritzian transgression caused the widespread deposition of marls across the Pyrenean area, and the general back-stepping of facies boundaries.

2.3.3.4 Middle–Late Eocene

During Middle–Late Eocene times, deformation propagated southwards, subdividing the foreland turbiditic troughs, and incorporating parts of them into the south Pyrenean thrust system as a series of thrust-top basins. From west to east, these thrust-top basins are called the Jaca, Aínsa, Tremp–Graus, Ager and Ripoll basins. Both the Guarga and Serres Marginals thrust sheets were active, dividing the Jaca Basin and the Tremp–Graus Basin, respectively, from the south Pyrenean foreland basin. The high levels of tectonic activity also led to the widespread emergence of the Pyrenean axial zone, forming rivers that fed increasing amounts of sediment into the thrust-top basins (**Fig. 2.19C**). The deltaic and fluvial infill of the thrust-top basins was strongly influenced by the growth of numerous intrabasinal, thrust-related structures (Millán *et al.*, 1994; Poblet *et al.*, 1998). Evidence of clasts of Hecho Group turbidites within Priabonian conglomerates implies that the axial zone had already seen some 1.5 km of uplift and unroofing by this point (Payros *et al.*, 2000).

2.3.3.5 Late Eocene–Middle Miocene

The last stage of Pyrenean orogenic growth, during Late Eocene to Middle Miocene times, was characterised by a change in deformational style (**Fig. 2.14**; **Fig. 2.18**). Iberian upper crustal units were under-thrust below previously southward-displaced basement and cover units, forming a basement antiformal stack in the middle of the chain. At the same time, lower cover thrust sheets were over-thrust on top of the southern foreland. The south Pyrenean foreland basin became cut off from the Atlantic Ocean by the developing topography in the Basque–Cantabrian Pyrenees, forming the internally draining, terrestrial, Ebro Basin (**Fig. 2.19D**; Coney *et al.*, 1996). This was progressively infilled by thick alluvial conglomerates, sourced partly from the high-relief areas of the Pyrenees. During this, the frontal thrusts that flank the Ebro Basin became buried, leading to a major change in the kinematics of the orogen. The buried thrusts became inactive, forcing deformation to step backwards towards the hinterland, producing break-back reactivation of older thrusts and new out-of-sequence thrusts (Vergés & Muñoz, 1990).

The end of contractional deformation in the Pyrenees was diachronous – from the Middle Oligocene in the eastern Pyrenees to the Early Miocene in the central Pyrenees (Hernaiz & Solé, 2000), and even later further west. The end of compression caused sediment supply rates to the foreland to wane, and alluvial fan development to decrease. During Miocene and Pliocene times, the southern Pyrenees were re-exposed by erosion, and the present-day fluvial system in the Ebro Basin was developed. Thermal re-equilibration of the lithospheric root and subducted lower crust beneath the Pyrenees (Pous *et al.*, 1995) began to drive post-orogenic isostatic rebound, favouring river incision. This processes is continuing today.

2.3.3.6 Quaternary

During Quaternary times, the present-day Pyrenean landscape was formed (Gutiérrez-Elorza *et al.*, 2002), determining the nature and degree of geological exposure across the area. Abundant glacial deposits record a discontinuous presence of Late Pleistocene glaciers across a large part of the range (Chueca *et al.*, 1998), with most dating from the Würm period. The modern-day major Pyrenean rivers run north to south, crossing the grain of the geological structure at structurally controlled points – some of which were operational as long ago as the Middle Eocene (Jones, 2004). The rivers have developed generally narrow valleys and therefore show only small, young terraces. However, where easily erodable materials are present, such as Eocene marls, wide east–west trending valleys have been formed, preserving many older terrace levels (Peña, 1994).

2.4 Jaca Basin

The Jaca Basin contains the geological formation that is the principal focus of this study – the Belsué-Atarés Fm. Understanding the structure and geological history of the basin is therefore of critical importance to this work.

The Jaca Basin is the westernmost thrust-top basin on the south side of the Pyrenean axial zone, laying to the west of the thrust sheets of the SPCU (**Fig. 2.17**; Hogan & Burbank, 1996). Simply put, it is a broad, WNW–ESE trending syncline, around 30 km across and 100 km long. Its present-day northern margin is defined by a series of WNW–ESE-trending thrusts and associated folds. Its eastern border is the N–S-trending Boltaña anticline – a structure that lies at the western end of the SPCU, and formed either above an oblique ramp on a thrust sheet (Holl & Anastasio, 1995), or as a propagation fold above a blind thrust (Remacha *et al.*, 1998). The southern margin of the Jaca Basin is defined by the External Sierras – created by the emergence of the Guarga thrust sheet, and representing the south Pyrenean thrust front in the west–central Pyrenees area. To the south of the thrust front lays the Ebro foreland basin. The western margin of the Jaca Basin is not clearly defined, but there is evidence for a topographic high preventing direct connection between the Jaca Basin and the Bay of Biscay at times during its development (Remacha *et al.*, 1998).

The Jaca Basin initially formed as part of the greater south Pyrenean foreland basin during the Early Eocene. By Middle Eocene times however, the Guarga thrust had propagated southwards beneath the basin, utilising a layer of Keuper (Triassic) evaporites as a detachment (Anastasio & Holl, 2001). As a thrust-top basin, the Jaca Basin was infilled by 5 km of syntectonic strata, initially deposited in marine conditions, and then terrestrial. The deposition of these sediments was strongly controlled by the ongoing compressional deformation of the Jaca Basin, its margins, and adjacent areas. This interaction between the sedimentation and the tectonics is the primary focus of this project, and in the Jaca Basin this happened to be most readily observed around the External Sierras along the southern basin margin.

2.4.1 External Sierras

The External Sierras are composed of the emergent front of the Guarga thrust sheet, which is the frontal thrust on the southern side of the west–central Pyrenees (Anastasio & Holl, 2001). The emergent front trends WNW–ESE and separates the Jaca thrust-top basin to the north from the overthrusted and undeformed Ebro Basin to the south. The growth of the External Sierras created significant topography that had a profound effect on the syntectonic sedimentary systems of the Jaca Basin. The relationships between the growth strata and the structures of the External Sierras are superbly exposed across most of the southern basin margin, and were studied in detail as part of this project.

Hogan & Burbank (1996) combined study of the relationships between the syntectonic strata and the structures of the External Sierras with palaeomagnetic dating, and some biostratigraphic data (Canudo *et al.*, 1991), to deduce a geological history of the range. They showed that the southward translation of the Guarga thrust sheet lasted until the Early Miocene. Shortening rates were initially as high as 2.4 mm/yr, but decreased through time.

The present-day structure of the External Sierras range was formed by three distinct phase of tectonic deformation, which overlapped to some degree. The first stage was the growth of a series of anticlines with NW–SE-trending axes in the External Sierras area (**Fig. 1.3**), beginning in the east in the Middle Eocene, propagating westwards, and continuing until the Early Oligocene. The nature of these well-studied yet controversial structures is discussed below (section **2.4.2**). Also occurring during the Middle Eocene, whilst the anticlines were growing, was a second phase of deformation – thrust sheet rotation. The entire Guarga thrust sheet, and therefore the entire Jaca thrust-top basin, rotated by around 38° clockwise (McElroy, 1990; Millán *et al.*, 1992; Hogan, 1993; Pueyo, 2000; Pueyo *et al.*, 2000; Pueyo *et al.*, 2002). This rotation was caused by either the emplacement of the SPCU thrust sheet to the east (Pueyo *et al.*, 2002), or because of the position of the southern pinch-out of the Keuper detachment horizon on which the thrust sheet moved (Capote *et al.*, 2002). The rotation also brought the orientations of the axes of the anticlines to their present-day N–S trends. The final phase of the deformation in the External Sierras area lasted until the end of the Priabonian, and occurred because of the continued movement of the Guarga thrust sheet over a ramp on the thrust plane. This resulted in the uplifting of the External Sierras, and a 30° north-directed tilting of the axes of the N–S-orientated anticlines (Millán *et al.*, 1994; Millán *et al.*, 2000).

2.4.2 N–S-orientated anticlines of the External Sierras

The N–S anticlines of the External Sierras began to form during the Middle Eocene, at a time when the Jaca Basin had newly become a thrust-top basin, and was beginning to be infilled by the deltaic systems of the Belsué-Atarés Fm. (Hogan & Burbank, 1996). Stratal relationships observable in the field indicate that the topography created by the uplift of these structures had a significant effect on the accumulation of the Belsué-Atarés Fm. The study of this controlling effect was one of the aims of this project, and therefore understanding the formation of the N–S orientated anticlines is of considerable importance.

Seven N–S oriented anticlines can be distinguished along the length of the External Sierras (**Fig. 1.3**). From west to east, they are called the Rasal, Bentué de Rasal, Pico del Águila, Lúsera, Gabardiella, Nocito, and Alcanadre anticlines. Forming the eastern margin of the Jaca Basin are a further two N–S-orientated anticlines, each with an axial trace of over 20 km in length (**Fig. 1.3**). The more northerly structure is the Boltaña anticline, whilst the Balces anticline lays to the south. Unlike the seven smaller N–S anticlines of the External Sierras that are related to the Guarga thrust sheet, these two large-scale folds were formed by the south-directed emplacement of the SPCU thrust sheet that lays to the east (Holl & Anastasio, 1995).

The unit most obviously folded by the anticlines is the Middle Eocene limestones of the Guara Fm., although the structures are cored by units of Triassic to Early Eocene age (**Fig. 1.1**). The folds themselves have amplitudes of around 1 km, and their axes plunge an average of 30° to the north. They take the form of tight, symmetric anticlines, separated by broad, flat-bottomed synclines. The folds are currently oriented around N–S, but if the post-folding, 38° rotation of the Guarga thrust sheet is removed (section **2.4.1**), then the original NW–SE rotation of the folds is revealed. This trend puts the folds as being oblique to southward displacement of the Guarga thrust sheet at the time that they formed.

In line with the general trend of east to west propagation of deformation throughout the Pyrenees, the oldest and most well developed anticlines are situated at the eastern end of the External Sierras (Puigdefàbregas, 1975; Millán *et al.*, 1994), where the displacement on Guarga thrust sheet was greatest (Anastasio & Holl, 2001). From here, the folds become progressively smaller and younger towards the west (**Fig. 1.1**).

The growth of the N–S oriented anticlines has been attributed to a number of different causal mechanisms, including fault-related folding above a westward imbricating oblique ramp (e.g. Hirst & Nichols, 1986), detachment folding – shortening of competent layers above an incompetent detachment (Millán *et al.*, 1994; Poblet & Hardy, 1995), and differential load halotectonics, due to westward sediment progradation in the Jaca Basin (e.g. Anastasio, 1992). The arguments have yet to be resolved, although it is entirely possible that all three suggested causal mechanisms contributed to the growth of the folds to some degree.

The superbly exposed relationships between the N–S-orientated growth anticlines of the External Sierras and the adjacent syntectonic sediments have been the subject of a number of studies over the past decade or so. These studies will be summarised and reviewed in Chapter 9, which will focus on this part of the Jaca Basin.

2.4.3 Sedimentary infill of the Jaca Basin

The Jaca Basin contains at least 5 km of foreland basin strata deposited during Eocene and Oligocene times (Puigdefàbregas, 1975; **Fig. 1.1**). **Fig. 2.20** depicts a schematic log of the infill of the Jaca Basin, the names of the various formations, their ages and depositional environments, a eustatic sea-level curve, and a summary of the local and regional tectonic events occurring at the time. The basin fill records a cycle of transgression and regression: an initial rapid deepening of the basin, due to loading by southward propagating thrust sheets, followed by progressive infill of the basin by first marine, and then continental depositional systems. These changes in relative sea-level do not correlate with the eustatic sea-level curve for the time (**Fig. 2.20**; Haq *et al.*, 1987), so we may conclude that they were driven by subsidence / uplift events in the south Pyrenean foreland area.

In this section, the units of sedimentary infill of the Jaca Basin are described in temporal order, beginning with the first deposits laid down when the basin was still part of the greater south Pyrenean thrust-top basin (Early Eocene), and ending with the youngest thick accumulations of sediment in the basin (Early Miocene). Many of the sedimentary and tectonic events that occurred in the basin during these times have been dated by the palaeomagnetic work of Hogan & Burbank (1996) and Pueyo *et al.* (2002).

2.4.3.1 Hecho Group

The turbidites of the Hecho Group were deposited in the axis of the Jaca Basin whilst it was still part of the greater south Pyrenean foreland basin, during Ypresian to Lutetian times. The south Pyrenean foreland basin at this time was a narrow E–W-trending trough, defined by a poorly developed submarine orogen to the north, and the SPCU thrust sheet to the east. To the south lay the emergent Iberian foreland, and to the west was a structural rise on the basin floor that prevented a direct connection to the Bay of Biscay (Remacha *et al.*, 1998). The depocentre of the basin itself was gradually migrating southwards due to the loading effect of the southwards propagating thrust sheets, causing the turbidites to develop south-directed onlap onto the basin margin (Labaume *et al.*, 1985).

The sediments that comprise the Hecho Group turbidites entered the basin via a single entry point in the southeast, which was partly controlled by the oblique lateral ramp structures of the SPCU, such as the Boltaña anticline (Mutti *et al.*, 1988). This structurally controlled funnel acted like a submarine canyon, channelling sediments from the shallow-water Ager and Tremp–Graus Basins to the east, westwards, into deep marine environments. Once in the basin, the sediment spread out across its floor, in a manner that was strongly controlled and confined by the active tectonic structures. By using carbonate megabreccias as marker beds, Remacha *et al.* (2003) were able to correlate even the thinnest turbidite beds across the entire basin. A maximum thickness of nearly 4500 m of turbidites accumulated, in six stacked, major-unconformity-bounded wedges (Mutti *et al.*, 1985; Remacha *et al.*, 1998).

The Hecho Group turbidites were accumulating at the same time as the Guara Fm. limestones (section **2.4.3.2**, below), evidenced by the fact that the former contains distinctive carbonate megabreccias sourced from the latter (Barnolas & Teixell, 1994).

2.4.3.2 Guara Formation

During the Ypresian and Lutetian, the Jaca Basin was still an undetached part of the greater south Pyrenean foreland basin, and being infilled by the Hecho Group turbidites. To the south of the basin lay the emergent Iberian margin, and in between the two, an area of relatively shallow water. The eastern margin of the basin was also at a relatively shallow water depth, because of the compressional deformation due to the ongoing south-directed emplacement of the SPCU thrust sheet to the east. In both these relatively shallow water areas, the extensive carbonate platforms of the Guara Fm. accumulated (Puigdefàbregas & Souquet, 1986). The timing of the deposition of the Guara Fm. was closely related to the movement of the thrust sheets and the growth of the associated folds that defined the two basin margins – the Guarga thrust sheet and folds of the External Sierras for the southern basin margin, and the SPCU and the Boltaña anticline for the eastern margin (**Fig. 2.21**).

The Guara Fm. is up to 800 m thick and can be divided into three main stratigraphic units, each a separate carbonate platform system: the Alveolina, Boltaña and Guara limestones (Barnolas *et al.*, 1991). The deposits are predominantly skeletal grainstones, made up of large benthic foraminifera tests such as *Alveolina*, *Nummulites* and *Assilina*, nodular wackestones and marls. The deposits accumulated on a low angle carbonate ramp, with skeletal facies of the inner ramp grading into more distal deposits of the outer ramp. Within the succession are stacked shallowing-upwards sequences of 10–30 m thickness. Pedley (1994) undertook a detailed sequence stratigraphic analysis of these cycles, and concluded that variations in eustatic sea level, combined with tectonic subsidence, were the dominant controls. The stacking pattern of the three main stratigraphic platform units is that of foreland-ward progradation, recording the progressive south-directed advance of thrust loads towards the foreland (Barnolas & Teixell, 1994).

Within the Guara Fm. of the southern basin margin, each of the carbonate platforms is cut on its basinward (northern) side by a series of major erosional truncations. These record large-scale failure and collapse of the platform margin, and gave rise to eight major carbonate megabreccia sheets in the coeval Hecho Group to the north (Barnolas & Teixell, 1994). Each successive slope failure truncation in the limestones is found to the south of the previous one, recording a stepped onlap onto the basin margin, resulting from the southward advance of thrust loading. Each one also passes landwards (southwards) into apparent conformities that display drowning (rapid deepening) sequences. It is inferred from the stepped nature of the back-stepping that the tectonic process responsible was episodic. During periods of tectonic quiescence, limited subsidence allowed shallow-water carbonate platform development on the southern basin margin. However, during periods of rapid thrust advance and loading,

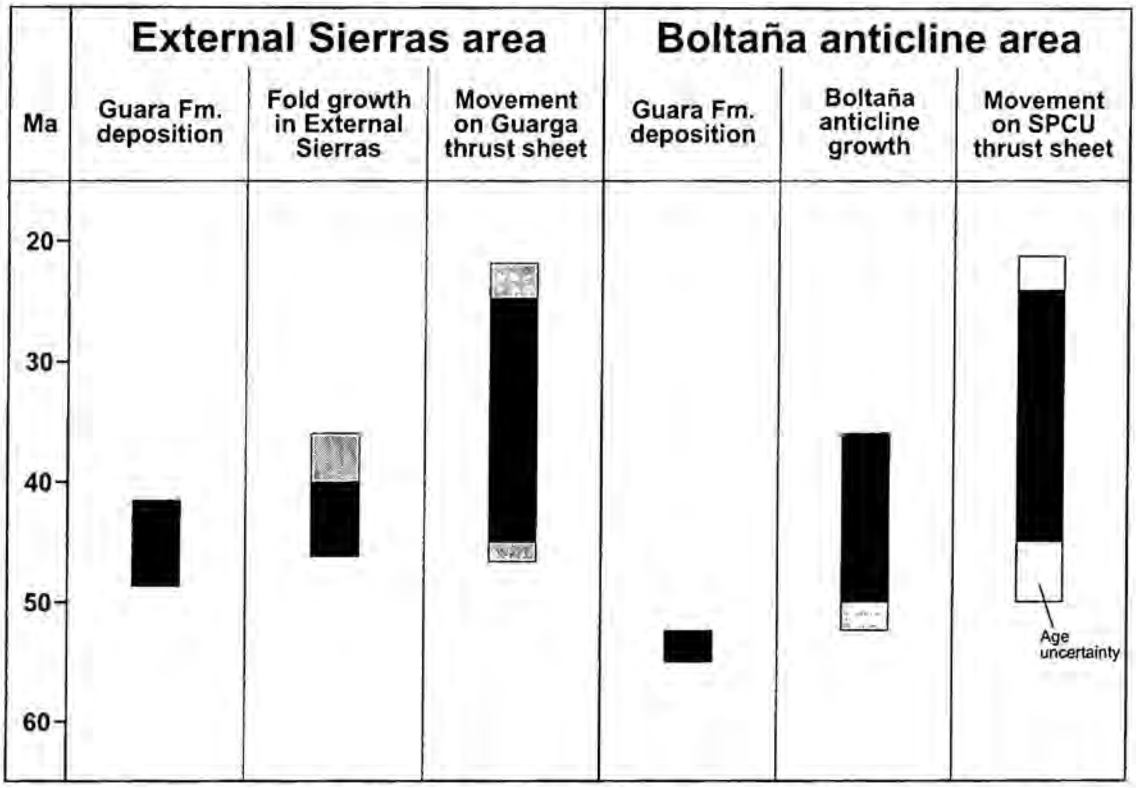


Fig. 2.21. Relative timings of the deposition of the limestones of the Guara Fm. and the structures which define / control the southern basin margin (N–S (originally NW–SE) anticlines of the External Sierras / Guarga thrust sheet) and the eastern basin margin (Boltaña anticline / SPCU thrust sheet). (Modified from Anastasio & Holl, 2001.)

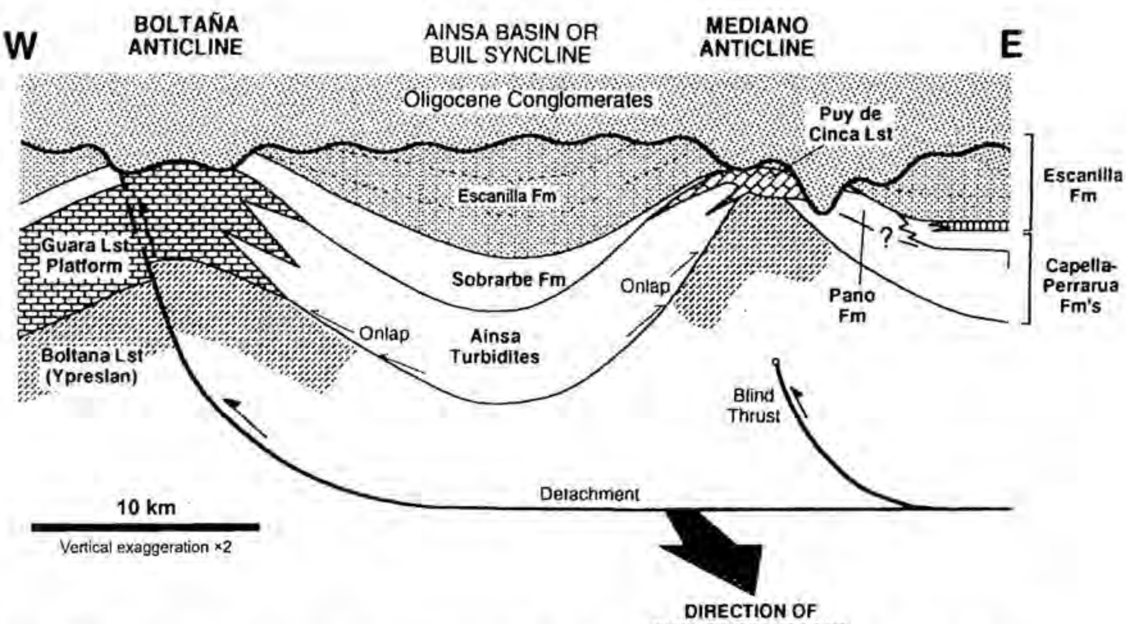


Fig. 2.22. West–east cross-section across the Aínsa Basin showing the major basin-bounding structures (the Boltaña and Mediano anticlines), and its sedimentary in-fill. (From Bentham *et al.*, 1992.)

down-warping of the lithosphere of the southern margin caused drowning and over-steepening of the platform on that margin. This led to major platform collapses and the creation of the base-of-slope megabreccia sheets.

The end of the accumulation of the Guara Fm. was brought about by a sudden rise in sea-level – the Biarritzian transgression – that caused the drowning of the carbonate platform. This sea-level rise occurred at 41.5 Ma (Pueyo *et al.*, 2002) across the whole Pyrenean area, and resulted in a sudden switch to marl deposition in the foreland basins (Puigdefàbregas, 1975).

2.4.3.3 Sabiñánigo Sandstones

The initiation of the deposition of the Sabiñánigo Sandstones occurred during a period of increased tectonic activity during Lutetian times. The western end of the SPCU was active, leading to uplift of the Boltaña anticline, and emergent areas were created in the hinterland to the north and northeast of the Jaca Basin (Remacha *et al.*, 1998). These emergent areas became the source of the first deltaic system to in-fill the Jaca Basin – the Sabiñánigo Sandstones delta. This delta may be considered to be an early expression of the later (Bartonian), regionally important, Santa Orosia fan delta (section **2.4.3.5**; Chapter 5), because it had the same basin entry point and source area (Oms & Remacha, 1992). This entry point was in the eastern half of the northern basin margin, to the north of the village of Yebra de Basa.

The deposits of the Sabiñánigo Sandstones delta amount to 100 m or less of fine grained, wave rippled, marl-rich sandstones. They are only found around the northern margin of the Jaca Basin, and were deposited coevally with the upper parts of the Guara Fm. from the southern and eastern basin margin. No coarser or more proximal facies were ever developed because, like the Guara Fm., their deposition was halted by the major marine Biarritzian transgression at 41.5 Ma (Pueyo *et al.*, 2002).

2.4.3.4 Árguis Formation

The Árguis Fm. is primarily composed of marls that were deposited after the Pyrenees-wide Biarritzian marine transgression at 41.5 Ma (Puigdefàbregas, 1975). This unit lies on top of the Guara Fm. in the south and east of the Jaca Basin, and above the Sabiñánigo Sandstones in the northern areas. The end of deposition of the Árguis Fm. occurred some time during the Bartonian. It is not possible to be more precise as it is difficult to locate the top of the formation because of its gradation into the overlaying Belsué-Atarés Fm. Furthermore, this boundary is thought to be diachronous across the Jaca Basin because of its direct association with facies progradation.

The Árguis Fm. reaches its greatest exposed thickness, close to 1000 m, in the central portion of the southern half of the basin. Facies vary from un-burrowed, nearly azoic blue marls, to silty and sandy bioturbated marls. In the sandier beds, bioclasts are sometimes abundant, including echinoids, bivalves, bryozoans, oysters, solitary corals, diverse planktonic foraminifera, and benthic foraminifera, especially *Nummulites* (Millán *et al.*, 1994). Some beds contain a significant amount of glauconite. The azoic blue marls formed on the outer part of a low angle carbonate ramp, in a poorly circulated and relatively deep marine environment, beneath storm wave base (Millán *et al.*, 1994). The presence of glauconite indicates low sedimentation rates. The sandy fossiliferous marls represent the distal parts of shallow marine bars, related to a deltaic complex, located in the middle parts of the carbonate ramp. Possible inner ramp storm beds are also present in places. Stacked cyclic variations between outer ramp facies and middle or inner ramp facies have been attributed to fluctuations in sea level (Castelltort *et al.*, 2003), possibly caused by pulses in tectonic activity (Millán *et al.*, 1994). A full description and discussion of the cyclicity that has been observed in the stratigraphy of the Árguis Fm. will be given in Chapter 9.

2.4.3.5 Belsué-Atarés Formation

The Bartonian (Pueyo *et al.*, 2002) Belsué-Atarés Fm. overlies the marls of the Árguis Fm., with a contact that is rarely sharp, and usually gradational over tens of metres. The upper boundary of the Belsué-Atarés Fm. represents the change from marine to continental sedimentation in the Jaca Basin, can also be sharp or gradational, and is easily recognisable basin-wide. The deposits of the Belsué-Atarés Fm. are the primary focus of this project.

The initiation of Belsué-Atarés Fm. sedimentation in the Jaca Basin was coeval with the basin changing from simply being a part of the greater south Pyrenean foreland basin to a discrete, thrust-top basin. This change was brought about by southwards propagation of the Guarga thrust fault beneath the basin, along a detachment horizon in the Triassic strata (Anastasio & Holl, 2001). The emergence of this thrust in the External Sierras area defined the southern basin margin. The southwards movement of this thrust sheet also caused the growth of a series of anticlines with NW–SE-trending axial traces in the External Sierras area, which continued to grow throughout the deposition of the Belsué-Atarés Fm. (Millán *et al.*, 1994). At this time, the northern basin margin was beginning to be defined by the growth of WNW–ESE-trending anticlines that were also related to the southwards-propagating trusts. The eastern basin margin was already defined by the Boltaña anticline, the growth of which had been initiated by earlier movement on the SPCU (Poblet *et al.*, 1998; Anastasio & Holl, 2001).

Beginning at the start of the deposition of the Belsué-Atarés Fm., and continuing throughout its deposition, the Guarga thrust sheet, and so the entire Jaca Basin, was progressively rotated by 38° clockwise (Pueyo *et al.*, 2002). This was probably a consequence of the continued southward movement of the SPCU thrust sheet to the east. The effects that the active tectonics, such as the thrust sheet rotation and the growth of the anticlines, had on the sedimentation and architecture of the Belsué-Atarés Fm. are the primary focus of this project. Sequence stratigraphic analyses of sections of the Belsué-Atarés Fm. have already been attempted by Millán *et al.* (1994) and Castelltort *et al.* (2003), and will be discussed in detail in Chapter 9.

Although the 38° clockwise rotation of the Guarga thrust sheet has obviously affected the palaeocurrent readings measured today, the palaeocurrents given throughout this thesis have *not* been corrected for this – for two reasons. Firstly, the rotation occurred whilst the Belsué-Atarés Fm. was being deposited (Pueyo *et al.*, 2002), so the amount of 'un-rotation' required would vary with age of each reading – and sufficiently accurate age dates are not available. Secondly, as well as the palaeocurrents, all structures and the general intrabasinal palaeogeography have also been rotated. Thus, simply 'un-rotating' the palaeocurrents would give a flow direction that was incongruous with the apparent intrabasinal palaeogeography at the time that the current operated. To correct for this, all maps of the basin would have to be 'un-rotated' as well, which would have been both impractical and misleading. In general, the rotation of the thrust sheet is only really important when considering the Jaca Basin or Guarga thrust sheet in the wider context of the south Pyrenean foreland area.

A diverse range of facies is preserved in the Belsué-Atarés Fm., including sandy marls, wave-rippled and cross-bedded sandstones, channelised units, bioclastic beds (bivalves and benthic foraminifera) and reefal units (Millán *et al.*, 1994). The reefal units consist of poorly sorted boundstones and floatstones of branching and massive hermatypic corals, bryozoans, calcareous algae, bivalves and benthic foraminifera. In the central portions of the northern Jaca Basin, conglomerates associated with the Santa

Orosia fan delta are preserved (Chapter 5). The Belsué-Atarés Fm. was deposited as a series of delta lobes prograding onto prodelta marls (Millán *et al.*, 1994). Palaeocurrents and gross lateral and vertical facies changes indicate that the deltas prograded towards the WNW, along the synclinal basin axis. The sands that built these deltas were supplied from the Pyrenean axial zone to the north of the basin, and the emergent Iberian massif to the south.

In the same way that the top of the Árguis Fm. is diachronous across the Jaca Basin because it is associated with facies progradation, the top of the Belsué-Atarés Fm. is also diachronous. However, the diachroneity is even stronger for the top of the Belsué-Atarés Fm. because the WNW-directed progradation of this boundary was held back by the growth of the N–S (originally NW–SE) anticlines in the southern Jaca Basin (De Boer *et al.*, 1991; Bentham *et al.*, 1992). A full discussion of this important tectonic control on sedimentation is given in Chapter 8.

2.4.3.6 Yeste-Arrés Formation

The Yeste-Arrés Fm. is a relatively thin (less than 100 m thick) succession of very distinctive facies that were deposited in the western parts of the Jaca Basin, coevally with the upper portions of the Belsué-Atarés Fm. (Puigdefàbregas, 1975). Along the western end of the northern basin margin, the Yeste-Arrés Fm. largely consists of sandstones with abundant parallel lamination and wave ripples, deposited in a tidal flat environment. At the western end of the southern basin margin, it is composed of marly sandstones that are rich in a diverse range of marine fossils, recording a protected, shallow marine environment. Like the Belsué-Atarés Fm., the Yeste-Arrés Fm. is overlain by the Campodarbe Group.

2.4.3.7 Campodarbe Group

The base of the Campodarbe Group represents the onset of non-marine sedimentation in the Jaca Basin. Although this occurred diachronously across the basin, Pueyo *et al.* (2002) found that the transition occurred at 36.6 Ma (early Priabonian) in the vicinity of Árguis, in the central portion of the southern basin margin. At this time, the growth of the N–S anticlines of the External Sierras had ceased in all but the westernmost structure, as had the clockwise rotation of the Guarga thrust sheet (Pueyo *et al.*, 2002). However, uplift was occurring in the External Sierras area due to continued southwards displacement of the Guarga thrust sheet over a frontal ramp (Millán *et al.*, 1994; Millán *et al.*, 2000), and the Boltaña anticline was continuing to grow (Jolley, 1987).

The contact between the top of the Belsué-Atarés Fm. and the base of the Campodarbe Group is usually gradational over a few metres or tens of metres. Although it is sometimes a little sharper, it is never erosional. The position of the boundary is most easily recognised in the field using the change in colour of the clay or silt lithologies, which go from grey to yellow, orange or red, and the disappearance of marine fossils.

The Campodarbe Group encompasses all fluvial sediments deposited in the Jaca Basin between the Priabonian and the late Rupelian (Early Oligocene) – a time interval of 15 Myr, and a total sediment thickness of 3–4 km (Jolley, 1987). Throughout the Campodarbe Group, Jolley (1987) recognised two distinct fluvial systems: the easterly derived system, concentrated in the southern and central portions of the basin, and the northerly derived system, dominant in the northern areas. Both systems record a variety of differing types of river systems, from stable, sinuous meandering rivers to rapidly shifting, large, low sinuosity braided bedload channels. The eastern system tended to be less confined and more able to laterally migrate than the northern one (Jolley, 1987; Jolley & Hogan, 1989). Between the channels, extensive floodplains were affected by the development of soils of varying type and maturity.

The Campodarbe Group is subdivided into the Lower, Middle and Upper Campodarbe formations, which were each deposited by distinct fluvial regimes (Jolley, 1987). Palaeocurrents in the Lower Campodarbe Fm. system were deflected away from the uplifting External Sierras. Rivers coming from the east, as part of the general south Pyrenean axial drainage system, were also deflected around the southern end of the still-growing Boltaña anticline. The eastern fluvial system was more dominant at this time; clast types indicate that it was sourced in the Pyrenean axial zone to the NE, and came via the alluvial systems of the Tremp–Graus Basin and the Aínsa Basin to the east. The northern fluvial system was derived from the unroofed axial zone directly to the north, and entered the basin via the Santa Orosia and Fablo fans, developed at structurally controlled entry points (Jolley, 1987).

Uplift in both the External Sierras and of crest of the Boltaña anticline had ceased by 33.5 Ma, when the Middle Campodarbe first began to accumulate (Hogan & Burbank, 1996), meaning that the two structures no longer acted as topographic barriers. By this time, the northerly fluvial system became more widespread across the Jaca

Basin. It was still fed by a point source at the Fablo, but also a new, more westerly point source at the Peña Oroel fan. The eastern fluvial system, no longer impeded by the Boltaña anticline, fed directly westwards into the Jaca Basin from the Aínsa Basin.

By 31.5 Ma, when the Upper Campodarbe Fm. first began to accumulate (Hogan & Burbank, 1996), tectonic activity had increased on the northern basin margin – causing further spreading and domination of the northerly-derived fluvial system. The northerly system was still fed by a point source at the Peña Oroel fan, but also by a new, more westerly point source at the San Juan de la Peña fan. Occurring at the same time was a major reorientation of palaeocurrent directions in the centre of the basin, from west-directed to southwest-directed. The easterly-derived fluvial system made little or no contribution to the Upper Campodarbe Fm., probably due to a cut-off in the supply of sediment from the Tremp–Graus Basin (Jolley, 1987).

The end of deposition of the Campodarbe Group occurred at 29.5 Ma (Hogan & Burbank, 1996), with a switch from dominantly fluvial sedimentation to the dominantly alluvial fan sedimentation of the Bernués Fm.

2.4.3.8 Bernués and Uncastillo Formations

The Bernués Fm. is Late Oligocene in age, and around 1100 m thick (Turner, 1992). It is made up of a series of conglomerates and sandstones, overlies the Upper Campodarbe Fm. in the central axis of the Jaca Basin, and also crops out along the northern margin of the Ebro Basin. The conglomerates usually fill erosively based channels, whilst the sandstones are more sheet-like. Both were deposited by semi-arid, sheetflood dominated alluvial fans that formed in response to the emergence of the westward continuation of the External Sierras – the Santo Domingo anticline or the Peña flexure (Turner, 1992). The fans become smaller in a westward direction along the structure, corresponding to the decrease in thrust displacement in that direction.

The Uncastillo Fm. is Early Miocene in age, and greater than 700 m thick (Turner, 1992). It crops out along the northern margin of the Ebro Basin, and is made up of ribbon sandstones arranged in unconnected, erosively based, multi-storey units, set in levees and overbank siltstones. The Uncastillo Fm. was deposited by a fluvial system that drained southwards, away from the Santo Domingo anticline, and into the Ebro Basin. The loading caused by the thrust advance associated with the formation of the Santo Domingo anticline caused rapid subsidence in the area. This is reflected by the vertical rather than lateral accretion seen in the sand-bodies, and the lack of well developed palaeosols in the overbank fines.

Since the cessation of the deposition of the Uncastillo Fm. at the end of the Early Miocene, no further thick and laterally extensive bodies of sediment have accumulated in the Jaca Basin. Instead, continued uplift, erosion and river incision has removed, in places, several kilometres of sediment, exposing the older formations.

2.5. Aínsa Basin

The Aínsa Basin lays adjacent to the eastern border of the Jaca Basin, and is another of the south Pyrenean thrust-top basins. Throughout its history it made an important contribution to the south Pyrenean axial drainage system that fed sediment from the Tremp–Graus thrust-top basin in the east, through the Aínsa Basin, and into the Jaca Basin to the west (Bentham *et al.*, 1992). Structurally, the Aínsa Basin is located on the western edge of the SPCU (**Fig. 2.17**), on which it was translated southwards as a thrust-top basin.

The Boltaña anticline forms the western margin of the Aínsa Basin, separating it from the Jaca Basin to the west (**Fig. 2.22**; Verges & Muñoz, 1990). Its eastern margin is defined by the Mediano anticline – a structure of similar form and origin to the Boltaña anticline (Muñoz *et al.*, 1998). The southern margin of the Aínsa Basin is defined by a hanging wall anticline of the W–E-trending Sierra Marginals thrust (Dreyer *et al.*, 1999). To the north of the basin lay further structures related to thrust ramps of the SPCU. Together these features define a small sedimentary basin, 25 km wide and 40 km long, with a north- to northwest-trending structural and depositional axis. In-filling it are approximately 5 km of Middle and Late Eocene sediments, arranged in an overall regressive succession (**Fig. 2.23**).

2.5.1 Geological history of the Aínsa Basin

The Aínsa Basin began to form at the start of the Lutetian due to flexural subsidence of the area laterally adjacent to the active SPCU. At this time sediment was supplied to the Aínsa Basin from the east by the deltaic and non-marine depositional systems of the Tremp–Graus Basin (**Fig. 2.24A**; Nijman, 1998). The Tremp–Graus Basin is the next thrust-top basin to the east, and was at this time being carried southwards on top of the SPCU thrust sheet (**Fig. 2.17**). To the west of the Aínsa Basin

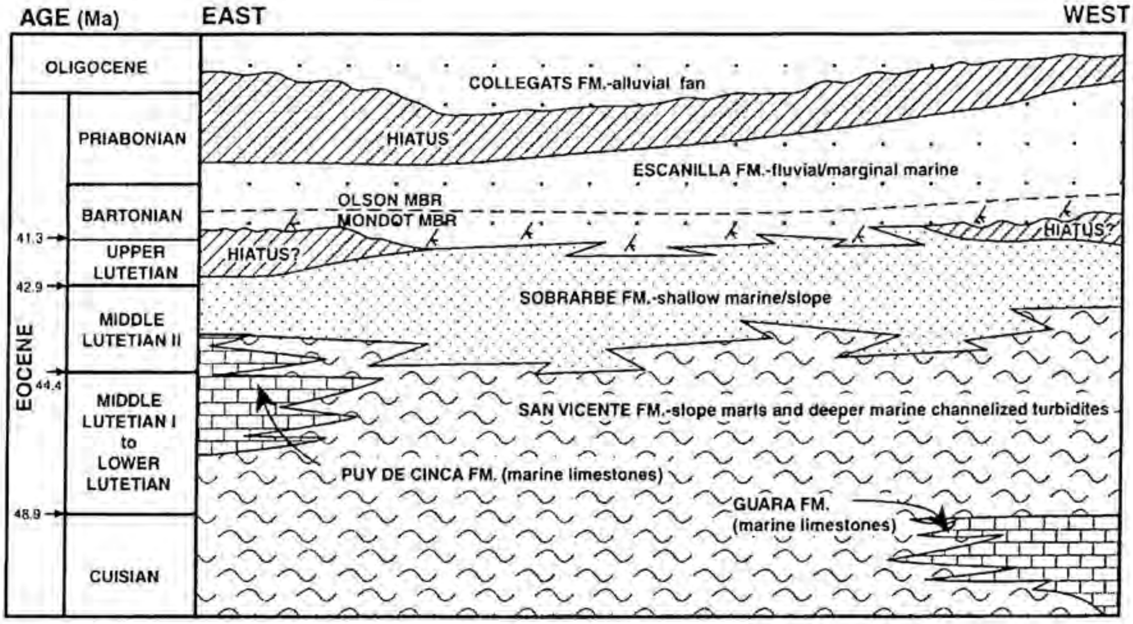


Fig. 2.23. The stratigraphy of the Aínsa Basin. (From Dreyer *et al.*, 1999.)

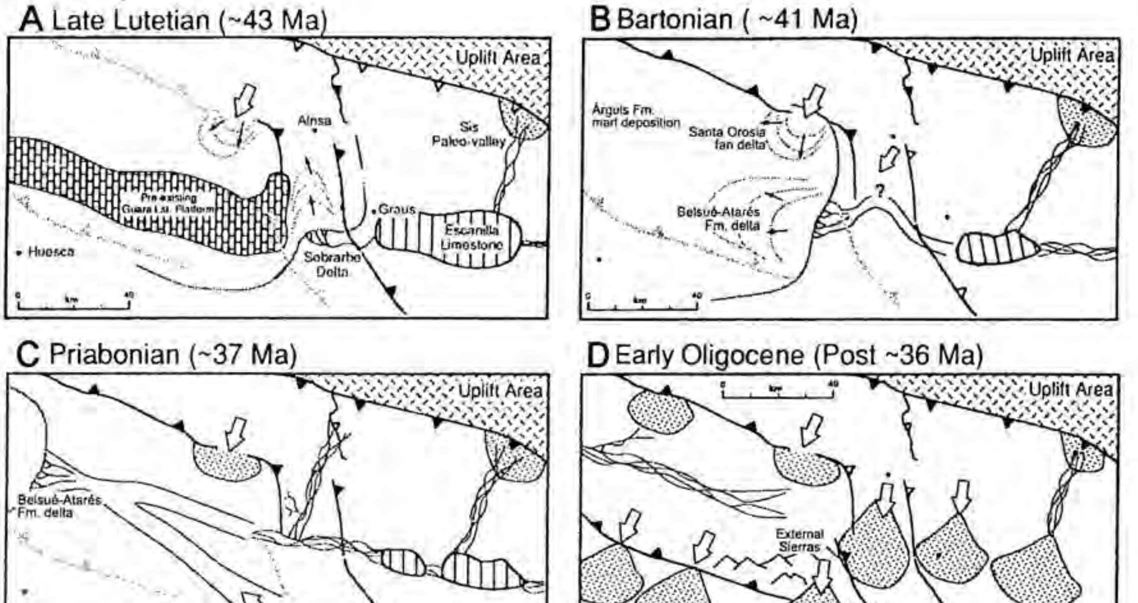


Fig. 2.25. Sequential palaeogeographic reconstructions of the Aínsa Basin, the eastern end of the Jaca Basin, and the western end of the Tremp–Graus Basin, during Late Eocene to Early Oligocene times. Whether a particular structure was blind / inactive / active is indicated, and differences in fluvial style are also shown. (From Bentham *et al.*, 1992.)

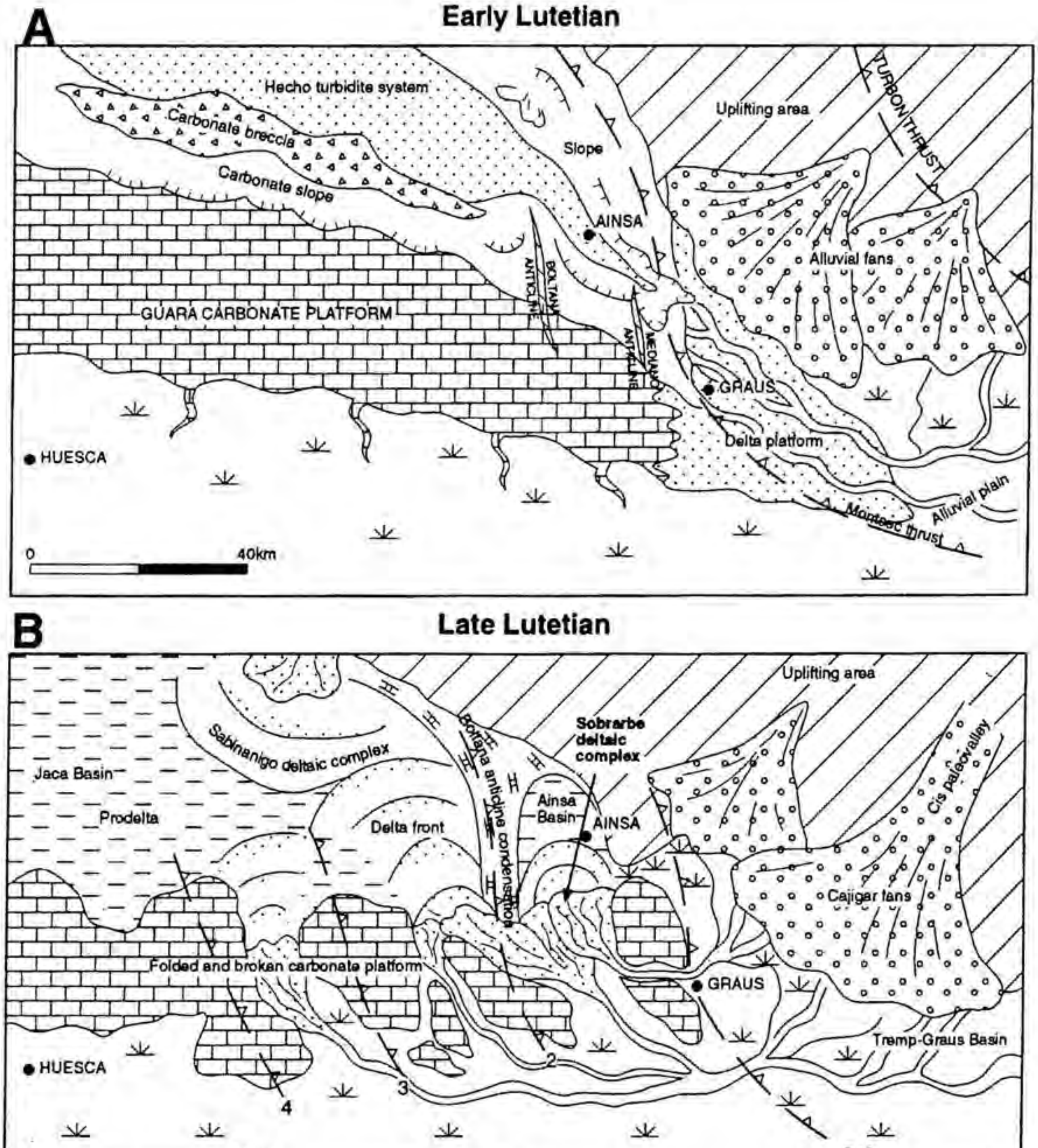


Fig. 2.24. Palaeogeographic reconstructions of the Aínsa Basin, the SE corner of the Jaca Basin, and the SW corner of the Tremp–Graus Basin, during the deposition of the Sobrarbe Fm. deltaic complex in the Aínsa Basin. **A**. During the early Lutetian, the Sobrarbe Fm. deltas were in the early stages of progradation northwards along the Aínsa Basin, with sediment principally being supplied from uplifted areas along the northern margin of the Tremp–Graus Basin. **B**. During the late Lutetian, the Sobrarbe Fm. deltas were in the late stages of progradation. At the same time, a succession of thrusts (1–4) created a series of anticlines and synclines in the External Sierras along the southern margin of the Jaca Basin, offering entry points for deltaic systems into the Jaca Basin. (From Dreyer *et al.*, 1999.)

lay the deep marine, turbidite dominated trough of the Jaca Basin (Dreyer *et al.*, 1999). The Aínsa Basin occupied a transitional position between the two, and in it accumulated the thick, deep-water slope deposits of the San Vicente Fm. (Muñoz *et al.*, 1998).

By the middle of the Lutetian, the sole thrust of the Aínsa Basin had broken the surface in several places, transforming the basin into a thrust-top basin. To the northeast, the antiformal stacking of thrust sheets created considerable relief and initiated alluvial fan development. These fans added to sediment that was already being carried out of the Tremp–Graus Basin, by axial drainage systems, and into the marine Aínsa Basin via its structurally lower southern margin. These incoming sediments formed a south-to-north prograding deltaic complex in the Aínsa Basin, depositing the Sobrarbe Fm. (Muñoz *et al.*, 1998; Dreyer *et al.*, 1999). Sedimentation rates were high, and up to 1000 m of deltaic sediments accumulated.

By the beginning of the Bartonian, delta top conditions had been established across the Aínsa Basin (**Fig. 2.24B**). At this point, a braided to meandering stream system took over the in-filling of the basin, depositing the alluvial channel sandstones, conglomerates, and red floodplain fines of the Escanilla Fm. (Bentham *et al.*, 1992).

2.5.2 Correlation between Aínsa and Jaca Basins

By combining the mapping and facies descriptions of earlier studies (Puigdefàbregas 1975; Jolley, 1987) with the chronological control of Hogan (1993), Bentham *et al.* (1992) attempted to correlate down the south Pyrenean axial drainage system, from the Aínsa Basin, westwards across the Boltaña anticline, and into the Jaca Basin. They found that a marine transgression observed at the base of the Escanilla Fm. in the Aínsa Basin occurred at the same time as a short-lived, 5-km-eastward transgression of the marine Belsué-Atarés Fm. over the non-marine Lower Campodarbe in the Jaca Basin (close to the village of Nocito on **Fig. 1.1**). Bentham *et al.* (1992) went on to correlate both these stratigraphic features with a short-term sea-level rise close to the Lutetian–Bartonian boundary on the Haq *et al.* (1987) sea-level curve (**Fig. 2.20**).

Bentham *et al.* (1992) also showed that the lower, middle and upper parts of the Escanilla Fm. of the Aínsa Basin were laid down at the same time as the Árguis Fm., the Belsué-Atarés Fm. and the Lower Campodarbe Fm. of the Jaca Basin, respectively. However, despite the synchronous timing, the facies involved were very different. Bentham *et al.* (1992) went on to note that the uppermost portions of the deltaic

Sobrarbe Fm. of the Aínsa Basin were 5 Myr older than the equivalent uppermost portions of the deltaic Belsué-Atarés Fm. of the Jaca Basin.

Using correlations such as these, Bentham *et al.* (1992) reconstructed the palaeogeography of the Jaca Basin–Aínsa Basin–Tremp–Graus Basin area from Middle Eocene to Early Oligocene times (**Fig. 2.25** – on page 44). In the late Lutetian (**Fig. 2.25A**), the Sobrarbe Fm. delta prograded northwards along the axis of the Aínsa Basin, whilst the deep marine Jaca Basin was fed material from the NE. By the Bartonian (**Fig. 2.25B**), the Jaca Basin was being in-filled by the Belsué-Atarés Fm. deltas, fed from the Escanilla Fm. fluvial system now operating in the Aínsa Basin. The Santa Orosia fan delta, sourced from the NE, was also in-filling the Jaca Basin at this time. During the Priabonian (**Fig. 2.25C**), the Belsué-Atarés Fm. deltas prograded westwards down the axis of the Jaca Basin, and the Santa Orosia alluvial fan superseded the fan delta. Finally, in the Early Oligocene (**Fig. 2.25D**), the External Sierras were uplifted, and the final period of growth of the Boltaña anticline occurred. Also at this time, a major phase of out-of-sequence thrusting, uplift and erosion in the axial zone of the central Pyrenees (Puigdefàbregas *et al.*, 1992) gave rise to a series of large alluvial fans across the area.

2.6 Conclusions

Fig. 2.20 summarises the formation of the Pyrenees and the structural and stratigraphic development of the Jaca Basin. The time period covered stretches from the Late Palaeocene, when the entire Pyrenean area was submarine, to the Early Miocene, when contraction had ceased and no further sediments were accumulating in the Jaca Basin. Also indicated on the figure are the timings of movement on certain key structures, and a correlation with the Aínsa Basin is given.

Although the complete evolution of the Pyrenees and the Jaca Basin is relevant, because this project focuses on the Belsué-Atarés Fm., the most important aspects of the geological history of the area for this work occurred during the Middle Eocene – and may be summarised as follows:

- The Jaca Basin became a discrete, thrust-top basin with the emergence of the Guarga thrust sheet in the late Lutetian.
- At around the same time (41.5 Ma), the Biarritzian transgression drowned the Guara Fm. carbonate platform, instigating the deposition of the offshore marine marls of the Árguis Fm.

- At the initiation of the Jaca Basin, and throughout its marine phase, the eastern basin margin was defined by the uplifting Boltaña anticline, related to the SPCU thrust sheet.
- When the basin first became formed, the general high levels of tectonic activity in the Pyrenees caused widespread emergence in the axial zone, feeding sediments into the Jaca Basin.
- Contemporaneously, sediment was also being fed north to south down the Aínsa Basin by the Escanilla fluvial system, and into the Jaca Basin.
- The siliciclastic sediment fluxing into the Jaca Basin was deposited as a succession of WNW-prograding delta lobes, forming the Belsué-Atarés Fm.
- Whilst the Belsué-Atarés Fm. was being deposited, a series of anticlines with axes trending NW–SE began to form in the External Sierras area, initially at the eastern end of the chain, but then progressively towards the west.
- At the same time, movement on the Guarga thrust sheet uplifted the External Sierras area, defining the southern basin margin.
- Also during the deposition of the Belsué-Atarés Fm., the Guarga thrust sheet (and hence the entire Jaca Basin, including the NW–SE anticlines) was progressively rotated by 38° clockwise.
- The end of deposition of the Belsué-Atarés Fm. – the switch from marine to non-marine sedimentation – occurred diachronously across the basin, between 37.0 Ma and 36.6 Ma (earliest Priabonian).
- The Belsué-Atarés Fm. was superseded by the fluvial Lower Campodarbe Fm.

As Belsué-Atarés Fm. deltas prograded across the Jaca Basin, they were strongly affected by the growing anticlines of the External Sierras (Millán *et al.*, 1994; Castelltort *et al.*, 2003), and by other uplifting intrabasinal structures. The understanding of these tectonic controls on sedimentation is the primary aim of this project, and will be addressed, for different parts of the basin, in Chapters 4 – 9.

The next chapter, Chapter 3, describes the sedimentological characteristics of the Árguis Fm., Belsué-Atarés Fm., Yeste-Arrés Fm. and lowermost Lower / Middle Campodarbe Fm. The twenty lithofacies and twelve facies associations defined therein will be utilised in subsequent chapters to describe the lateral and vertical variations that characterise the sedimentary infill of the Jaca Basin.

Chapter 3:
Facies and Facies Associations

3. Facies and Facies Associations

Contents

3. Facies and Facies Associations

3.1 Introduction

This principal aim of this project is to study the tectonic controls on the sedimentation of the marine Belsué-Atarés Fm. in the thrust-top Jaca Basin. It has already been established by other studies that tectonic structures growing within a sedimentary basin may strongly affect the depositional processes and environments found therein (e.g. Ramos *et al.*, 2002; López-Blanco, 2002; Drzewiecki & Simó, 2002), as well as giving rise to more obvious affects such as thickness changes and unconformities within the syntectonic strata. Thus, in order to understand how the Belsué-Atarés Fm. was affected by the coeval growth of tectonic structures within the basin (**Fig. 1.3**; Castelltort *et al.*, 2003), it is necessary to study the facies present in the formation. This chapter presents a detailed study and interpretation of these facies, which will then be utilised by subsequent chapters (Chapters 4 – 9) to deduce the tectonic controls on sedimentation in the basin.

The Belsué-Atarés Fm. was studied by undertaking 33 graphic logs through its complete thickness, across the Jaca Basin (**Fig. 1.1**). Where it was felt to be appropriate (for example, if a formation boundary seemed to be gradational), the logs were extended down into the underlying Árguis Fm. or Guara Fm., and/or up into the overlying Lower Campodarbe Fm. or Middle Campodarbe Fm. All sedimentological features of each bed were recorded on a series of graphic logs, which have been reproduced in Volume 2 of this thesis. The logging process allowed beds with similar sedimentological characteristics to be identified and grouped together into a particular lithofacies. In this way, a total of 20 distinct lithofacies were recognised and given an appropriate descriptive name. The key sedimentological characteristics of each one are summarised on **Fig. 3.1**, and laid out in detail in the first half of this chapter.

Grouping beds into lithofacies gives a broader classification that grouping them into facies because beds of the same facies not only have the same sedimentological characteristics, but must, by definition, have been formed by a common depositional process in the same depositional environment. A lithofacies-based classification was thought to be more appropriate for this work because it was felt that in such a large dataset, there could be beds that appeared to be very similar but which had formed in different depositional environments. Beds such as these could correctly be placed in the same lithofacies, but should not be placed in the same facies. However, it should be noted that for the sake of brevity, the word 'lithofacies' has been abbreviated to 'facies' in the lithofacies names (**Fig. 3.1**).

Once the beds on each of the logs had been grouped into lithofacies, it became clear that some lithofacies commonly lay in close association with one another, either as interbeds or laying laterally adjacent. This observation lead onto the definition of 12 distinct and reoccurring facies associations (**Fig. 3.2**). Each facies association is made up of deposits that were laid down in a specific depositional environment (**Fig. 3.3**), and each has been given an interpretive name to reflect this.

The lithofacies and facies association to which every logged bed belongs are represented on the logs using colours, as detailed on **Fig. 3.2** and on the Key for Logs (Vol.2, p.1 – 4). The facies associations and a simplified version of the lithofacies are depicted on the Summary Logs (Vol.2, p.5 – 44), whilst a detailed breakdown of the lithofacies may be seen on the Graphic Logs (Vol.2, p.45 – 223). Key sections from both these sets of logs are also featured throughout this chapter.

In the first part of this chapter (section **3.2**), the 20 distinct lithofacies are characterised with descriptions, key examples from the logs, and photographs of their most important features. From these, the depositional processes that may have been responsible for the formation of each one are interpreted, and a range of possible depositional environments suggested. In the second part of this chapter (section **3.3**), the make-ups of the 12 facies associations are described, and the depositional environments that they represent are determined. Finally (section **3.4**), the key findings that have been presented in this chapter are summarised.

3.2 Lithofacies descriptions and interpretations

The sedimentological characteristics of the 20 lithofacies identified within the Belsué-Atarés Fm. (and immediately adjacent units) of the Jaca Basin are described in this section. The features detailed for each lithofacies are:

- Formation most commonly found in
- Common range of bed thicknesses
- Common range of package thicknesses (a packages consists of two or more beds of the same lithofacies)
- Morphology of beds (planar and laterally extensive / channel-form etc)

- Bed contacts (gradational / sharp / erosional)
- Architecture within beds or packages (internally bedded / massive etc)
- Common grainsize range
- Most common grainsize
- Grainsize distribution within beds (fining upwards / coarsening upwards / invariant)
- Degree of grainsize sorting
- Depositional structures
- Clasts ('small' = 2 – 10 mm diameter, 'medium' = 10 – 30 mm, 'large' = 30 – 64 mm)
- Intensity of bioturbation (terminology of Taylor & Goldring, 1993)
- Identified ichnofacies
- Fossil content
- Weathered colour

The key features of each lithofacies are also summarised in **Fig. 3.1**. The final two columns of this table list the depositional process or processes that are thought to have been responsible for each lithofacies, and the depositional environments in which they may have operated.

To supplement the descriptions, each lithofacies is illustrated with a at least one example section taken from a graphic log, and several colour photographs depicting its characteristic features. For the symbols and colours used on the example log sections, see Key for Logs (Vol.2, p.1 – 4). Where possible, the captions to the photos contain cross-references to the photo symbols given on the logs in Volume 2, enabling the exact location of every photo to be determined.

What is not included in the lithofacies descriptions:

Although many palaeocurrent readings were taken during the logging, these are not included in this chapter. This is because almost all of the logged sections were no more than a couple of kilometres away from one or more kilometre-scale tectonic structures that were actively growing during the deposition of the Belsué-Atarés Fm. (**Fig. 1.3**; Puigdefàbregas, 1975; Bentham *et al.*, 1992; Millán *et al.*, 1994, Hogan & Burbank, 1996; Pueyo *et al.*, 2002; Castelltort *et al.*, 2003). It was anticipated that these structures would have had a strong affect on palaeocurrents, and so the palaeocurrent data is discussed in context with the structures in Chapters 4 – 9.

Specimens were collected roughly every 100 m on each of the logged sections. These were then thin-sectioned and their compositions analysed. However, the primary aim of collecting this data was to determine the sediment provenance area and not depositional processes, and so this work is not presented until Chapters 4 – 9. Furthermore, to enable comparisons of provenance area to be made both between beds on the same section and between logs, where possible most specimens were taken from the same lithofacies (fine, well bioturbated sandstones facies; section **3.2.5**).

Although the distribution of various facies across the Jaca Basin is mentioned in the facies descriptions, a detailed treatment and interpretation of this is included in subsequent chapters (Chapters 4 – 9), and summarised in Chapter 10.

The layout of the lithofacies descriptions:

The descriptions and interpretations of the lithofacies are presented in a broadly 'distal' to 'proximal' order: the first lithofacies (section **3.2.1**) was deposited in low-energy marine conditions, whilst the last (section **3.2.20**) was formed in high-energy terrestrial conditions. The first 12 lithofacies described here all formed in marine conditions: the first eight (sections **3.2.1** – **3.2.8**) are clastic units, presented in order of increasing sand content and grainsize; there are then three different types of limestones (sections **3.2.9** – **3.2.11**), and a highly distinctive sandstone lithofacies (section **3.2.12**). The next three lithofacies contain no clear indicators of either marine or non-marine conditions: two different types of conglomerate (section **3.2.13** – **3.2.14**), and a unit consisting entirely of clay and silt (section **3.2.15**). The final five lithofacies contain evidence that they were deposited in terrestrial conditions, and are presented in order of increasing sand content and grainsize (sections **3.2.15** – **3.2.20**).

Terminology used in the lithofacies descriptions:

A series of qualitative terms are used in the lithofacies descriptions to describe the abundance of particular features (and on the summary table **Fig. 3.1**). The *quantitative* abundances to which the qualitative terms correspond depend upon the type of feature being described. For 'volume features' (for which their volumetric extent throughout the lithofacies is important e.g. channel-form beds or cross-lamination), the percentage volume of the lithofacies affected by the feature that each term corresponds to is given by the second column in the table below. For 'point features' (for which the total number of examples throughout the lithofacies is important e.g. clasts or fossils), the number of examples seen per square metre of exposure inspected to which each term corresponds is given by the third column in the table below:

Term	**Volume features (total volume of lithofacies affected by feature)**	**Single features (number of examples per m^2 of exposure)**
'Ubiquitous'	100%	
'Almost ubiquitous'	90 – 99%	>999
'Very common'	75 – 89%	100 – 999
'Common'	50 – 74%	50 – 99
'Fairly common'	25 – 49%	10 – 49
'Occasional'	10 – 24%	1 – 9
'Fairly rare'	2 – 9%	0.1 – 0.9
'Rare'	0.1 – 1%	0.01 – 0.09
'Very rare'	<0.1%	<0.01

For example, if cross-lamination were described as being 'common' in a particular lithofacies, then 50 – 74% of the total volume of that lithofacies which was studied would be symmetrically rippled. If a bivalve were described as being 'occasional' in a particular lithofacies, then an average of 1 – 9 examples of that bivalve would have been seen per square metre of exposure of the lithofacies that was inspected.

3.2.1 Pure marls facies

3.2.1.1 Occurrence and description

Accumulations of pure marls facies that are at least tens-of-metres thick were recorded on around two-thirds of the logged sections. The best-exposed examples are at the base of the Árguis log (0 m – 19 m; **Fig. 3.4** & **Fig. 3.5**; Vol.2, p.202), and at various intervals on the Bentué de Rasal log (0 m – 616 m; Vol.2, p.216 – 222). Beds of this facies are most commonly found in the Árguis Fm., but also make up 5 – 40% of the thickness of the Belsué-Atarés Fm. in at least half of the logged sections. This facies is, however, not always easy to distinguish from silty and sandy marls facies (section **3.2.2**) in the field, because both weather easily and so develop a layer of grey mud that covers the outcrops.

Pure marls facies

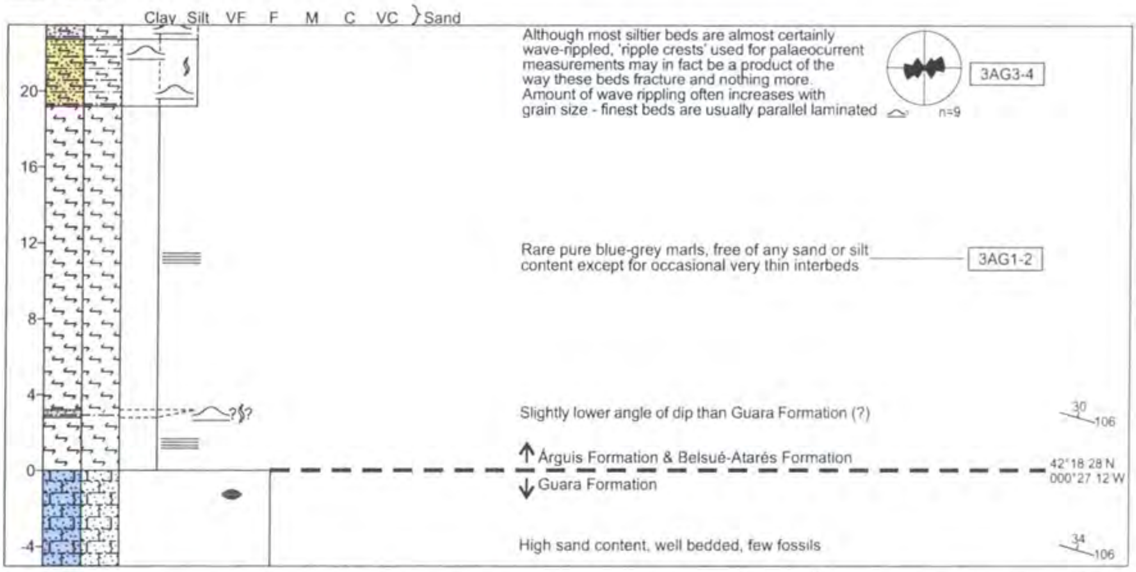


Fig. 3.4. A typical package of this facies. From the base of the Árguis log (Vol.2, p.202).

Fig. 3.5. Weak parallel-lamination at the base of the Árguis log (photos '3AG1-2', Vol.2, p.202). Hammer is 25 cm long.

Fig. 3.6. A thick succession of weathered pure marls facies at the base of the Yebra de Basa log (photos '2YB1-5', Vol.2, p.76). The arrowed sandstone interbed is 1 m thick.

Pure marls facies occurs in beds of a very wide range of thicknesses: from 100-m-thick accumulations with little or no internal structure (**Fig. 3.6**), down to centimetre thick interbeds between sandstones. Bed geometries are always planar and very laterally extensive (over several kilometres), except where the bed is only centimetres thick and has been eroded away in places. Depositional structures are limited to occasional parallel-lamination, seen only where exposure is best (**Fig. 3.5**). Neither bioturbation nor macrofossils were evident in exposures of this lithofacies.

Canudo *et al.* (1988), Canudo *et al.* (1991), Millán *et al.* (1994) and Sztràkos & Castelltort (2001) undertook detailed work on the composition of this lithofacies. It was found to be primarily composed of calcareous and siliceous tests of microscopic marine planktonic foraminifera, and some non-biogenic mud, but had absolutely no silt or sand content.

3.2.1.2 Interpreted depositional processes and environment

The lack of any depositional structures beyond parallel-lamination in this lithofacies indicates that there were no currents operating i.e. deposition must have occurred simply via gravity-driven settling out of suspension from a water column. The lack of any bioturbation or macrofossils may indicate that the palaeoenvironment was inhospitable to macroscopic life or, more likely, that neither have been preserved. The water column itself, however, must have been rich in microscopic marine foraminifera (Sztràkos & Castelltort, 2001).

This lithofacies was deposited in a very low energy marine environment, well below storm wave base, and far away from any sources of clastic sediment. Using the detailed work on the foraminifera undertaken by Sztràkos & Castelltort (2001), and analysis of the sedimentological characteristics of the lithofacies, Castelltort *et al.* (2003) interpreted that this very low energy marine environment lay in the lower offshore zone, at 100 – 150 m water depth.

3.2.2 Silty and sandy marls facies

3.2.2.1 Occurrence and description

Silty and sandy marls facies occurs on around half of the logged sections, most commonly in the Árguis Fm., and typically comprises 5 – 20% of the total thickness of the section (though it makes up almost 50% of a few sections). The best examples of this facies are found at the bases of the Árguis log (50 m – 1027 m; Vol. 2, p.202 – 212) and the Albella log (-8 m – 357 m; **Fig. 3.7**; Vol.2, p.49 – 52). As stated above, this facies weathers easily, and can be difficult to distinguish from the pure marls facies (section **3.2.1**) in the field, particularly because the two often grade into one another (**Fig. 3.8**). However, the fact that this facies is slightly more resistant to weathering offers one way of telling the two apart.

This lithofacies is predominantly composed of marls, with lesser amounts of silt and/or sand (which may account for anything from 0 – 49% of the make-up). Poorly developed internal planar bedding is commonly seen (**Fig. 3.9**), whereas parallel-lamination, tabular cross-lamination and symmetrical ripples are all rarely seen but present. Shell fragments, larger foraminifera and small pieces of plant debris are only very rarely seen. Bioturbation is absent in these beds.

Occasionally, thin (less than 20 cm thick), sharp-based silt or sand interbeds are present. These commonly contain symmetrical ripples and occasional tabular cross-lamination. 'Moderate bioturbation' (Taylor and Goldring, 1993) in them is common, whereas shell fragments, larger foraminifera and small pieces of plant debris are rare.

As with the pure marls facies (section **3.2.1**), Canudo *et al.* (1988), Canudo *et al.* (1991), Millán *et al.* (1994) and Sztràkos & Castelltort (2001) undertook detailed work on the composition of this lithofacies. The marl fraction was found to be primarily composed of calcareous and siliceous tests of microscopic marine planktonic foraminifera.

3.2.2.2 Interpreted depositional processes and environment

The presence of rare tabular cross-lamination and poorly developed symmetrical ripples in this lithofacies implies that weak oscillatory flow was occasionally operating. However, the relative rarity of these current-formed features suggests that gravity-driven settling out of suspension was the most important depositional processes. The water column, from which the marls settled out, was rich in microscopic marine foraminifera (Sztràkos & Castelltort, 2001).

Where present, the thin (< 20 cm), sharp-based silt and sandstone interbeds record occasional episodes of clastic sediment supply via a current. The very common occurrence of bioturbation within these thin interbeds demonstrates that macroscopic life was present. This also suggests that the reason why bioturbation was not recorded

Silty and sandy marls facies

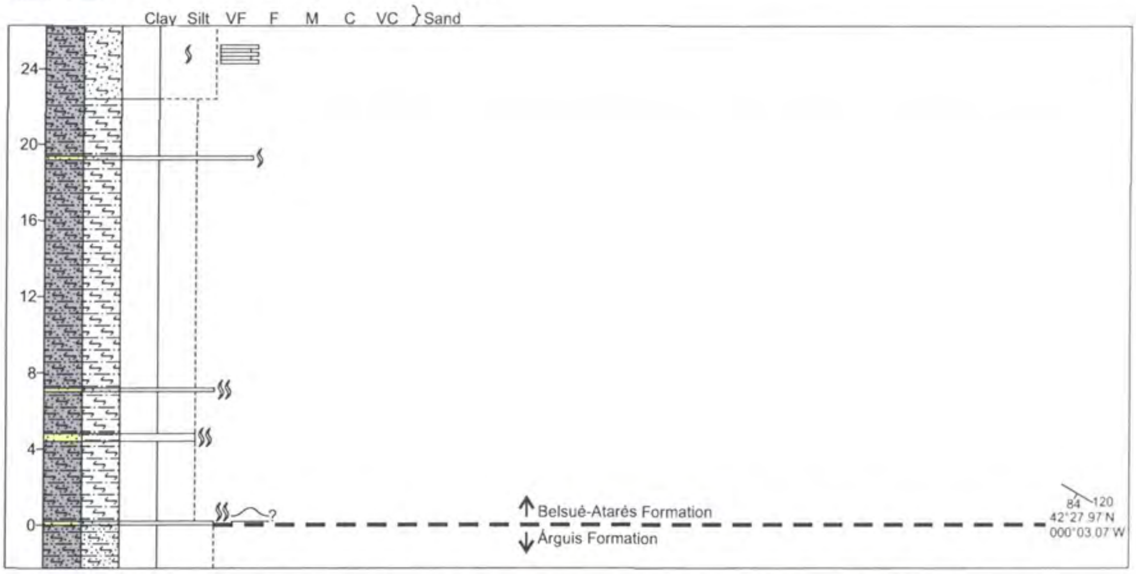


Fig. 3.7. Typical beds of this facies. From the base of the Albella log (Vol.2, p. 49).

Fig. 3.8. Silty and sandy marls facies beds with gradationally varying silt and sand content. From the base of the Árguis log (photos '3AG5-6', Vol.2, p.202).

Fig. 3.9. A thick succession of this facies, from close to the lower portions of the Árguis log (off section). Telegraph poles (arrowed) for scale.

within the predominantly marl beds of this lithofacies (or in the pure marls facies, section **3.2.1**) may simply be because any traces formed were ultimately not preserved.

This lithofacies was deposited in a low energy marine environment that was distant, but not entirely removed, from a source of clastic sediment. The rare and poorly developed symmetrical ripples implies that water depths were around wave base, whilst the unidirectional cross-lamination suggests the presence of weak seafloor currents. Where present, the thin (<20 cm), sharp-based silt and sandstone interbeds record discrete deposition events, probably related to storms or distal turbidity currents. Using the detailed work on the foraminifera undertaken by Sztràkos & Castelltort (2001), and analysis of the sedimentological characteristics of the lithofacies, Castelltort *et al.* (2003) interpreted that this low energy marine environment lay in the upper offshore zone, at 50 – 100 m water depth.

3.2.3 Marly silts and sandstones facies

3.2.3.1 Occurrence and description

This lithofacies is similar to the marl-dominated silty and sandy marls facies (section **3.2.2**), but contains a higher proportion of silt and/or sand (>50%) than marl. Indeed, there is a continuous spectrum of compositions between all the marl-, silt- and sand-containing lithofacies: from pure marls facies (which contains neither silt nor sand), through the silty and sandy marls facies, then this facies, and then up to the various clean sandstones facies (sections **3.2.5 – 3.2.8**). This compositional spectrum is reflected in exposures by the common gradational relationships between the above-mentioned lithofacies. This lithofacies is recognised as being more resistant to weathering than silty and sandy marls facies, but less resistant than any of the clean sandstones.

This facies is most commonly seen in the Árguis Fm. of the southern basin, particularly between Lúsera and Bentué de Rasal. The best examples are seen at intermittent intervals in the lower two-thirds of the Lúsera log (37 m – 745 m; Vol.2, p.174 – 181), the lower portions of the Belsué log (25 m – 300 m; Vol.2, p.185 – 188), and the lower half of the Árguis log (19 m – 567 m; **Fig. 3.10**; Vol.2, p.202 – 207).

Like the other marly facies, this facies tends to occur in thick accumulations (up to 80 m thick), but these very commonly have fairly well developed, metre-scale, internal planar bedding. The most common grainsize is very fine sandstone, with lesser

Marly silts and sandstones facies

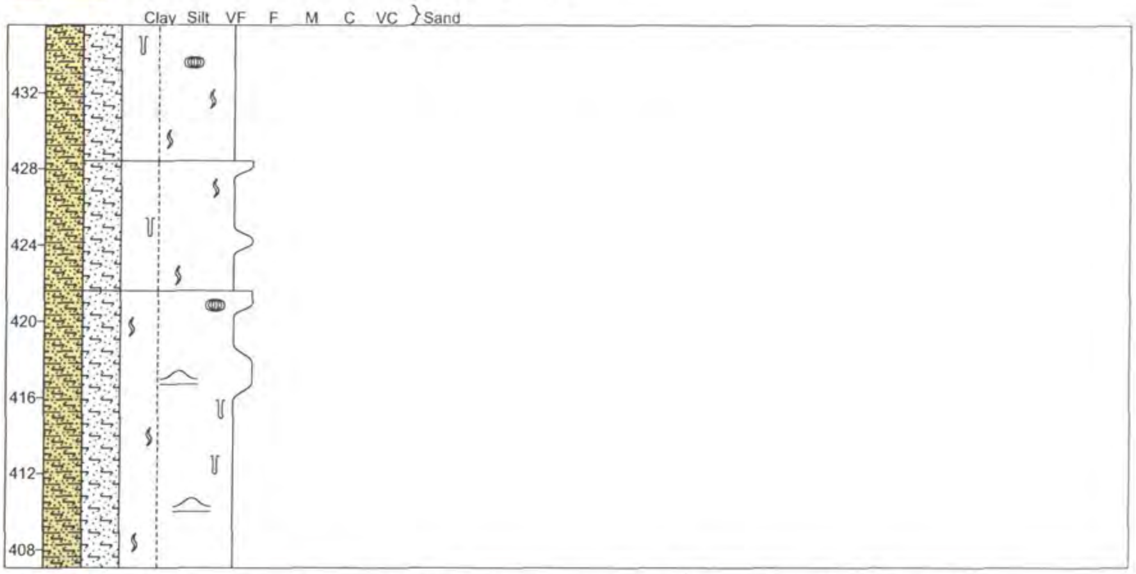


Fig. 3.10. A typical package of this facies. From the Árguis log (Vol.2, p.206).

Fig. 3.11. Rippled marly silts and sandstones facies. From near the base of the Bentué de Rasal log (photos '2BR1-2', Vol.2, p.217).

Fig. 3.12. Detail of ripples on a bedding surface (ripple crests indicated by arrows). From near the base of the Árguis log (photos '3AG3-4', Vol.2, p.202).

(Marly silts and sandstones facies, continued)

Fig. 3.13. A patch of concentrated glauconite. From near the base of the Árguis log (photos '3AG7-8', Vol.2, p.203).

Fig. 3.14. Possible *Zoophycos* traces (arrowed). From the lower-middle Árguis log (photos '3AG19-20', Vol.2, p.207).

Fig. 3.15. A *Spirophyton* or spirally coiled *Zoophycus* trace. From near lower-middle portion of Árguis log (off section).

Fig. 3.16. An *Ophiomorhpa* (feeding) burrow. From the base of the Bara log (photo '4BA4', Vol.2, p.151).

Fig. 3.17. Unidentified trace fossil or fossils. From the lower-middle Árguis log (photos '2AG9-12', Vol.2, p.207).

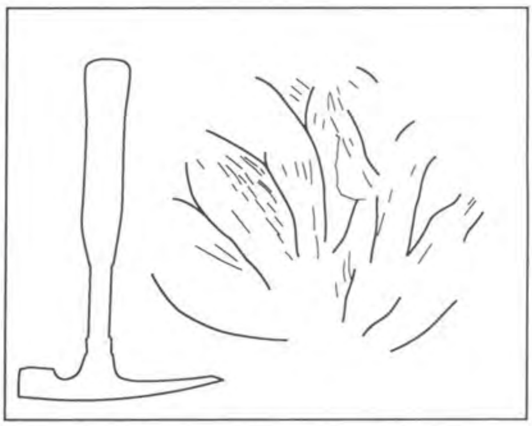


Fig. 3.18. Tracing of unidentified trace fossil or fossils from **Fig. 3.17**.

components of silt and marl, though coarser and finer beds are also common. This facies features occasional parallel-lamination and symmetrical ripples (**Fig. 3.11**) – the latter tends to be poorly developed and without a dominant palaeocurrent direction (**Fig. 3.12**).

As with the pure marls facies (section **3.2.1**) and the silty and sandy marls facies (section **3.2.2**), Canudo *et al.* (1988), Canudo *et al.* (1991), Millán *et al.* (1994) and Sztràkos & Castelltort (2001) undertook detailed work on the composition of this lithofacies. The marl fraction was found to be primarily composed of calcareous and siliceous tests of microscopic marine planktonic foraminifera.

The dark green mineral glauconite is fairly common in this lithofacies. Occasionally it is concentrated into certain horizons or as patches on bedding surfaces (**Fig. 3.13**), but more often it is simply dispersed throughout the beds.

This facies is much more fossiliferous than the previously-described marly facies. It contains occasional plant debris and fairly rare shell fragments, *Nummulites*, bivalves, echinoids, bryozoans and oysters.

This facies is also much more heavily bioturbated than the other marly facies, with the intensity very commonly reaching 'moderate bioturbation' (Taylor & Goldring, 1993) – this may however simply be because the bioturbation in the latter was poorly preserved. The best examples of each of the types of trace seen were photographed and identified. A possible *Zoophycos* trace was noted at 560 m on the Árguis log (**Fig. 3.14**; Vol.2, p.207). Also in the vicinity of the Árguis log, a *Spirophyton* or spirally coiled *Zoophycos* trace was observed (**Fig. 3.15**). An *Ophiomorpha* trace was seen at 78 m on the Bara log (**Fig. 3.16**; Vol.2, p.151), and a probable *Thalassinoides* trace at 653 m on the Nocito log (Vol.2, p.164). Between 549 m and 575 m on the Árguis log (Vol.2, p.207) an unusual, extremely abundant trace fossil was seen, spanning several lithofacies (**Fig. 3.17**). This trace fossil has not yet been identified with any certainty, so is described in detail below.

Description of unidentified trace fossil from the Árguis log:

The unidentified traces are endogenic (formed within the bed), and may be observed in full relief where they have weathered out, or in epirelief (on top of exposed beds) where they have not. Their appearance is difficult to describe with certainty as they occur with considerable density, heavily cross-cutting one another. They do however appear to be unlike anything pictured in the trace fossil Treatise. The traces consist of horizontal burrows or infills of depressions, which have the form of a barrel, lying on its side, elongated horizontally and compressed vertically (**Fig. 3.18**). This vertical compression of the burrows is, however, probably due the compaction of the sediment and not a reflection of their primary shape. The barrels are 10–20 cm long, and 3–6 cm across. In some examples, faint parallel grooves line the walls of each barrel. Barrels at the same vertical level appear to partly radiate from a common centre. Barrels on different vertical levels have different apparent centres of radiation, causing them to cross-cut those from lower levels. R. Goldring (pers. comm., 2002) has suggested that this trace may be *Estrellichnus jacaensis*, first described from outcrops of the Hecho Group (section **2.4.3.1**) to the north of the Jaca Basin (Uchman, 2001), although the resemblance between the two is not striking.

3.2.3.2 Interpreted depositional processes and environment

This facies records two different depositional processes: that of silt and marl settling out of suspension, and a degree of current activity, delivering and depositing sand. Occasional symmetrical ripples record oscillatory flow within a body of water. The common gradational contacts between this lithofacies and marl-rich or marl-free facies records how the relative proportions of marl, silt and sand brought into the area often varied gradually. The presence of the mineral glauconite implies a low sedimentation rate. The relatively rich content of fossils, which did not appear to have been transported, and the plentiful trace fossils, record an abundant and diverse marine community.

Like the previous two marly lithofacies, this facies was also deposited in a low energy marine environment, but with a greater supply of siliciclastics (assuming the marl production rate of the water column was similar). Where present, the rare and poorly developed symmetrical ripples formed above wave base. Trace fossils are present from the *Zoophycos*, *Cruziana*, and *Skolithos* ichnofacies. These are associated with background sedimentation in the abyssal zone to shallow continental shelf, mid and distal continental shelf between normal and storm was base, and relatively shallow shifting-sand environments, respectively (Seilacher, 1967). This level of diversity suggests that this lithofacies was deposited at varying water depths in different marine environments, but with similar sediment inputs and depositional processes operating.

Using the detailed work on the foraminifera undertaken by Sztràkos & Castelltort (2001), and analysis of the sedimentological characteristics of the lithofacies, Castelltort *et al.* (2003) interpreted these range of environments to be from the upper offshore zone of a marine basin to the distal front of a delta, at 50 – 100 m water depth.

3.2.4 Very fossiliferous sandy marls and sandstones facies

3.2.4.1 Occurrence and description

Although beds of this facies tend to account for no more than 1% of the thickness of many sections, they occur in the Belsué-Atarés Fm. from across the Jaca Basin. The thickest and best-exposed examples of this facies are seen at Albella (124 m – 346 m; **Fig. 3.19**; Vol.2, p.50 – 52).

Beds of this facies are often thin (around 20 cm thick), although thicker accumulations of up to nearly 16 m thickness were occasionally observed. Individual beds are always planar and laterally extensive. The thicker beds tend to simply be very fossiliferous layers within one of the marly lithofacies (sections **3.2.1** – **3.2.3**), may have a sandstone matrix or just be marly, and often have gradational contacts (**Fig. 3.19**). The thinner beds are also usually found within thick marly successions, but have much sharper boundaries, and always contain a sandy matrix, which is often very poorly sorted (**Fig. 3.20**). Between these two end-members is a continuum of highly fossiliferous beds, sharing some of the characteristics of each type.

The only depositional structures associated with this facies are rare coarsening upwards grainsize trends within beds and very rare symmetrical ripples. Bioturbation has not been preserved in the predominantly marl beds, but commonly reaches 'moderate bioturbation' levels (Taylor & Goldring, 1993) in the sandy beds, and includes the trace *Thalassinoides*. All beds of this facies are very rich in one or more types of shelly fossil and/or foraminifera: *Nummulites* and miscellaneous well-broken shell fragments are very common (**Fig. 3.21** & **Fig. 3.22**), and may sometimes be enriched to the point that the bed is bioclast-supported. *Chlamys*-type bivalves (often broken) and other foraminifera (besides *Nummulites*) are common. Oysters shells are fairly common; gastropods and bryozoa are fairly rare. Usually, the thicker very fossiliferous beds are extremely enriched in *Nummulites*, which are usually undamaged, and little else. The thinner beds often consist of any combination of the above-mentioned shelly fossils, usually well broken, and any *Nummulites* tend to be abraded to some degree.

Very fossiliferous sandy marls and sandstones facies

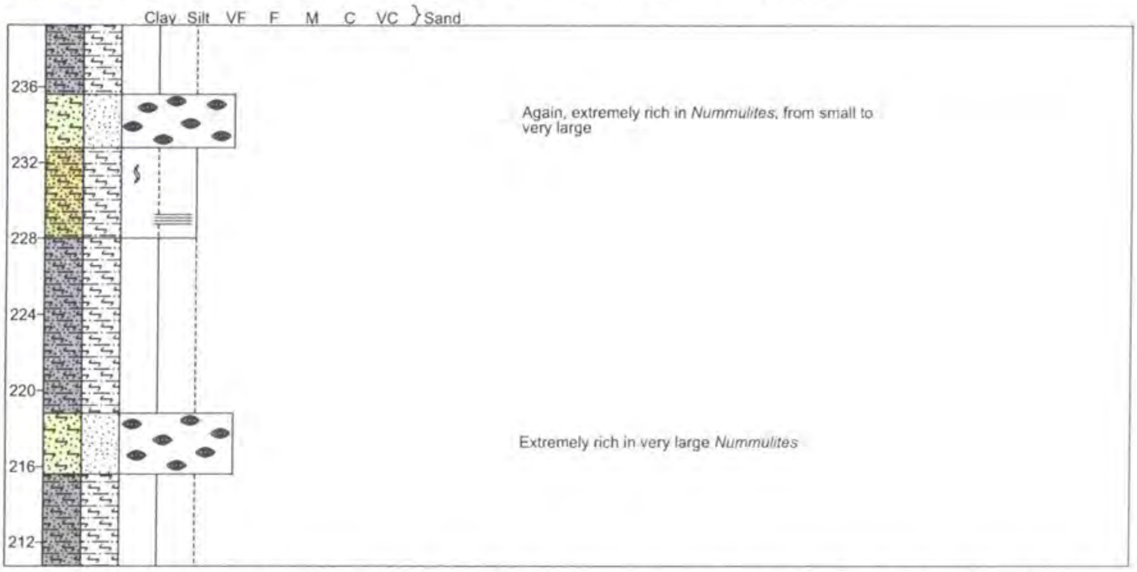


Fig. 3.19. Typical thicker beds of this facies. From lower half of Albella log (Vol.2, p.51).

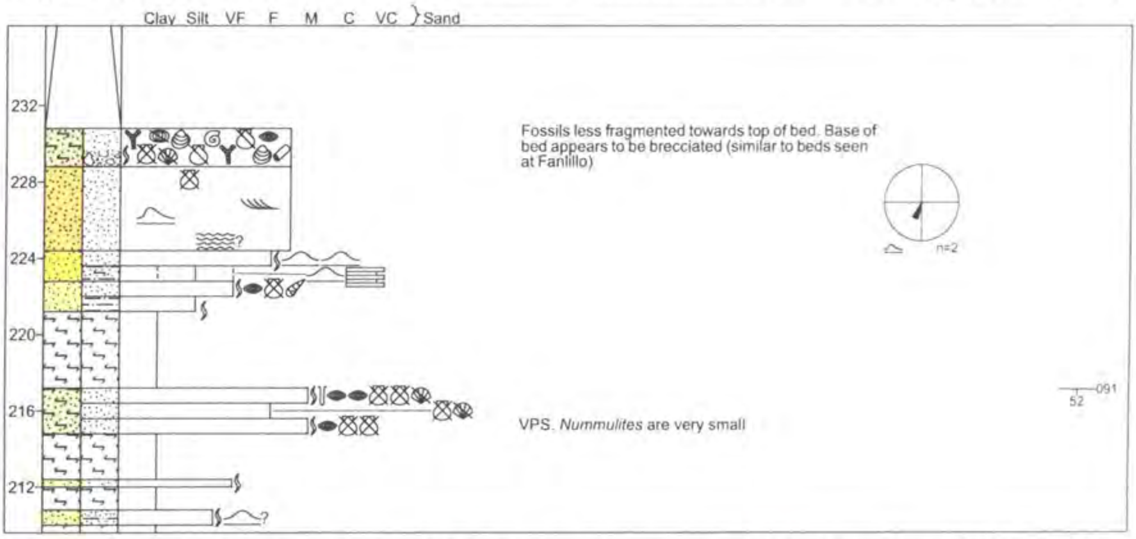


Fig. 3.20. Typical thinner beds of this facies. From lower half of Jaca log (Vol.2, p.109).

Fig. 3.21. Thick *Nummulites* bed. From the lower half of the Albella log (photos '3AB1-3', Vol.2, p.50).

Fig. 3.22. Bed very rich in broken bivalves. From lower half of San Julián de Basa log (photos '3SJ5-6', Vol.2, p.84).

3.2.4.2 Interpreted depositional processes and environment

This facies seems to record two end-member processes. The thicker very fossiliferous beds, with lithologies varying from silty marl to sandstone and most commonly very rich in *Nummulites*, seem to simply record times of great *Nummulites* abundance across the area, with no special depositional mechanism. The generally undamaged nature of the *Nummulites* tests suggests that they were not transported by currents. The thinner very fossiliferous beds, with sharp contacts, poorly sorted sandy matrix, and diverse range of broken fossils, seem to have been formed by relatively strong currents, concentrating and breaking the shells into layers of large lateral extent (hundreds of metres at least). Between these two end-members are beds that appear to record a degree of increased life abundance, and a degree of reworking and concentration by currents.

The highly variable nature of the beds grouped into this lithofacies suggests a range of depositional environments. The presence of the genus *Nummulites* almost ubiquitously in the thicker beds implies that environment was broadly a warm, shallow sea. However, without identification of the precise species of *Nummulites* present, it is not possible to make any inferences beyond that. The thinner very fossiliferous beds probably had their diverse fossil content concentrated by strong currents, perhaps resulting from storms, operating on the shelf of a marine basin (Beavington-Penney, 2004; Roetzel & Pervesler, 2004). However, there are no indicators present to constrain the environment beyond that.

Castelltort *et al.* (2003) encountered this same lithofacies in the Belsué-Atarés Fm. and interpreted it as having been formed by storms, and deposited on the upper shoreface of a marine basin, at water depths of anywhere between 10 m and 100 m.

3.2.5 Fine, well bioturbated sandstones facies

3.2.5.1 Occurrence and description

This lithofacies occurs ubiquitously, throughout all logs and across the entire Jaca Basin. Approximately two-thirds of its total thickness forms part of the Belsué-Atarés Fm., with most of the rest lying in the Árguis Fm. Beds of this facies tend to increase in thickness (from less than 1 m up to almost 4 m) and frequency of occurrence up-section. Thick and well-exposed examples can be seen at intervals throughout the Lúsera (Vol.2, p.174 – 184), Belsué (**Fig. 3.23**; Vol.2, p.185 – 195) and Árguis logs (Vol. 2, p.202 – 214).

Beds of this facies are usually planar and laterally extensive over hundreds of metres at least, but their lateral extent tends to decrease to no more than a few tens of metres towards the tops of the Belsué-Atarés Fm. The beds also tend to occur singly in the lower portions of the logged sections, but become thicker and increasingly amalgamated into packages of usually 2 – 4 beds (or more, e.g. **Fig. 3.23**) higher up.

Grainsize varies from silt up to medium sand, with fine sand being the average. The sand is generally moderately sorted, and grading is rare.

Although the range of depositional structures preserved in this lithofacies is quite diverse, none are very common. Symmetrical ripples and parallel-lamination (**Fig. 3.24**) are occasional. Flaser bedding (**Fig. 3.25**), grooves on the bases of beds, loading and general dewatering structures are all very rare. This facies is distinguished from the coarser sandstone facies (sections **3.2.7 – 3.2.8**) primarily on the basis of grainsize, but also because it does not contain any cross-lamination / -bedding, rip-up clasts, and the beds are never erosively based.

Bioturbation is almost ubiquitous in this facies, typically at the 'low bioturbation' to 'moderate bioturbation' levels (Taylor & Goldring, 1993). Rarely however, the bioturbation intensity increases to reach 'high bioturbation' or even 'intense bioturbation' levels. Vertical burrows of various types are fairly common. Identified traces include *Thalassinoides* (**Fig. 3.26**), *Planolites* (R. Goldring, pers. comm., 2002) and a possible *Diplocraterion* trace (**Fig. 3.27**). Also seen are the possible *Estrellichnus jacaensis* traces (pictured in **Figs. 3.17–3.18**, and described in section **3.2.3**), between 553 m and 555 m on the Árguis log (Vol.2, p.207).

Fossils are common and fairly diverse. Miscellaneous shell fragments are common, and plant debris is fairly common. *Nummulites* and other foraminifera, *Chlamys*-type bivalves and oysters are all seen occasionally. Gastropods, echinoids and *Alveolina* make rare appearances. On average the shells vary from being undamaged to a little broken (usually with some corners chipped off, and no worse than being broken in half).

3.2.5.2 Interpreted depositional processes and environment

This lithofacies does not seem to be the product of one or two dominant depositional processes, operating in a single depositional environment. Rather, it is

Fine, well bioturbated sandstones facies

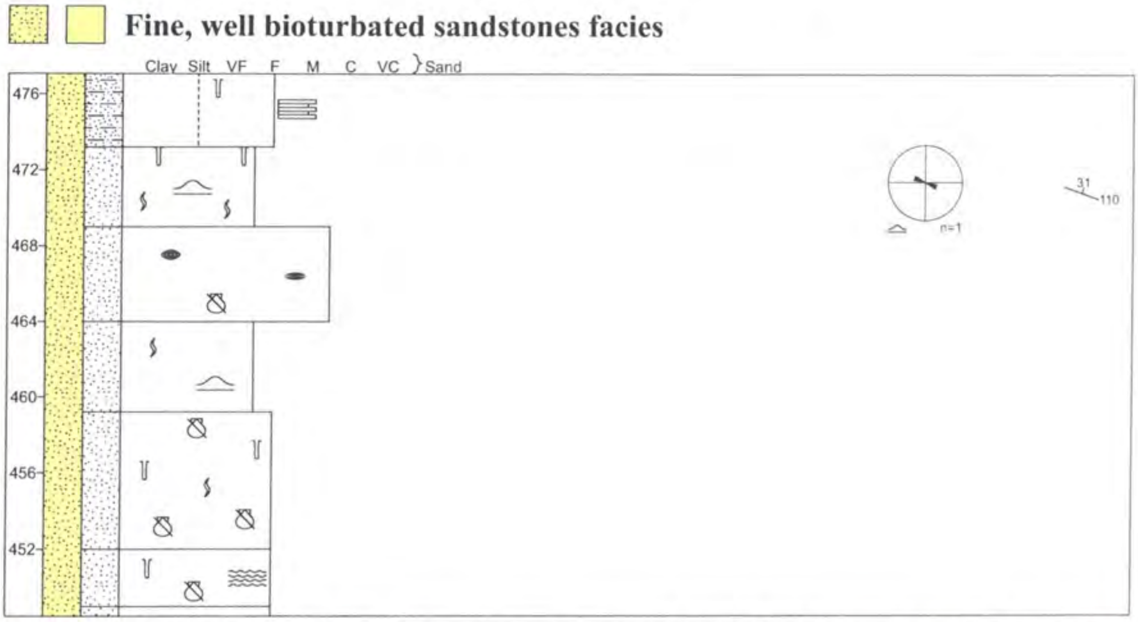


Fig. 3.23. Typical beds of this facies. From the lower half of the Belsué log (Vol.2, p.189).

Fig. 3.24. Well developed parallel lamination. From the middle of the Eripol log (photo '2EP11', Vol.2, p.145).

Fig. 3.25. Flaser bedding. From near base of Las Almunias (Upper) log (off section).

Fig. 3.26. *Thalassinoides* trace. From close to the lower portions of the Lardiés log (off section).

Fig. 3.27. Possible *Diplocraterion* trace. From middle of Belsué log (photos '2BS5-6', Vol.2, p.191).

more likely the product of the interaction between several different depositional processes, operating across a range of palaeoenvironments.

In the lower halves of the logged sections, where this lithofacies is found to form thin beds between thick marly units, it records an episode of a particular depositional process that was able to transport sand into normally sand-free parts of the basin. The slightly broken nature of the shells within the sands suggests that the currents that moved the sands around also reworked the fossils. During and after their deposition, the sands were worked over by bioturbating organisms. Up-section, the sand beds become thicker and more amalgamated, implying that the supply process was either longer lasting, or was supplying sediment at an increased rate. Occasional symmetrical ripples indicate that oscillatory currents reworked these higher beds. Further up-section still, the beds retain more or less the same characteristics – indicating that the same kinds of processes were operating – but are thinner and less frequent, losing out to coarser sandstones and their associated higher-energy depositional processes.

It is difficult to pinpoint the depositional environment of this fairly broad lithofacies, which has few diagnostic features. The evidence for some oscillatory flow and currents with the capability of fragmenting shells implies deposition around wave base in a marine basin. The identified trace fossils belong to the *Cruziana* ichnofacies, which suggests a depositional environment that may lie below normal wave base, but be very much affected by storms (Seilacher, 1967).

Castelltort *et al.* (2003) also encountered this lithofacies in the Belsué-Atarés Fm. These authors felt that the sparse record of preserved sedimentary structures was due to intense bioturbation. They interpreted a depositional environment of upper offshore prodelta to distal delta front, with a wide range of possible water depths, but less than 100 m.

3.2.6 Intensively symmetrically rippled sandstones facies

3.2.6.1 Occurrence and description

This is not a common lithofacies. It is only represented on around one third of all logged sections, and even then there is usually no more than a 5 m thickness per log. But despite being rare, the sedimentary structures that define this lithofacies make it very distinctive. It is most commonly part of the Belsué-Atarés Fm., and is almost always found in the lower half of the sequence. Probably the best examples of this facies are seen on the Belsué log (306 m – 447 m; **Fig. 3.28**; Vol.2, p.188 – 189), although the 30-m-thick amalgamated packages there are unique. Individual beds of more representative thicknesses can be seen on the Yebra de Basa log (65 m – 88 m; **Fig. 3.29**; Vol.2, p.76). Regardless of their thickness, the beds are almost always planar and laterally extensive (over several hundreds of metres).

Common grainsizes range from very fine to fine sand, with fine sand being the most common. The sands tend to be moderately sorted.

Symmetrical ripples are the sedimentary structures that characterises this facies. Whilst these features are fairly common in some of the other sandy lithofacies, they are usually poorly developed, restricted to a few horizons within a given bed, and can give somewhat variable palaeocurrent directions. In contrast, within this lithofacies, symmetrical ripples are always well developed, usually throughout the whole volume of each bed, and give consistent (bi-directional) palaeocurrent directions (e.g. **Fig. 3.30**; the palaeocurrents themselves are dealt with in Chapters 4 – 9). Typically, the ripples have wavelengths of 4 – 8 cm, and straight, rounded crests. More complex patterns were however occasionally seen, involving unusually common bifurcations (every few tens of centimetres along the ripple crests, e.g. **Fig. 3.31**) or a variety of apparent palaeocurrent directions (interference ripples). Other sedimentary structures present include occasional flaser bedding, and rare asymmetrical ripples.

Bioturbation very commonly reaches 'moderate bioturbation' levels in this facies (Taylor & Goldring, 1993), with vertical burrows being fairly common. However, no distinctive types of trace fossils could be identified. Fossils are common in this facies: miscellaneous shell fragments are common, *Nummulites* are fairly common, plant debris is seen occasionally, and oysters are very rare.

3.2.6.2 Interpreted depositional processes and environment

The almost ubiquitous, and very commonly well formed, symmetrical ripples indicate that this lithofacies was deposited by oscillatory flow, above wave base in a body of water of large lateral extent. Where the pattern of rippling within a particular bed is more complex, or where asymmetrical ripples are also present, it seems likely that other palaeocurrents were operating. This is more likely to occur at shallower water depths, for example in the breaker zone where there is a net landward transport of water superimposed upon any surface wave pattern (Komar, 1976).

Intensively symmetrically rippled sandstones facies

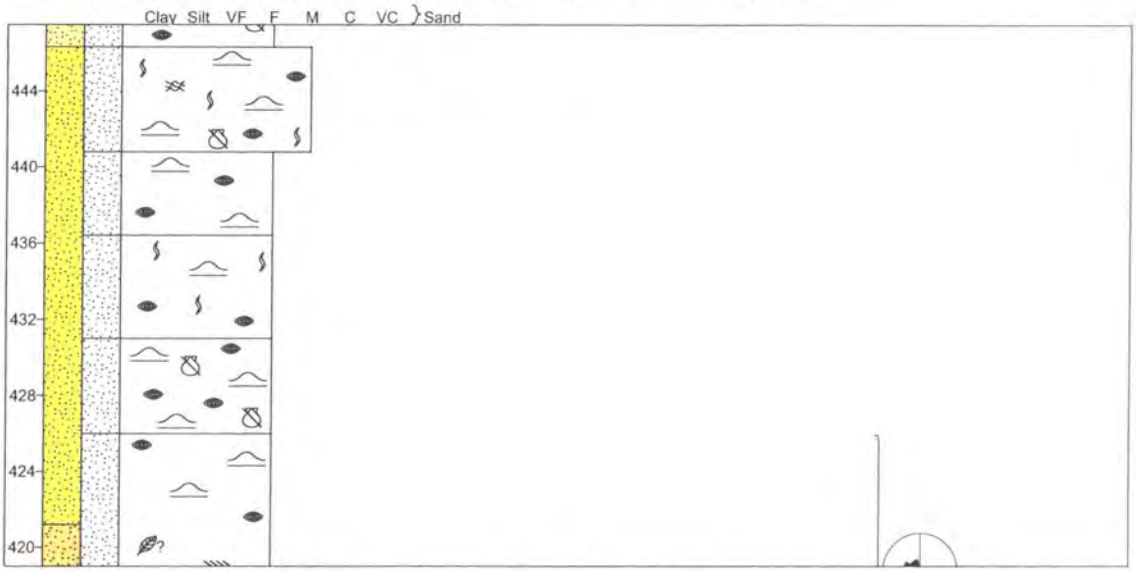


Fig. 3.28. A very thick amalgamated package. From the Belsué log (Vol.2, p.189).

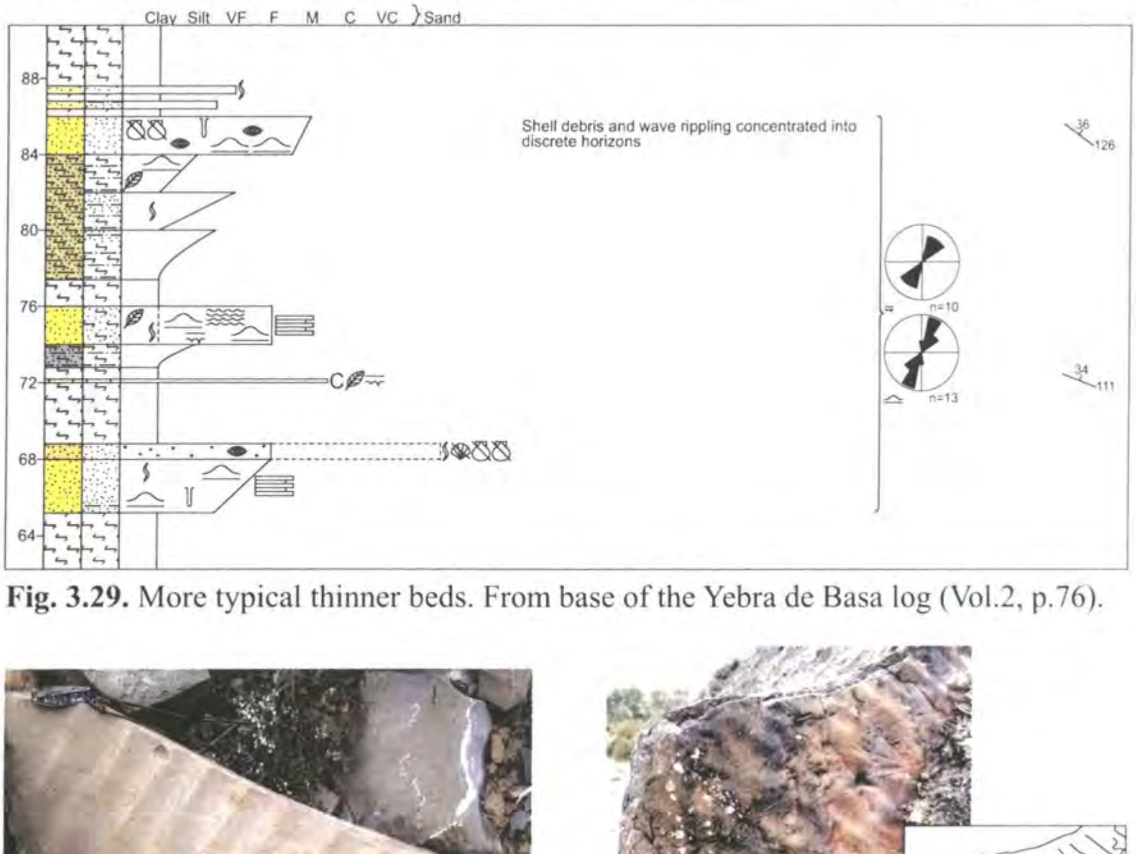


Fig. 3.29. More typical thinner beds. From base of the Yebra de Basa log (Vol.2, p.76).

Fig. 3.30. Classical straight-crested symmetrical ripples. From near the Puente La Reina log (off section).

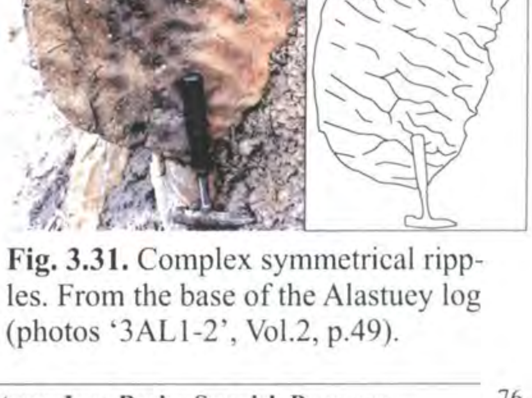


Fig. 3.31. Complex symmetrical ripples. From the base of the Alastuey log (photos '3AL1-2', Vol.2, p.49).

Unfortunately, none of the other features of this lithofacies, such as the generic bioturbation or the reworked marine fossils, can help further constrain its depositional environment.

3.2.7 Medium, cross-laminated sandstones facies

3.2.7.1 Occurrence and description

This facies is one of the most common in the Jaca Basin. It is found in the Belsué-Atarés Fm. in almost every logged section, and often makes up a considerable thickness on each log (usually 10 – 20% of the total). Probably its two best examples are from the middle portions of the Fablo log (183 m – 381 m; **Fig. 3.32**; Vol.2, p.67 – 69), and from the upper portions of the Nocito log (167 m – 1118 m; Vol. 2, p.159 – 169).

This lithofacies forms thick beds, usually around 1 – 5 m thick. Commonly the beds are amalgamated into packages of 3 – 5 beds, which reach up to 10 m thick. This lithofacies has a general increase in thickness, grainsize and frequency of occurrence upwards through the Belsué-Atarés Fm. Beds are usually planar and laterally extensive, though towards the tops of the logged sections, erosive bases, pinch-out and even channelisation are all occasionally observed.

This facies is commonly composed of grainsizes between fine and coarse sand, with medium sand being the most common. Fining upwards is occasionally seen, although it is common on some logged sections (e.g. 148 m – 370 m at Fablo; Vol. 2, p.67 – 69), whilst not seen at all on many others. Typically the sands are moderately to poorly sorted, although the coarser beds, and particularly the erosively-based ones, are very poorly sorted in 50% of instances (**Fig. 3.33**). The fine sand beds are typically moderately sorted or well sorted.

Clasts are common within this facies. Small (of diameter less than 10 mm) marl (or less commonly, clay) rip-up clasts are common, especially at the base of beds. Occasionally the rip-up clasts exceed 10 mm in diameter, and very rarely may exceed 30 mm. Small, and usually well-rounded pebbles are fairly common. They usually consist of either sandstone or limestone lithologies, that were not recognised as being intrabasinal, and a few exotic clasts such as granite, which most probably came from the Pyrenean axial zone to the north (Jones, 1997).

As well as by its generally coarser grainsize, this lithofacies is distinguished from the previous two finer sandy lithofacies (sections **3.2.5** and **3.2.6**) by the presence of

Medium, cross-laminated sandstones facies

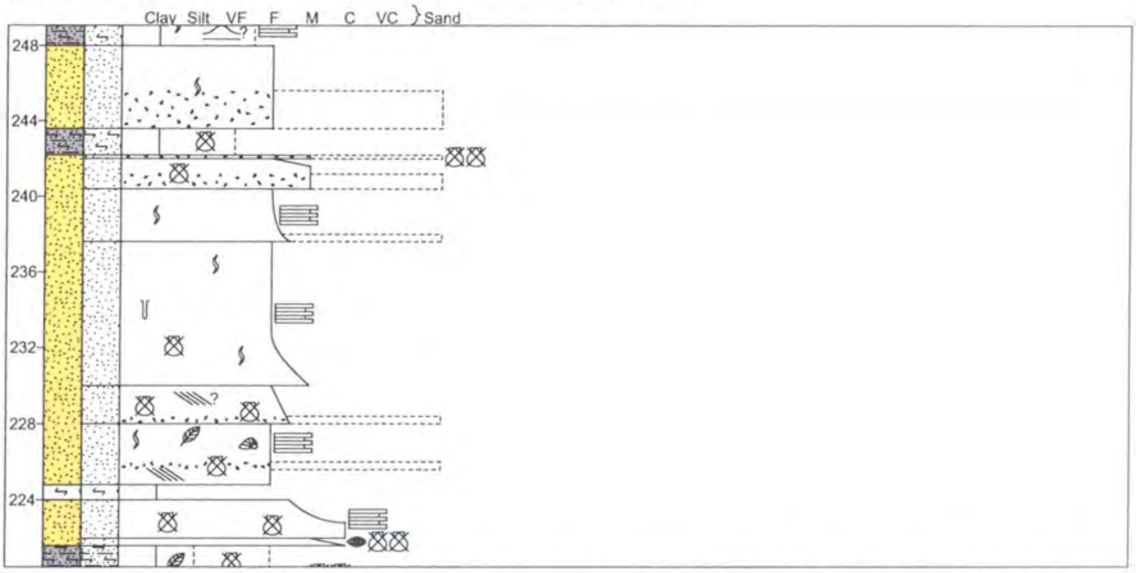


Fig. 3.32. Typical beds of this facies. From the middle of the Fablo log (Vol.2, p.68).

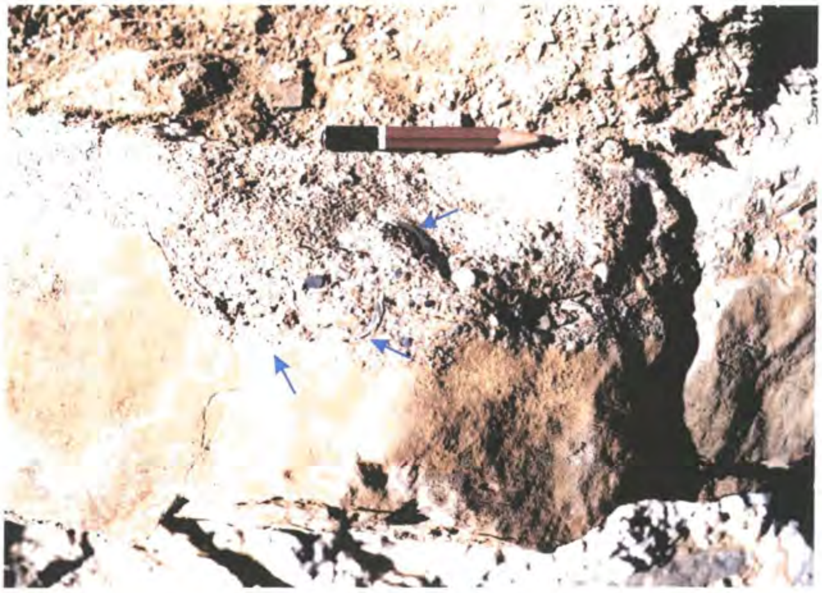


Fig. 3.33. Very poorly sorted sands, gravels, and oyster fragments (arrowed). From the lower portions of the Monrepos log (photos '3MN5-6', Vol.2, p.196).

Fig. 3.34. Well developed trough cross-lamination in a fine sandstone. From near the top of the Jaca log (off section).

(Medium, cross-laminated sandstones facies, continued)

Fig. 3.35. Large de-watering pipe cutting through a bed. From the base of the Monrepos log (photos '3MN1-2', Vol.2, p.196).

Fig. 3.36. Probable *Palaeophycus* movement traces on a bedding surface. From low on the San Julián de Basa log (photos '3SJ3-4', Vol.2, p.84).

Fig. 3.37. Plant debris concentrated on a bedding surface in a fallen block. From the middle of the Fanlillo log (photos '3FL3-4', Vol.2, p.74).

several characteristic sedimentary structures: tabular cross-lamination, which is almost ubiquitous, and fairly common trough cross-lamination (**Fig. 3.34**). Symmetrical ripples are fairly rare, and never well developed. Although loading and dewatering structures are very rare, they are more common in this facies than any other (e.g. **Fig. 3.35**).

The lithofacies very commonly contains bioturbation at the 'low bioturbation' to 'moderate bioturbation' levels (Taylor & Goldring, 1993), with rarely occurring 'high bioturbation'. Vertical burrows are occasionally seen. Observed inchnogenera include a probable *Palaeophycus* trace (**Fig. 3.36**; R. Goldring, pers. comm., 2003).

This lithofacies is rich in many of the different types of fossils observed in the Jaca Basin, and most have undergone some degree of breaking. Shell fragments of miscellaneous type, plant debris (**Fig. 3.37**) and oysters (also usually well broken) are very common. *Nummulites* are fairly common, and *Chlamys*-type bivalves are occasionally seen. Other types of bivalves are rare, and bryozoa and echinoids are very rare.

3.2.7.2 Interpreted depositional processes and environment

The variable nature of this lithofacies, in terms of bed thickness, bed morphology, grainsize, clasts, and bioturbation, suggests that it was the product of a number of different depositional processes, interacting in one or more depositional environments. Cross-lamination is the most common depositional structure, and implies that unidirectional currents were chiefly responsible for the deposition of the sediment. The occasional erosive bases indicate that sometimes the currents had sufficient energy to erode into the beds beneath them. This same process probably created the marl (or clay) rip-up clasts that are commonly seen. The fairly rare symmetrical ripples suggest that at times the unidirectional currents were not operating, and oscillatory flow in the water column was able to shift the sands around.

The very common shelly fossils of marine organisms indicate that a rich and diverse marine fauna existed either in the depositional environment, or elsewhere and was transported in on death. The fact that the majority of the shelly fossils were broken to some degree suggests that they were transported by currents before deposition. The significant level of bioturbation (up to 'intense bioturbation', terminology of Taylor & Goldring, 1993) indicates that some organisms were living and/or feeding in this environment. Unfortunately, the only identifiable trace fossil, a probable *Palaeophycus* trace, does not help constrain the environment as simple, rarely branched repichnia (movement traces) such as these occur at many water depths, and in many facies (R. Goldring, pers. comm., 2003).

There are two possible depositional environments in which this lithofacies could have been laid down. They are described below, although it is important to note that they are essentially end-members in a spectrum of shallow marine siliciclastic settings. The first possible environment is the upper shoreface of a siliciclastic coast. In this setting, symmetrical ripples created by oscillatory flow (due to surface waves) in the lower shoreface pass landwards into asymmetrical ripples as the power of landward-directed flow increases (Davidson-Arnott & Greenwood, 1974 & 1976). In this environment, sand is transported by longshore currents in the sea, and so has a more mature texture and composition than if it had been supplied directly by a river (i.e. deposited on a delta).

The second possible environment is that of a delta front. In this environment, sediment-laden fluvial currents from the distributary channels of the delta expand laterally and vertically, and decelerate, depositing their sediment load to be acted on by basinal (in this case, marine) processes. The coarser sediments are deposited as distributary mouth bars, although many other types of sand accumulation may form where wave processes are important (Wright, 1977; Orton & Reading, 1993).

The commonly occurring extrabasinal pebbles, particularly granite clasts from the Pyrenean axial zone (Jones, 1997), suggest that the sediment that constitutes this lithofacies was supplied from uplifted areas that were undergoing subaerial erosion. The most likely mechanisms to transport subaerially eroded material into a marine basin are that of a river or an alluvial fan. Thus, the presence of extrabasinal pebbles in this marine lithofacies suggests that sediment was at least partly being supplied by a delta or fan delta. The generally highly variable degree of sorting in this lithofacies, from moderately sorted to very poorly sorted, implies that sorting by marine processes sometimes occurred, and sometimes did not. Thus, it seems that this lithofacies was deposited in a shallow marine environment that had contributions from both deltaic / fan deltaic processes and marine shoreline processes.

This lithofacies was also encountered by Castelltort *et al.* (2003) during their work on the Belsué-Atarés Fm., and interpreted in a very similar way. These authors concluded that the depositional environmental was "upper offshore to lower shoreface / bypass in delta front environment". However, they did feel that it could have been deposited at a very broad range of water depths – anywhere between 0 m and 100 m.

3.2.8 Coarse, cross-bedded sandstones facies

3.2.8.1 Occurrence and description

This lithofacies is fairly common in the Belsué-Atarés Fm. – it is seen on around three-quarters of logged sections, but tends to account for less than 5% of the total thickness of each section. The best examples of this facies are seen in the SE corner of the basin, particularly at Lúsera (805 m – 1071 m; **Fig. 3.38**; Vol.2, p.182 – 184), Gabardiella (194 m – 289 m; Vol.2, p.172), and slightly further west at Monrepos (22 m – 84 m; Vol.2, p.196).

Beds of this facies most commonly have an individual thickness of 1 – 5 m, but are very commonly amalgamated into 10-m-thick packages consisting of 2 – 4 beds. The beds themselves vary from being laterally extensive over hundred of metres (with or without internal variations in character along their lateral extent), through to taking channel-like forms of only 10 m lateral extent or less. Erosive bases are commonly seen – but are by no means ubiquitous.

Grainsizes are highly variable – both between and within beds. The normal range is from fine sand up to very coarse sand, with coarse sand being the most common. Fining upwards is commonly observed (typically with a drop in a whole grainsize per 2 metres of thickness), and is occasionally very strongly developed (up to a drop in two grainsizes every metre of thickness). The sands themselves are poorly or very poorly sorted, with the poorest sorting usually being found in the lowermost portions of erosively-based, fining upwards beds.

The depositional structures that define this facies are the almost ubiquitous tabular cross-bedding and fairly common trough cross-bedding. In addition, tabular cross-lamination is very common, and trough cross-lamination is fairly common. The distinction between cross-lamination and cross-bedding is that the latter has a average set height that is greater than 6 cm, whilst the former is less. Beds are commonly cross-laminated and cross-bedded throughout, at different scales (from set heights down to 2 cm to up to 1 m), and with differing types of foresets and dip directions (**Fig. 3.39**; **Fig. 3.40**).

Beds of this facies commonly contain clasts: small (4 – 10 mm diameter), medium (10 – 30 mm) and large (30 – 64 mm) marl or clay rip-up clasts are very common (**Fig. 3.41**), and are often concentrated towards the base of each bed, decreasing in size and numbers upwards. Pebbles are also occasionally seen – they are usually small, well-

Coarse, cross-bedded sandstones facies

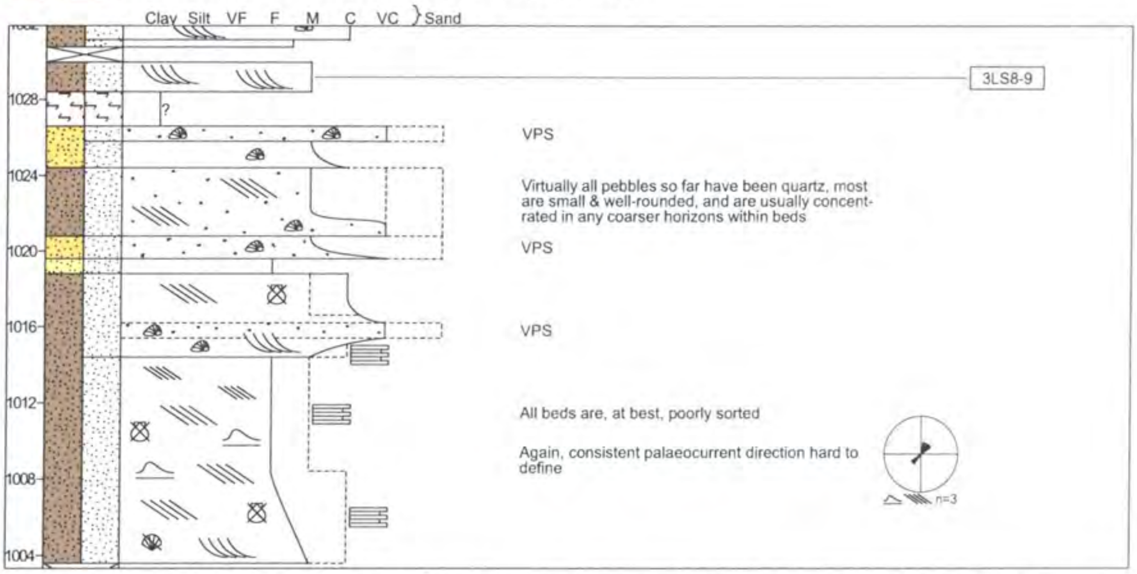


Fig. 3.38. Typical beds of this facies. From the top of the Lúsera log (Vol.2, p.184).

Fig. 3.39. Well developed trough cross-bedding in a bed of coarse, cross-bedded sandstones facies. From high on the Árguis log (off section).

Fig. 3.40. Cross-bedding and plant debris (rusty stains mark carbonised fossils). From near top of Lúsera log (off section).

Fig. 3.41. Moulds of large spherical rip-up clasts. From upper portions of Jaca log (photos '3JC3-4', Vol.2, p.113).

rounded and of limestone lithology, though sometimes sandstone (neither of which were recognised as being from intrabasinal lithologies).

Bioturbation is rare, but where present is commonly concentrated either towards the tops of each bed, or on the upper bedding surface itself, where its intensity may reach that of 'moderate bioturbation' (Taylor & Goldring, 1993). The only positively identified trace fossil was *Ophiomorpha* (R. Goldring, pers. comm., 2003).

Well fragmented miscellaneous shells are very common in this facies. Oysters and woody plant debris are common (**Fig. 3.40**), and *Nummulites* are rare.

3.2.8.2 Interpreted depositional processes and environment

The variable nature of this lithofacies suggests that it is the product of more than one type of depositional processes, and may have formed in more than one depositional environment. The almost ubiquitous cross-bedding is its most prominent sedimentary feature. Cross-bedding is formed by the migration of dunes under the influence of a high energy, unidirectional current. For the most commonly occurring grainsize in this lithofacies – coarse sand – to be formed into migrating dunes (that would give rise to the cross-beds), the minimum flow velocity would be 0.4 m/s (Ashley *et al.*, 1990). A flow of this velocity would also be sufficient to form the coarsest commonly observed grainsize – very coarse sand – into dunes. The commonly occurring erosive bases to beds imply that the currents were often powerful enough to erode down into layers of sediment that had already been deposited.

The commonly observed fining upwards within beds could have been created simply by the current that was supplying the sediment experiencing a drop in energy, or by the lateral migration of a channel axis – causing the coarsest sediment to also move laterally.

The fossils, which are very common in this lithofacies, are of marine organisms. The heavy fragmentation that many have undergone implies that vigorous currents transported them. The presence of abundant woody plant debris suggests that the marine depositional environment had a connection to a terrestrial source area with trees or other woody plants. Bioturbation is rare, and even then only usually seen towards the tops of the beds, which may suggest that deposition was often too rapid to allow organisms to burrow throughout the body of sediment.

The most likely environment for the formation of this facies is on the proximal parts of a delta front. In this scenario, poorly sorted, (extrabasinal) pebble- and rip-up clast-rich sands would be delivered by an extrabasinally-sourced fluvial system, via deltaic distributary channels, into a marine basin (Wright, 1977; Orton & Reading, 1993). The channel-forms adopted by some of the sandstones would reflect the in-filling of the subaqueous continuations of the deltaic distributary channels. Fining upwards beds could result from the migration or gradual abandonment of these channel systems. The almost ubiquitously cross-bedded sands could form either as the infill of the subaqueous channels, or as mouth bars at the channel termination points. The fine and moderately sorted beds could result from times of lower water and sediment flux through the delta system, or from reworking by marine processes.

The only other shallow marine environment in which extensive cross-bedded sandstones are likely to be formed is that of the shoaling wave zone of a non-deltaic siliciclastic coast (Davidson-Arnott & Greenwood, 1974 & 1976). However in this environment, dunes or channels are not so extensively developed, and the abundant rip-up clasts, small extrabasinal pebbles and plant debris found would be difficult to account for without a major fluvial system connecting with the marine depositional environment at some point (i.e. a delta).

The only identified trace fossil in this lithofacies, the pellet-lined fodinichnia (feeding trace) burrow *Ophiomorpha*, is associated with the *Skolithos* ichnofacies. This ichnofacies is typical of shifting-sand environments in the intertidal zone, where organisms have to respond rapidly to stressful conditions (Seilacher, 1967; Goldring pers. comm., 2003), and is consistent with the inferred shallow marine depositional environment.

3.2.9 Bioclastic limestones facies

3.2.9.1 Occurrence and description

This lithofacies was noted on less than one quarter of the logged sections, and then usually accounts only 1 – 2 m of the thickness. It does however make up the uppermost couple of hundred metres of the Guara Fm., on which nearly all of the logs from the southern basin margin were based. The formations that overlie the Guara Fm. are however the primary concern of this work, and amongst these the best examples of this lithofacies come from the Pico del Águila log (133 m – 218 m; Vol.2, p.199 – 200) and Bentué de Rasal log (300 m – 440 m; **Fig. 3.42**; Vol.2, p.219 – 220).

Bioclastic limestones facies

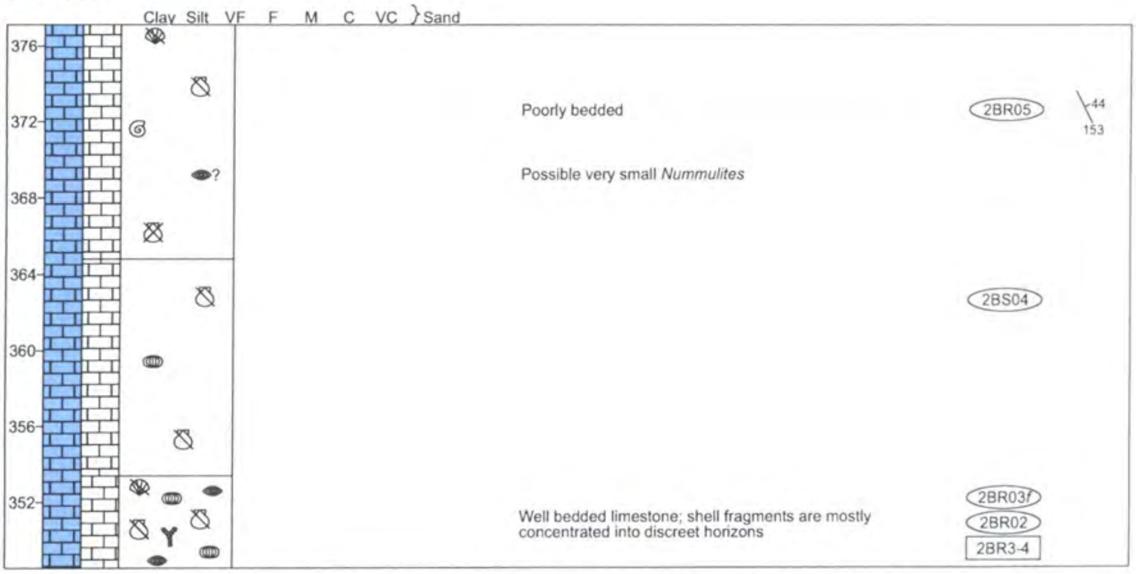


Fig. 3.42. Typical beds of this facies. From middle of Bentué de Rasal log (Vol.2, p.219).

Fig. 3.43. A thick but poorly bedded accumulation of bioclastic limestones facies. From near the village of Rasal (off section, but see **Fig. 1.1**).

Fig. 3.44. Biomicrite rich in *Nummulites* of varying size and diameter / thickness ratio. From near base of Nocito log (off section).

Beds of this facies come in a wide range of bed thicknesses, from 0.4 – 5 m. The beds are always planar and laterally extensive, and are usually massive, although poorly developed internal planar beds were occasionally seen (**Fig. 3.43**). The bed contacts are usually sharp, but may be gradational with the sandy bioclastic limestones facies (section **3.2.10**). No current-formed sedimentary structures of any type were observed in this lithofacies.

This lithofacies is chiefly composed of micrite, with the proportion of bioclasts usually being 1–50 % (**Fig. 3.44**). This makes these rocks fossiliferous micrites or sparse biomicrites in the classification of Folk (1962).

Miscellaneous shell fragments are almost ubiquitous in this facies, and *Nummulites* are also very common (**Fig. 3.44**). Other types of large foraminifera are fairly common, and *Chlamys*-type bivalves are seen occasionally. Bryozoa, *Alveolina* and echinoids are all rare. The bioclasts themselves do not show any evidence of sorting, as they are usually of varying sizes and fossil types. Approximately half of them have suffered some degree of fragmentation. Bioturbation is only occasionally seen in this lithofacies. The shapes of the *Nummulites* tests varied significantly. In terms of diameter / thickness ratios, some were as high as 10 (relatively very thin), whereas other were down to 4 (relatively thicker). Most tests had ratio that lay in the 6 – 8 range.

3.2.9.2 Interpreted depositional processes and environment

The siliciclastics-free micrite beds that make up this lithofacies record the deposition of carbonate mud during times of no significant sand supply. The deposition of this mud, and the lack of any current-formed depositional structures or sand input, implies that the environmental energy was very low. The often thin and brittle forms of the *Nummulites* tests (diameter / thickness ratios of 6 – 8) are suggestive of a low energy environment, where the foraminifera were able to maximise their surface area without risk of being damaged by water energy (Trevisani & Papazzoni, 1996).

The very common *Nummulites* indicate that the environment of deposition was a warm sea, with normal marine conditions. The deposition of carbonate mud and the presence of undamaged, thin and brittle *Nummulites* forms suggest that the water depth of deposition was below normal wave base. However, the apparently in-situ *Nummulites* and other benthic foraminifera imply that the environment must still have lain within the photic zone (so probably less than around 100 m depth).

3.2.10 Sandy bioclastic limestones facies

3.2.10.1 Occurrence and description

This lithofacies is similar in character to the bioclastic limestones facies (section **3.2.9**), except that it contains 1 – 50% of silt and/or sand. It also tends to be found in the same parts of the Belsué-Atarés Fm., but is usually not to be found in the uppermost Guara Fm. The amount of silt and/or sand in this facies can vary gradually, which may give rise to gradation into the siliciclastics-free bioclastic limestones facies (section **3.2.9**) or calcareous versions of one of the sandstones lithofacies (section **3.2.5 – 3.2.8**). The best examples of this facies are from the southern basin margin – at Bara (0 m – 47 m; Vol.2, p.151), at Pico del Águila (130 m – 159 m; **Fig. 3.45**; Vol.2, p.199), and at Nocito (0 m – 38 m; **Fig. 3.46**; Vol.2, p.158).

Beds of this facies tend to be in the range of 0.4 – 5 m thick, although can be up to several tens of metres thick (with no internal bedding). They are always planar and laterally extensive (over many hundreds of metres). Sharp contacts with other (non-carbonate rich) lithofacies occur more commonly than gradational ones.

This lithofacies is made up of 50 – 99% carbonate material – a combination of micrite and bioclasts. The remainder is the siliciclastic component, which tends to be moderately to well sorted and varies in grainsize from silt to fine sand, with very fine sand being most common. The proportion of bioclasts present is in the range of 1 – 50 %, which makes these rocks fossiliferous micrites or sparse biomicrites (Folk, 1962). No depositional structures were observed in this lithofacies.

Miscellaneous shell fragments are almost ubiquitous, and *Nummulites* are also very common (**Fig. 3.46 – Fig. 3.47**). Occasionally seen were other types of large foraminifera (including *Alveolina*), and *Chlamys*-type bivalves. Bryozoa and echinoids were only very rarely seen. The bioclasts themselves do not show any evidence of sorting, as they are usually of varying sizes and fossil types, and have undergone varying degrees of fragmentation (from none to moderate). Evidence of bioturbation was only occasionally seen preserved.

The shapes of the *Nummulites* tests were not as variable as in the bioclastic limestones facies (section **3.2.9**). In terms of diameter / thickness ratios, some were as high as 5 (relatively thin), whereas other were down to 2.5 (relatively thick). Most tests had ratio that lay in the 3 – 4 range.

Sandy bioclastic limestones facies

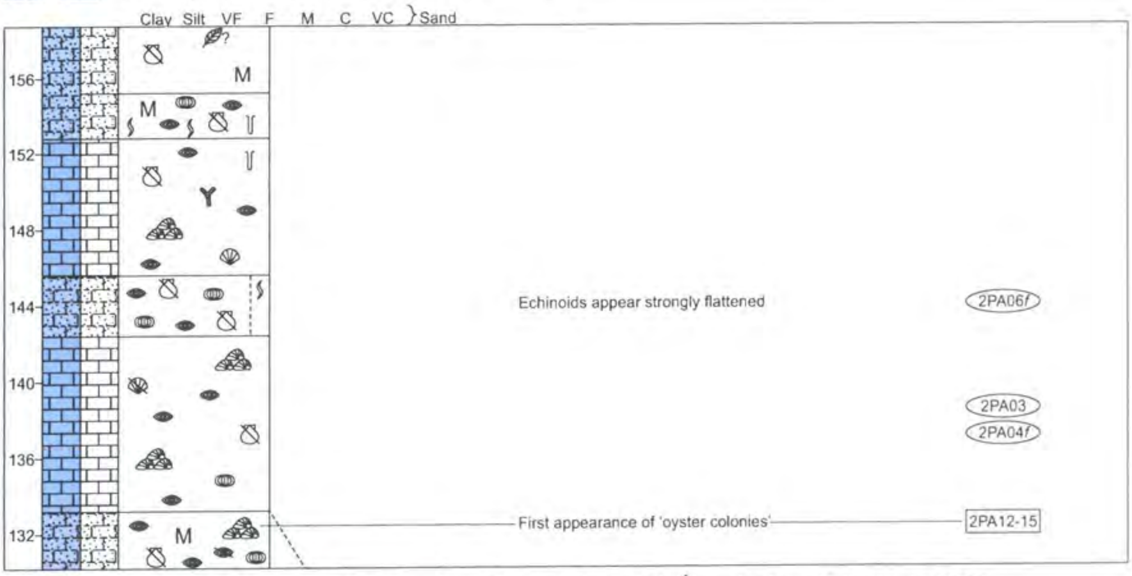


Fig. 3.45. Typical beds of this facies. From Pico del Águila log (Vol.2, p.199).

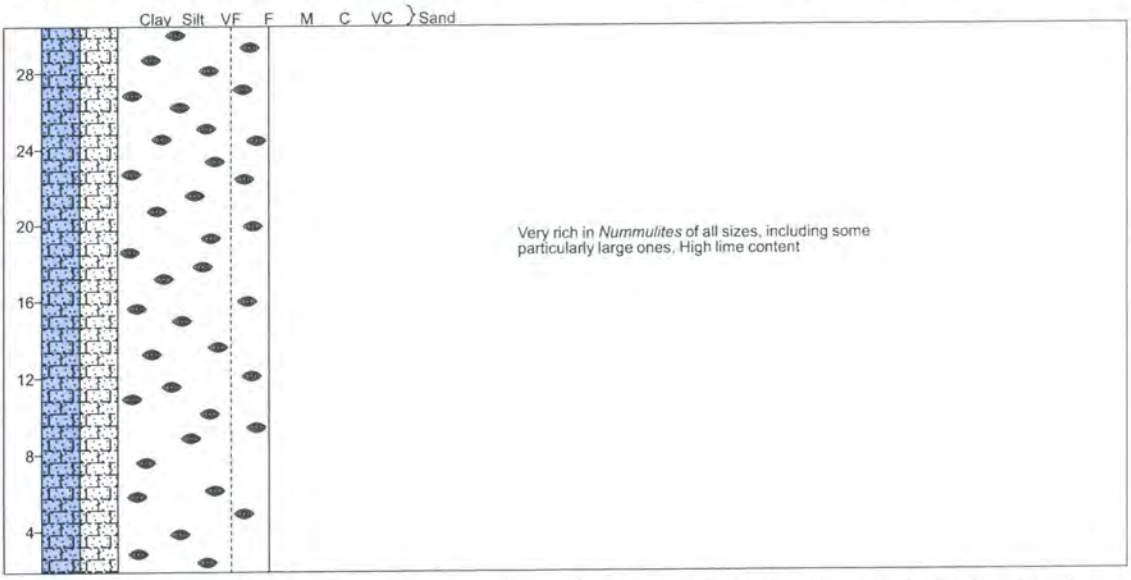


Fig. 3.46. Unusually thick and *Nummulites*-rich bed. From Nocito log (Vol.2, p.158).

Fig. 3.47. A bed of this facies that is very rich in *Nummulites* and *Alveolina* of all sizes. From near the base of the Bara log (photos '4BA1-2', Vol.2, p.151).

3.2.10.2 Interpreted depositional processes and environment

This lithofacies documents two main depositional processes – the deposition of carbonate muds, and a small but significant supply of, on average, very fine, moderately sorted sands. The relatively thick and robust forms of the *Nummulites* tests (diameter / thickness ratios of 3 – 4) are suggestive of a moderate energy environment, where the foraminifera had to grow in a thicker form to avoid damage by water energy (Trevisani & Papazzoni, 1996).

The very common *Nummulites* indicate that the environment of deposition was a warm sea, with normal marine conditions. The presence of the siliciclastic component, the commonly broken fossils, and the more robust *Nummulites* forms suggest that deposition occurred in moderate energy waters above normal wave base. The common benthic organisms, such as larger foraminifera, must have originated in the photic zone (although the fact that most of them have suffered some degree of fragmentation implies that they may have been transported in).

3.2.11 Coral limestones facies

3.2.11.1 Occurrence and description

This distinctive yet rare lithofacies accounts for only a couple of metres of the Belsué-Atarés Fm. on a cluster of logs towards the western end of the northern basin margin (Bernués – Alastuey; **Fig. 1.1**). The best examples are from the Bernués log (65 m – 98 m; Vol.2, p.97 – 98), and the Peña Oroel log (170 m – 193 m; **Fig. 3.48**; Vol.2, p.103 – 104).

Beds of this facies always occur singly, and come in a very wide range of thicknesses: from 0.4 – 20 m. The beds are planar and laterally extensive over several kilometres (see the 'Reef horizons' mapped on **Fig. 1.1**). They rarely show any internal bedding.

This lithofacies is primarily composed of corals set in a micrite matrix. In addition to this, the beds often contain significant quantities of marl, which may be present as discrete interbeds or admixed within the limestones. On rare occasions, silt to fine, well-sorted sands are present. Similar to the previous two limestone facies (sections **3.2.9** and **3.2.10**), no depositional structures were observed.

Coral limestones facies

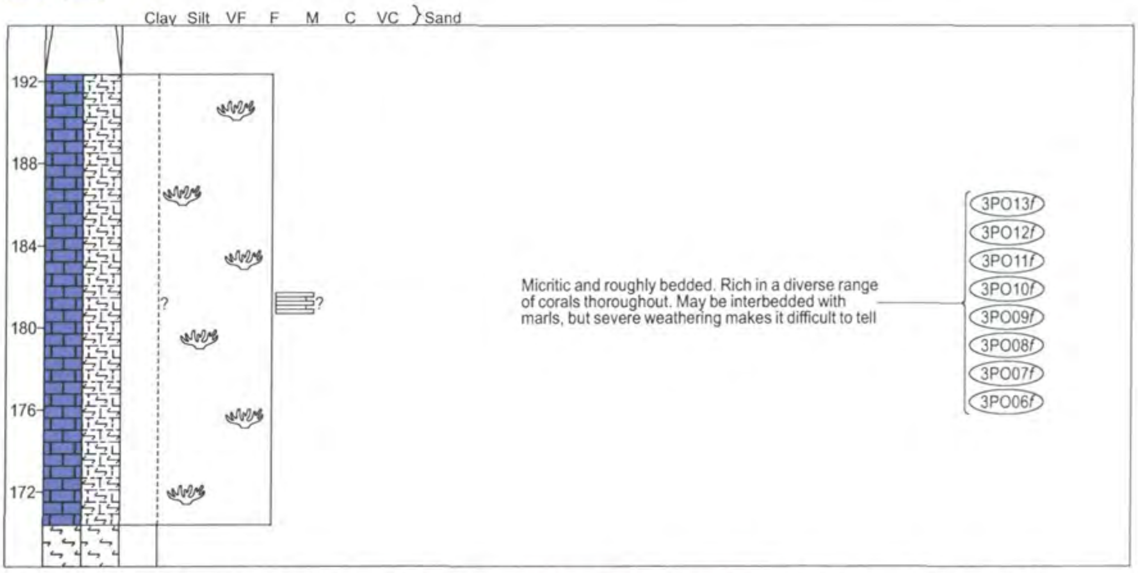


Fig. 3.48. A thick bed of this facies. From the Peña Oroel log (Vol.2, p.103 – 104).

Fig. 3.49. A delicate phaceloid coral. From the middle of the Atarés log (photos '3AT4-7', Vol.2, p.120).

Fig. 3.50. A thicker and more robust coral growth form. From near the village of Rasal (off section, but see **Fig. 1.1**).

The main characteristic that distinguishes this facies is the ubiquitous presence of colonial corals. These tend to be very diverse, with at least fifteen different types of coral observed. Some individual beds contained ten or more coral types in a few metres of thickness. Although it was not possible to describe with certainty the overall growth form of any of the corals (because of the weathered and rubbley nature of the exposures), the blocks and coral fragments observed seemed to record at least four basic corallite forms: dendroid, phaceloid, cerioid, meandroid. Some corals appear to have a delicate structure (particularly the branching dendroid and phaceloid types; e.g. **Fig. 3.49**), whilst others appear in more robust globular or bulbous forms (particularly the cerioid and meandroid types; e.g. **Fig. 3.50**). Approximately three-quarters of the corals seem to be in their life positions, whereas the others are preserved as non-in-situ fragments. In the former case, the rock could be classified as a coral framestone (Embry & Klovan, 1971). No evidence of bioturbation was seen preserved within this lithofacies.

This lithofacies contains a few other fossils, besides corals. Miscellaneous shell fragments are common. Various types of large foraminifera are rare but present, although unusually, *Nummulites* are not. Gastropods, bivalves and bryozoa are very rare.

3.2.11.2 Interpreted depositional processes and environment

This facies is a product of the growth of coral reefs. The coral types present and the fabric of the limestones (framestones) indicate that a rigid framework of colonial corals existed. Between the corals, marls and lesser amounts of fine, well-sorted sands were accumulated. Although most of the corals were in their life positions, the areas of broken corals record erosion of the reef, either by storms or by boring organisms (bioerosion).

Modern coral reefs tend to grow in conditions of warm, normal salinity water, with low turbidity. It is most likely that the same is true for ancient reefs. The corals, assuming that they were hermatypic (contained photosynthetic organisms), would have required some sunlight to grow, and so could not have formed at water depths greater than the base of the photic zone (around 100 m for clear waters, much less if turbid). Although the exposures were not sufficient to recognise the different reefal sub-environments, the framestones observed are most typical of the reef front of the classic reef model (Tucker & Wright, 1990), but may sometimes also be seen on the reef crest.

Poor exposure also made it impossible to deduce, with certainty, the overall form of the reefs. However, a more laterally extensive type, such as a barrier reef, would more easily account for the kilometre wide lateral extent of beds of this lithofacies (**Fig. 1.1**) than a more localised type, such as a patch reef.

If the reef did take the form of the classical model, the growth forms of the corals can be used to infer the environmental conditions on the reef front or crest (Stearn, 1982; Pomar *et al.*, 1985). The more delicate branching forms are associated with low wave energy and high sedimentation rates (because an erect growth form is adopted to avoid sediment smothering; Tucker & Wright, 1990). The more robust globular and bulbous forms observed are associated with moderate wave energy (and hence water depths that are above wave base), and again, high sedimentation rates. Although poor exposure prevented recognition of any zonation between these two basic growth forms, it would be expected that the globular and bulbous forms grew closer to the reef crest, in shallower and more energetic waters, than the delicate branching forms (Pomar *et al.*, 1985).

To summarise, the presence of corals and the different growth forms that they exhibit suggests the growth of a reef, or series of reefs, above (or partly above) wave base in the photic zone of a warm, normal salinity sea, in which sedimentation rates were generally high.

3.2.12 Parallel-laminated sandstones facies

3.2.12.1 Occurrence and description

This very distinctive lithofacies was only seen on three logged sections at the western end of the northern margin of the Jaca Basin, where it makes up a considerable proportion of the thickness of the Yeste-Arrés Fm. The three logs were: the Alastuey log (56 m – 111 m; **Fig. 3.51** & **Fig. 3.52**; Vol.2, p.127 – 128), the Puente La Reina log (1 m – 87 m; Vol.2, p.129), and the Arrés log (193 m – 227 m; Vol.2, p.133).

The feature that distinguishes this lithofacies is its strongly developed and ubiquitous parallel-lamination to thin internal bedding (**Figs. 3.53** & **Fig. 3.54**). The thickness of the laminae to internal beds varies from 5 mm up to 10 cm. Occasionally, adjacent laminae or internal beds may consist of different grainsizes, although, more commonly, the grainsize is fairly constant. The most common range of grainsizes is very fine to medium sand (although interbeds may sometimes be as fine as clay-grade

Parallel-laminated sandstones facies

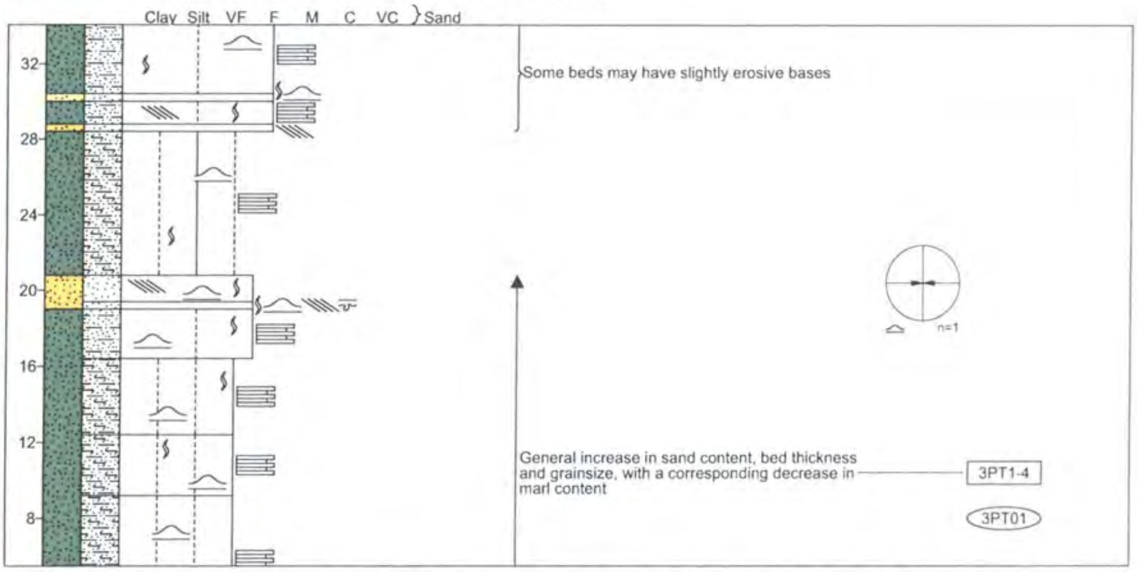


Fig. 3.51. Typical packages of this facies. From base of Puenta La Reina log (Vol.2, p.129).

Fig. 3.52. 0 m – 58 m of the Puente La Reina logged section (Vol.2, p.129). Slightly coarsening-up parallel-laminated sandstones facies is capped by medium, cross-laminated sandstones facies (section **3.2.7**).

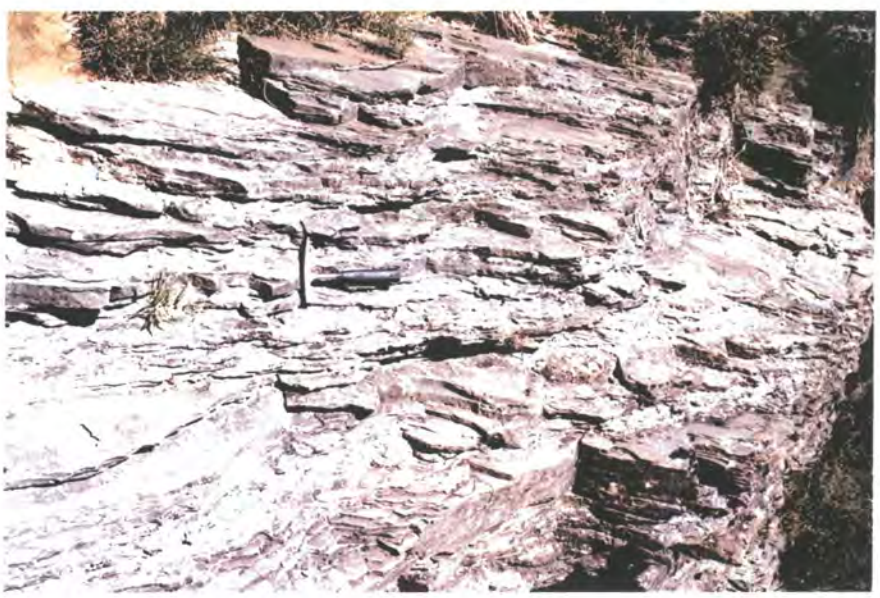


Fig. 3.53. Parallel -lamination typical of this facies. From towards the top of the Puente La Reina log (photo '3PT8', Vol.2, p.129).

(Parallel-laminated sandstones facies, continued)

Fig. 3.54. Close-up of very thin bedding (partly disrupted). From the lower half of the Puente La Reina log (photos '3PT5-7', Vol.2, p.129).

Fig. 3.55. A symmetrically rippled fine sandstone bed. From the middle of the Alastuey log (photos '3AL3-4', Vol.2, p.127).

Fig. 3.56. An asymmetrically rippled bedding surface, with desiccation cracks (arrows mark one polygon). From near the top of the Arrés log (photos '3AR7-8', Vol.2, p.133).

marls), with fine sand being the most common. The sands are usually moderately sorted, but never graded.

Laminae or internal beds of similar thicknesses, grainsizes and other characteristics may be grouped together into beds of 1 – 8 m thickness. In the upper portions of the three logged sections on which this lithofacies occurs, the beds usually occur in amalgamated packages (uninterrupted by other lithofacies) that may be 20 m thick or more. In the lower portions of the logged sections, the beds tend to occur singly. All beds of this lithofacies are planar and sharp based – erosional or gradational relationships are never seen. Even the thinnest internal beds tend to be laterally extensive across the width of the studied exposures (of the order of 20 m).

Symmetrical ripples are common in beds of this lithofacies (**Fig. 3.55**), and asymmetrical ripples are fairly common (**Fig. 3.56**). Cross-lamination and desiccation cracks are fairly rare throughout the lithofacies, but may be very common in particular beds e.g. 68 m – 87 m on the Puente La Reina log (Vol.2, p.129). The desiccation cracks tend to be restricted to around the uppermost stratigraphic limit of occurrence of this lithofacies (**Fig. 3.56**).

The degree of bioturbation was very variable. In the logged sections at Alastuey and Arrés, large and continuous thicknesses of this facies are apparently unbioturbated: 56 m – 92 m at Alastuey (Vol.2, p.127), and 193 m – 227 m at Arrés (Vol.2, p.133). Bioturbation is however common throughout the Puente La Reina log and on other parts of the Alastuey and Arrés logs, where it may reach 'moderate bioturbation' levels (Taylor & Goldring, 1993). However, no distinctive, identifiable trace fossils were noted. The only fossils observed were very rare woody plant debris.

Marl or clay rip-ups clasts are present but limited to isolated parts of one slightly unusual bed belonging to this lithofacies – a very thick, coarse and poorly-sorted unit occurring between 68 m – 87 m on the Puente La Reina log (Vol.2, p.129).

3.2.12.2 Interpreted depositional processes and environment

This lithofacies records two main depositional processes: the transport and deposition of sand by unidirectional and bi-directional currents, creating the symmetrical and asymmetrical ripples, and fluctuations in the grainsize of the sediment being supplied or the environmental energy, creating the ubiquitous parallel-lamination to internal bedding.

The variations in the intensity of the bioturbation of the sediments (from none to 'moderate bioturbation') are hard to explain. However, the bioturbating organisms were probably soft-bodied as no fossil shells were recorded. The abundant marine fossils found in many of the other lithofacies of the Jaca Basin were notably absent. Towards the upper limit of this facies, fairly rare desiccation cracks record occasional sub-aerial exposure and drying out of the sediments.

The depositional environment in which the key features and processes recorded by this lithofacies (uni- and bi-directional currents, rapidly fluctuating environment energy, a lack of a marine fauna, and period subaerial exposure) are most likely to have occurred is that of a tidal flat (Weimer *et al.*, 1982). The uni- and bi-directional currents indicate that wave, current and tide energy were all still significant, suggesting that most of this lithofacies was deposited in the lower portions of the tidal flat. The millimetre- to centimetre-scale parallel-lamination to internal bedding probably reflects an annual cycle in energy and sediment supply on the flat, with sandier periods most likely caused by stormy winter weather. The fairly rare, abundantly cross-laminated beds (68 m – 87 m on the Puente La Reina log; Vol.2, p.129) were probably the product of broad tidal channels on the flats. Although the majority of this facies was deposited in completely inter-tidal conditions, the desiccation cracks in the uppermost portions indicate vertical transition to a supra-tidal flat environment (Woodroffe *et al.*, 1989).

Puigdefàbregas (1975) mapped the occurrence of the Yeste-Arrés Fm. in the Jaca Basin, of which this lithofacies makes up the vast majority. This formation was described as being made up of "sandstones and marls of inter-tidal zone facies", which is in agreement with the depositional model presented here. The interpreted presence of thick deposits of tidal flats in the Jaca Basin implies that the sea that occupied the basin at the time had a significant tidal range.

3.2.13 Matrix-supported conglomerates facies

3.2.13.1 Occurrence and description

This lithofacies is the rarest of all those distinguished in the Jaca Basin, accounting for only 0.1% of the total thickness of sediment studied. Although many of the coarser sandstone beds contain pebbles, very few contain sufficient 'floating' pebbles to be considered a matrix-supported conglomerate. Although it usually forms part of the Belsué-Atarés Fm., there is at least one instance of it occurring in the Lower

Campodarbe Fm. with the same sedimentological characteristics (482 m – 485 m at Fanlillo; Vol.2, p.75). The best-exposed example of this lithofacies occurs on the Lúsera log (1061 m – 1062 m; **Fig. 3.57**; Vol.2, p.184).

Beds vary from 0.2 – 3 m thick, and only ever occur singly, isolated within other facies. Their form varies from lenses of only a metre or less lateral extent, up more planar forms that may persist for up to 10 m laterally. The bases of the beds tend to be sharp, rather than erosive.

The grainsize of the matrix varies from medium sand up to very coarse sand, with coarse sand being the most common. Continuous variations in grainsize were not noted in the logged beds. The sands were most commonly poorly sorted or, in the case of the coarsest examples, very poorly sorted. Tabular cross-lamination and cross-bedding were occasionally noted in the sandstones of the matrix (**Fig. 3.58**), but no clast alignment fabric was observed.

Within the beds of this facies that lie within the Belsué-Atarés Fm., fossils include fairly common miscellaneous shell fragments, and occasional oysters and *Nummulites*. However, no unambiguous trace fossils were observed.

The pebbles in this lithofacies vary from sub-angular to well-rounded, with rounded pebbles being the most common. The sizes of pebbles vary from 'small' (4 – 10 mm in diameter), through 'medium' (10–30 mm), and up to 'large' (30 – 64 mm), with at least one cobble-sized clast being recorded (>64 mm; **Fig. 3.59**). The requirement for a bed to be considered a conglomerate was that it contained at least 10% 'medium' sized (10 – 30 mm diameter) or larger pebbles. 70% of the pebbles were limestones (micritic, no obvious fossils), the rest being sandstones (fine to medium grained, brown). Neither lithology was recognised as originating from within the Jaca Basin (extrabasinal). Small and medium marl rip-up clasts are also common in this lithofacies (**Fig. 3.58**).

3.2.13.2 Interpreted depositional processes and environment

The tabular cross-lamination and cross-bedding that are occasionally observed in this lithofacies imply the activity of strong unidirectional currents, causing the migration of straight-crested asymmetrical ripples and dunes. The minimum flow velocity that could cause the formation of dunes from the most common grainsize in this lithofacies – coarse sand – would be 0.4 m/s (Ashley *et al.*, 1990). The fact that cross-lamination and cross-bedding are difficult to recognise in the relatively thin,

Matrix-supported conglomerates facies

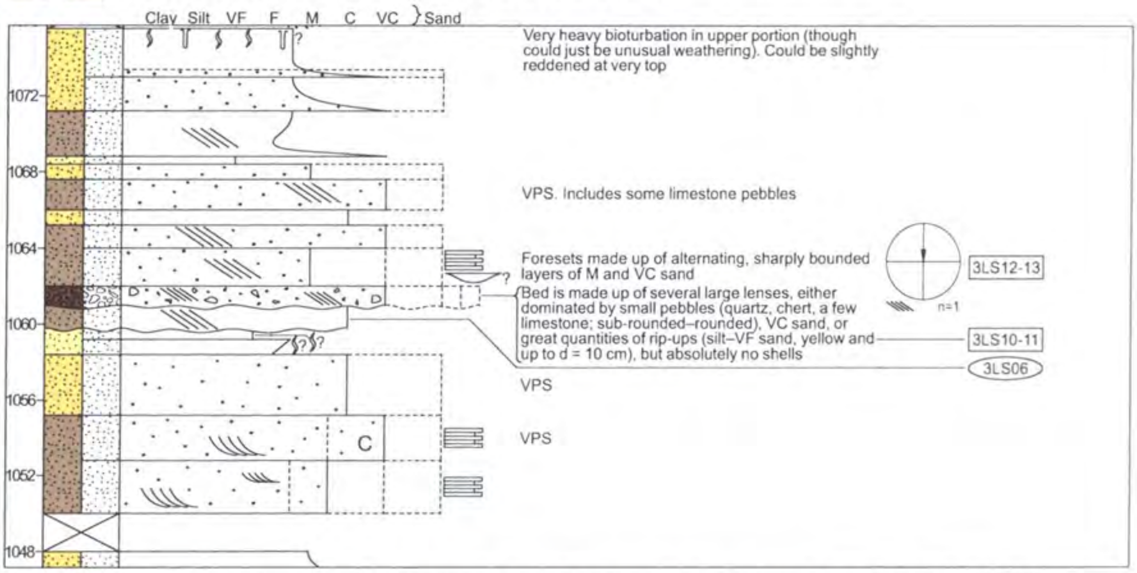


Fig. 3.57. A bed typical of this facies. From high on the Lúsera log (Vol.2, p.184).

Fig. 3.58. Cross-bedded, pebble and rip-up clast rich, matrix-supported conglomerate bed. From the mid-portions of the Monrepos log (photos '3MN9-10', Vol.2, p.196).

Fig. 3.59. Cobble sized limestone clast, and a few smaller pebbles, set in a very coarse sandstone matrix. From the upper portions of the Jaca log (photos '3JC10-11', Vol.2, p.114).

heterogeneous beds of this lithofacies probably explains why they were not more commonly observed, rather than it being the case that they were not often formed.

The coarse sand matrix, the matrix-supported texture, the lenticular nature of the beds, and the presence of cross-lamination and cross bedding all imply that the sediment was transported by strong unidirectional currents as bedload within channels, rather than as any kind debris flow (which must have a mud matrix; Nemec & Steel, 1984; Postma, 1990). The fact that this lithofacies has the same sedimentological characteristics whether part of the marine Belsué-Atarés Fm. or the non-marine Lower Campodarbe Fm. implies that it was formed by essentially the same depositional process that was operating in both settings.

Channelised unidirectional currents carrying a bedload of poorly sorted, coarse sands and pebbles, thought to have originated from a drainage basin outside the Jaca Basin, are most likely to be associated with a fluvial system. The existence of not completely broken marine fossils in some beds of this lithofacies implies that their deposition occurred in a marine basin. If the fossils had been reworked from pre-existing deposits by the fluvial system, then the vigorous currents required to transport the pebbles and form the dunes found within this lithofacies (velocities of 0.4 m/s or greater) would have broken the shells beyond recognition. The inference from this is that the fluvial system was feeding into a marine basin – presumably via a delta or fan delta. The pebbly and channelised nature of the beds suggests deposition in the submarine channels that exist on the proximal parts of a delta front, close to the debouching point of the river, or in mouth bars at the termination points of these channels (Sohn & Son, 2004). Their rare occurrence, and texture, implies that they are most likely to be the product of unusually high discharge events in the river–delta system.

The existence of other beds of this lithofacies, lacking in marine fossils, well within the unambiguously non-marine Lower Campodarbe Fm. (Jolley, 1987) implies that their deposition occurred within the fluvial system itself, prior to entry into any marine basin. In this environment, the pebbly and channelised nature of the beds suggests deposition as lags either in the main river channels or in the distributary channels in a delta top setting. As is the case with the marine depositional environment described above, the rare occurrence and unusual sedimentological characteristics of this lithofacies suggests that it is most likely be the product of unusually high discharge events in the river system.

3.2.14 Clast-supported conglomerates facies

3.2.14.1 Occurrence and description

This lithofacies is very distinctive yet rare in occurrence – it only accounts for a few metres of thickness at the very tops of just two of the logged sections – the Yebra de Basa log (529 m – 666 m; Vol.2, p.81 – 82) and San Julián de Basa log (661 m – 675 m; Vol.2, p.89). At Yebra de Basa, beds of this lithofacies can be seen in both the Lower Campodarbe Fm. (**Fig. 3.60**), and the Belsué-Atarés Fm. (**Fig. 3.61**) with exactly the same sedimentological characteristics (except for some thickness differences and a few fossils).

Beds of this lithofacies always occur singly, though may contain crude internal lens-shaped beds of no more than 10 m lateral extent. They are also usually relatively thick – up to around 5 m (**Fig. 3.62**) – but can be much thinner (down to 0.4 m). Erosive bases are very common. The beds found in the Lower Campodarbe Fm. were around 2 – 3 times thicker than those in the Belsué-Atarés Fm. Superb exposure at the top of the Yebra de Basa log revealed the beds of this facies there to be planar and laterally extensive over hundreds of metres (though sometimes quite variable, in terms of clast sizes and internal bedding, along their lateral extent).

The conglomerates contain a matrix of coarse to very coarse sand, which was never seen to be graded and always very poorly sorted. As well as this, occasional lenses of pebble-free coarse sandstone, usually no more than a couple of metres in lateral extent and a few tens of centimetres high, were also occasionally present. No depositional structures, such as a clast alignment fabric, were observed in the conglomerates, although tabular cross-lamination was occasionally seen in the sandstone lenses.

The only trace fossil noted in this facies was a single instance of borings into a calcareous sandstone pebble (**Fig. 3.63**). R. Goldring (pers. comm., 2003) noted that these were mollusc borings, and are typical of *Gastrochaenolites*. Although the pebble could have been bored at any stage during its transport, the 'mouths' of the borings do not appear to be have suffered any rounding off, so it seems likely that the boring occurred shortly before or just after the final deposition of the pebble.

Fossils are very rare in this facies. Indeed, the only examples found were a few fragmented miscellaneous shells and oyster shells in a single bed of the Belsué-Atarés Fm. at San Julián de Basa (667 m – 669 m; **Fig. 3.63**; Vol.2, p.89).

Clast-supported conglomerates facies

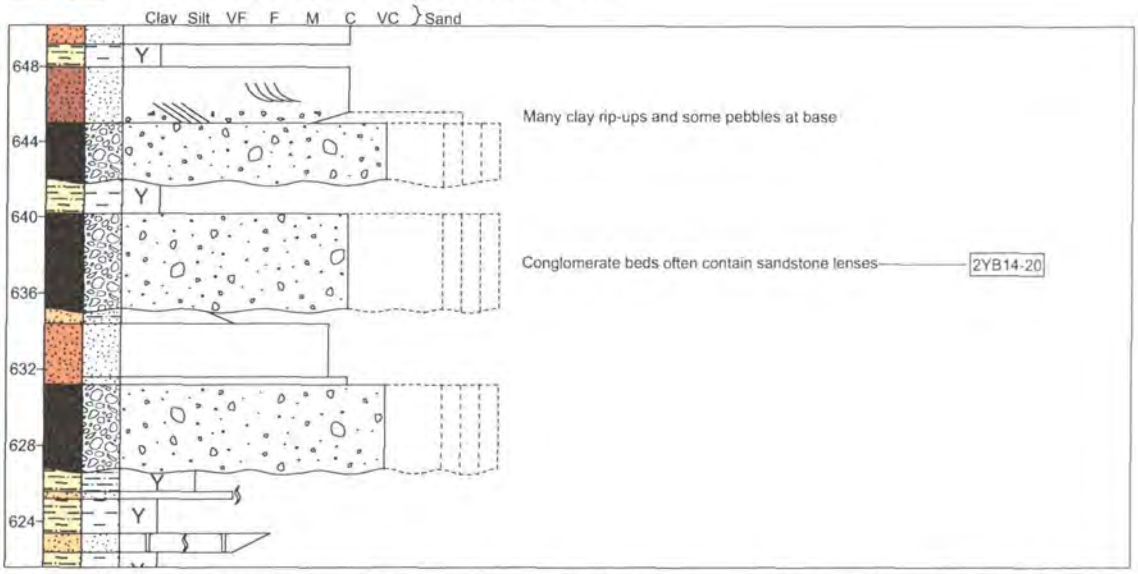


Fig. 3.60. Beds of this facies in Lower Campodarbe Fm. From Yebra de Basa log (Vol.2, p.82).

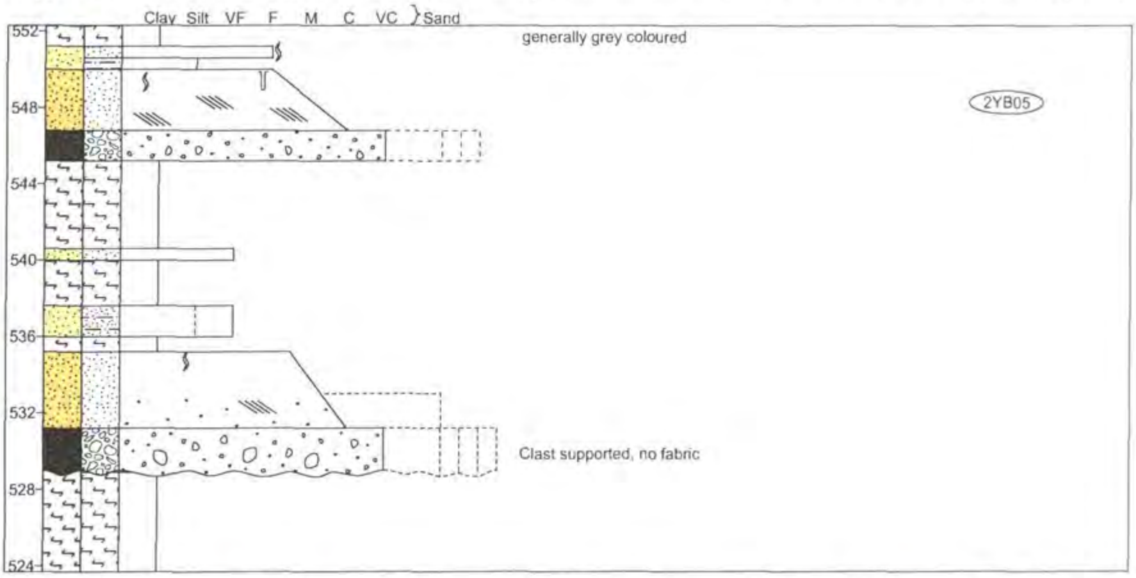


Fig. 3.61. Beds of this facies in Belsué-Atarés Fm. From Yebra de Basa log (Vol.2, p.81).

Fig. 3.62. A 5 m thick bed, in Lower Campodarbe Fm. Some clast size sorting (arrows mark lenses of cobble clasts). No imbrication. From Yebra de Basa log (photos '2YB14-20', Vol.2, p.82).

(Clast-supported conglomerates facies, continued)

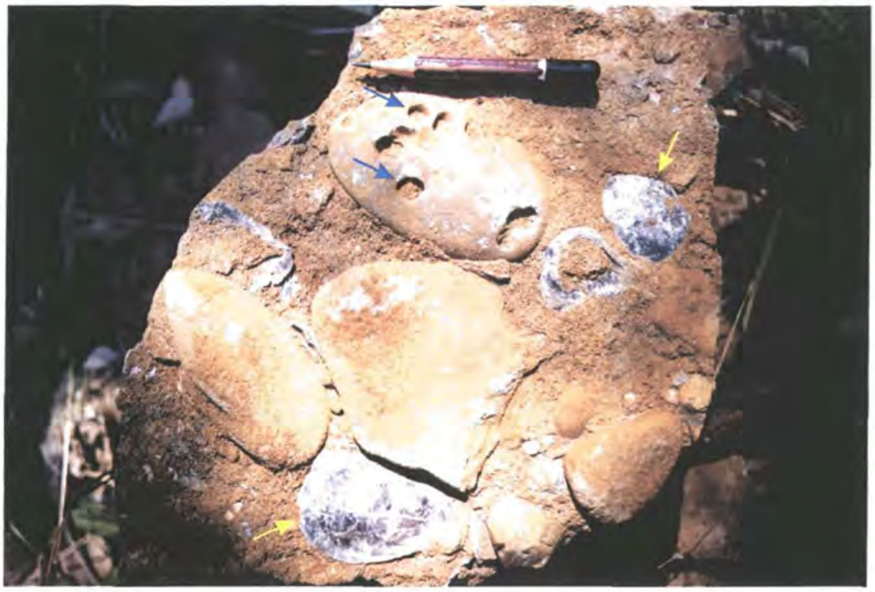


Fig. 3.63. Mollusc borings into a calcareous sandstone pebble (arrowed), and oyster shells (also arrowed). From close to the top of the San Julián de Basa log (off section).

Fig. 3.64. Conglomerate with poor sorting (clasts vary from small pebble up to cobble size) and a sandstone lens (arrowed). No imbrication. From upper portions of the Yebra de Basa log (photos '2YB6-7' Vol.2, p.80).

Fig. 3.65. A better-sorted, massive bed of large pebble and cobble, clast-supported conglomerate. From high on the Yebra de Basa log (off section).

Clasts in the conglomerate vary from sub-angular to well rounded, come in all sizes right up to cobble size (diameter greater than 64 mm; **Fig. 3.64** & **Fig. 3.65**), and are always in contact with one another, giving a clast-supported texture. Most are of limestone and sandstone lithologies (which were not recognised as originating from within the Jaca Basin), although a few small and rare exotic clasts of igneous and metamorphic origins were noted. A degree of size sorting was observed amongst the clasts, with the largest ones often being restricted to lenses of only a few metres lateral extent, and a few tens of centimetres vertical thickness.

3.2.14.2 Interpreted depositional processes and environment

This facies is a product of the transport and deposition of large quantities of coarse, very poorly sorted material. The texture of the conglomerates – clast-supported, with a very coarse sandstone matrix and no clast alignment fabric – suggests that they were transported via non-cohesive, chaotic flows driven by either a surge of water (sheetflood) or instability due to gravity – gravity-driven grain flow (Nemec & Steel, 1984; Postma, 1990).

The form that these beds take – laterally extensive (though variable along their lateral extent) – indicates that these chaotic flows were widespread in nature and not confined by channels etc. The fact that the beds always occur singly, separated by other lithofacies, suggests that each was the product of a single large-scale event. Occasionally observed crude sorting of clasts into horizons and lenses within each bed may record elements of localised flow surging and waning within each major depositional event. Cross-laminated sandstone lenses record times when the flow was reduced, at least locally, to small channels in which rippled sands were deposited (Nemec & Steel, 1984).

Although this lithofacies was found in both the marine Belsué-Atarés Fm. and non-marine Lower Campodarbe Fm., there were no obvious sedimentological differences between the two (besides thickness differences, and a few rare marine fossils and mollusc borings). From this it is inferred that the depositional processes that operated in both settings were very similar, and that marine reworking was not significant.

The well-rounded extrabasinal pebbles, including igneous and metamorphic types that could only have come from the Pyrenean axial zone (Jones, 1997), were most likely transported into the Jaca Basin via a fluvial system. However, the unconfined nature of the conglomerate sheets, and their largely chaotic internal structure, indicates that the depositional process was not restricted to channels. These unrestricted flows were partly deposited in terrestrial conditions, and partly in marine conditions. In the marine setting, a few oysters and other shells were picked up, and some of the pebbles bored by molluscs.

The most likely depositional environment in which these processes could occur is that of an alluvial fan that was partly prograding into a marine basin (Sohn & Son, 2004). The clast-supported, chaotic nature of the conglomerates implies that material was carried down from the apex of the fan via sheetfloods, caused by severe rainfall events in the hinterland. The cross-laminated sandstone lenses indicate that as the sheetfloods waned, periods of streamflow occurred. The similar texture and lateral extent of the marine conglomerates suggests that when the conglomeratic material reached the sea, it continued its down-fan movement via unconfined gravity driven grain flows, in a manner that was analogous to the subaerial sheetfloods. This process resulted in the building of a fan delta out into the marine basin. The fact that the beds of marine conglomerate are 2 – 3 times thinner than their non-marine equivalents is probably due to the radiating and expanding nature of the flows as they progressed down the alluvial fan and fan delta front. Other than the incorporation of a few marine fossils, and mollusc borings, there is no evidence of marine processes reworking the conglomerates.

A more complete discussion of the significance of this important lithofacies for the Jaca Basin will be given in Chapter 5.

3.2.15 Grey and yellow clays and silts facies

3.2.15.1 Occurrence and description

This facies occurs quite widely across the Jaca Basin, on approximately two out of every three logs, and makes up an average of a few tens of metres of thickness per log. It occurs in the Belsué-Atarés Fm. and in the Lower / Middle Campodarbe Fm., with no distinctive variations in character. In the Belsué-Atarés Fm., it usually only occurs within 100 m of the boundary with the Lower / Middle Campodarbe Fm., although can sometimes be seen much further down the section (e.g. 210 m – 364 m at Atarés; Vol.2, p.118 – 119).

The best examples of this facies from the Lower Campodarbe Fm. can be seen on the northern margin of the Jaca Basin, at: Ligüerre de Ara (102 m – 285 m; Vol.2, p.56 – 57), Fanlillo (450 m – 491 m; **Fig. 3.66**; Vol.2, p.75), Yebra de Basa (560 m – 667 m; Vol.2, p.81 – 82), and Bernués (238 m – 432 m; Vol.2, p.99 – 101). The best examples of this facies from the Belsué-Atarés Fm. again come from the northern basin margin, at: Albella (366 m – 538 m; Vol.2, p.52 – 54), and Atarés (210 m – 364 m; **Fig. 3.67**; Vol.2, p.118 – 119).

The grey or yellow colour (**Fig. 3.68**) and non-calcareous composition of this lithofacies distinguishes it from the other fine-grained lithofacies of the Jaca Basin – the three marly lithofacies (sections **3.2.1** – **3.2.3**), and the brightly coloured clays and silts facies (section **3.2.16**). However, gradational relationships between all these fine-grained lithofacies were commonly observed. Indeed, colour gradation was also commonly observed within this lithofacies, with the typical trend being a grey colouration low down in the section, then becoming increasingly yellow upwards. Pure grey beds are however always restricted to the Belsué-Atarés Fm., which provided a useful constraint on formation boundaries in poorly exposed areas. It is also worth noting that in areas of marl outcrop with significant vegetation cover, the modern soil-forming processes often imparted a yellow colouration to the uppermost metre of the marls that, without care, could be mistaken for an outcrop of this facies.

The thicknesses of accumulations of this facies vary greatly between logs and between beds, from as little as 0.4 m right up 40 m. The beds are always planar and laterally extensive over the extent of the exposures (tens to hundreds of metres). The thickest accumulations by far are of clays, which are apparently homogenous and always unlithified. Silts may be present as very thin interbeds within the clays (<20 cm thick), or as significant beds in their own right.

Because of their completely unlithified nature, it was not possible to observe primary sedimentary structures or bioturbation in the clay lithologies. However, the more competent silt units commonly contain parallel-lamination (**Fig. 3.69**) and bioturbation up to 'moderate bioturbation' levels (Taylor & Goldring, 1993). Occasionally associated with this bioturbation is yellow/grey colour mottling, where the fills of the traces have a different colour or hue to that of the host rock. Single occurrences of an unbroken gastropod, a bryozoan, an unbroken *Chlamys*-type bivalve and a piece of plant debris were found in beds of this lithofacies that belong to the Belsué-Atarés Fm.

Grey and yellow clays and silts facies

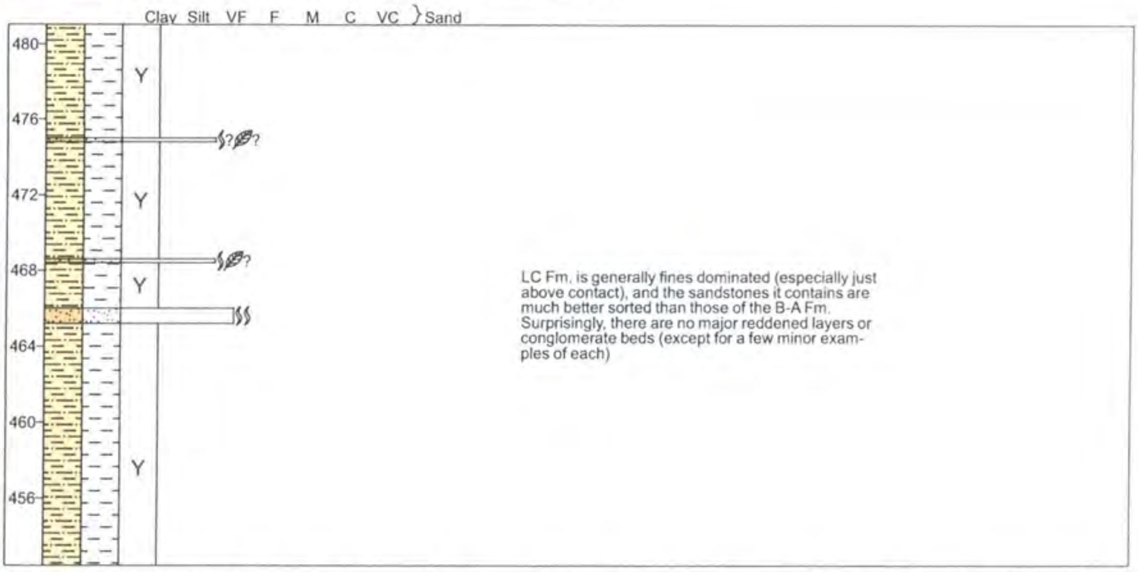


Fig. 3.66. Typical beds in Lower Campodarbe Fm. From top of Arrés log (Vol.2, p.135).

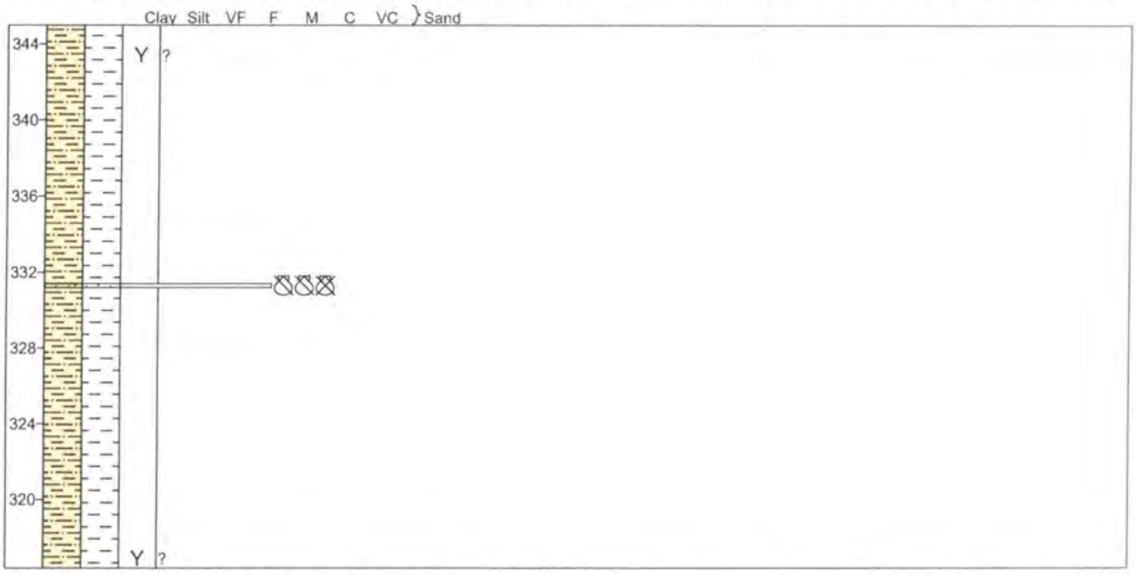


Fig. 3.67. Typical beds in Belsué-Atarés Fm. From middle of Arrés log (Vol.2, p.134).

Fig. 3.68. Thick yellow clays (and a thin wedge of grey marls). Looking towards upper Ligüerre de Ara log (off section).

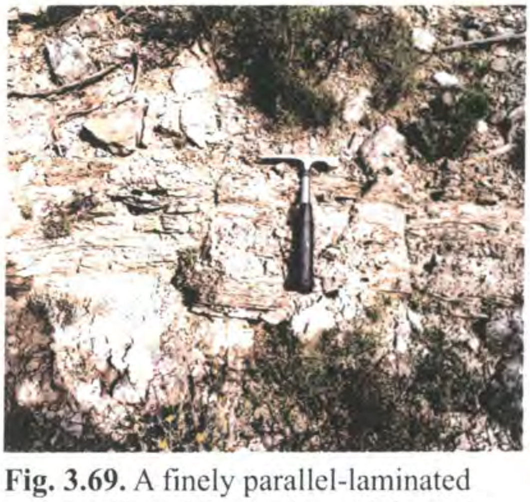


Fig. 3.69. A finely parallel-laminated yellow silt bed. From the middle of the Eripol log (photo '2EP10', Vol.2, p.145).

3.2.15.2 Interpreted depositional processes and environment

The presence of parallel-lamination but the lack of cross-lamination in the silts of this lithofacies implies that they settled out of suspension from a relatively static water column. Presumably, the clay lithologies of this lithofacies had a similar origin.

The spectrum of grey to yellow colours seen reflects variations in the composition of the clays and silts. A body of fine sediment is usually given a yellowish colouring by the oxidation / hydration of various iron minerals, caused by weathering (Tucker, 1996). Thus, the differently coloured clay and silt beds either had different pre-depositional iron contents (in terms of the quantity or chemical form of the iron), underwent different digenetic processes, or have undergone different modern-day weathering since their exposure. The latter two seem unlikely as beds of this lithofacies that are very close to one another in the vertical sequence, and are similarly exposed, were sometimes seen to have rather different colours (e.g. 466 m – 492 m at Atarés; Vol.2, p.116). Although soil formation processes may cause profound colour changes in terrestrial sediments, it seems extremely unlikely that such processes operated on the variously grey and yellow beds that contain unbroken marine fossils and are situated well within the marine Belsué-Atarés Fm.

If the colour differences in this lithofacies can be explained by primary compositional differences in the clays, then the general vertical colour trend from grey to yellow could be due to the yellow, more iron rich (and so denser) clay particles not making it as far down the depositional system as iron poor, grey clay particles.

Clays and silts settle out of suspension in a wide range of low-energy depositional environments, such as: deep ocean basin, off-shore, delta front, low-energy shoreline, lagoon, interdistributary bay and marsh on a delta top, lake and river floodplain. It is likely that this lithofacies was deposited in several of these environments; distinguishing between them will only be possible by looking at the other facies that this is found in associated with (section **3.3**).

3.2.16 Brightly coloured clays and silts facies

3.2.16.1 Occurrence and description

This facies is very common in the Jaca Basin, being seen throughout the logged portions of the Lower Campodarbe Fm. and Middle Campodarbe Fm. on most logs. It often occurs right from the base of the Lower / Middle Campodarbe Fm. upward, and as such provides a highly distinctive and useful indicator of the location of this boundary in poorly exposed areas.

Thick and well-exposed examples of this facies can be seen at Ligüerre de Ara (112 m – 160 m; **Fig. 3.70**; Vol.2, p.56) and Alastuey (114 m – 148 m; Vol.2, p.128) from the northern basin margin, and at Las Almunias (Upper) (60 m – 119 m; Vol.2, p.147 – 148) and Villalangua (172 m – 191 m; Vol.2, p.142) from the southern margin.

Most beds are thicker than 1 m, which is considerably thicker than the minimum thickness of the beds of grey and yellow clays and silts facies (0.4 m; section **3.2.15**). Individual beds tend not to exceed 10 m in thickness, although several beds of differing characteristics may be amalgamated into packages up to 25 m thick. Beds are always planar and laterally extensive over many hundreds of metres.

This facies consists of silt and clay grade sediments. Most often, the clays and silts occur separately, but are on occasions mixed together or thinly interbedded. Some minor sand content or thin interbeds are occasionally seen. Clay is the most common grainsize, but is always unlithified, making it impossible to observe sedimentary structures within the beds. The less common silt beds are however well lithified, and were seen to contain occasional parallel-lamination, and very common 'moderate bioturbation' and occasional 'high bioturbation' (Taylor & Goldring, 1993). The only fossils seen were very rare plant debris.

Colour is the most distinguishing feature of this facies, yet it varies considerably. Observed colours included: deep yellows, oranges, pinks and reds (**Fig. 3.71** & **Fig. 3.72**), rarely, almost magenta (**Fig. 3.73**) and, very rarely, green (e.g. 681 m – 683 m at Bentué de Rasal; Vol.2, p.222). Beds may be a mixture of any of the above colours; if so they are most commonly vertically stratified, with gradual (more common) or sharp contacts between each colour layer. In silt beds, mottling between any mixture of the above colours is common, and is always associated with bioturbation (**Fig. 3.74** & **Fig. 3.75**). This facies may grade into the less brightly coloured grey and yellow clays and silts facies (section **3.2.15**).

3.2.16.2 Interpreted depositional processes and environment

This lithofacies, like the grey and yellow clays and silts facies (section **3.2.15**), records the settling of clay and silt grade sediments out of suspension from a relatively

Brightly coloured clays and silts facies

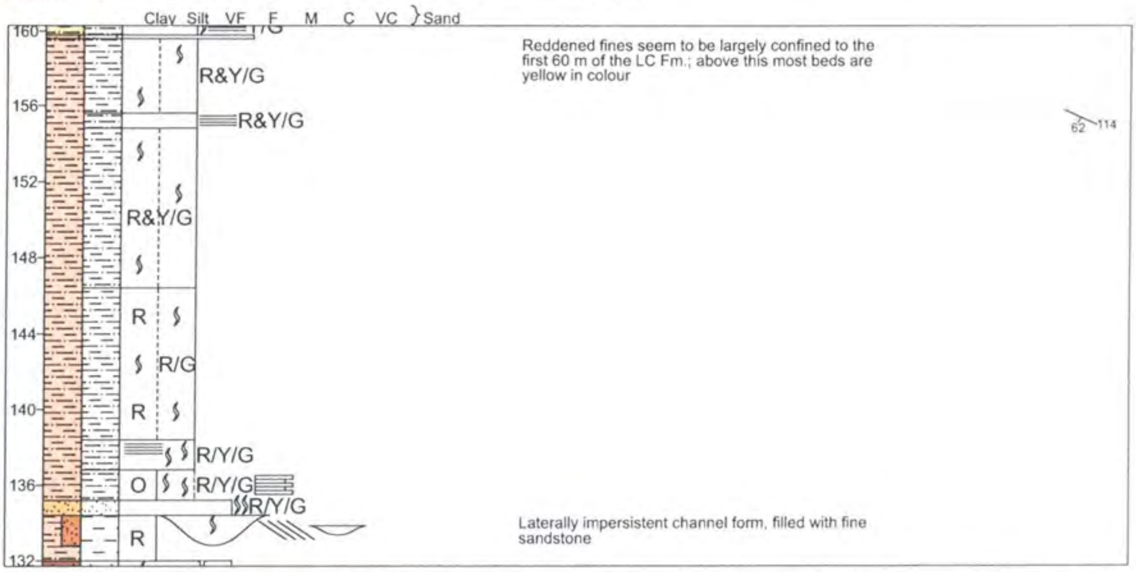


Fig. 3.70. Typical beds of this facies. From middle of Ligüerre de Ara log (Vol.2, p.56).

Fig. 3.71. Red clayey silts, grading upwards into grey and yellow clays and silts facies. (Hill is *ca.* 30 m high.) From lower half of Ligüerre de Ara log (photos '3LG7-11', Vol.2, p.56).

Fig. 3.72. A thin red silt bed, overlain by a yellow clay bed. From top of the Eripol log (photos '2EP18-19', Vol.2, p.146).

(Brightly coloured clays and silts facies, continued)

Fig. 3.73. An almost magenta coloured clay bed, beneath a clast-supported conglomerate. From the top of the Yerbra de Basa log (photos '2YB21-22', Vol.2, p.82).

Fig. 3.74. Fallen block from a well bioturbated silt bed, with red-yellow colour mottling. From high on the Martes log (photo '2MT1', Vol.2, p.134).

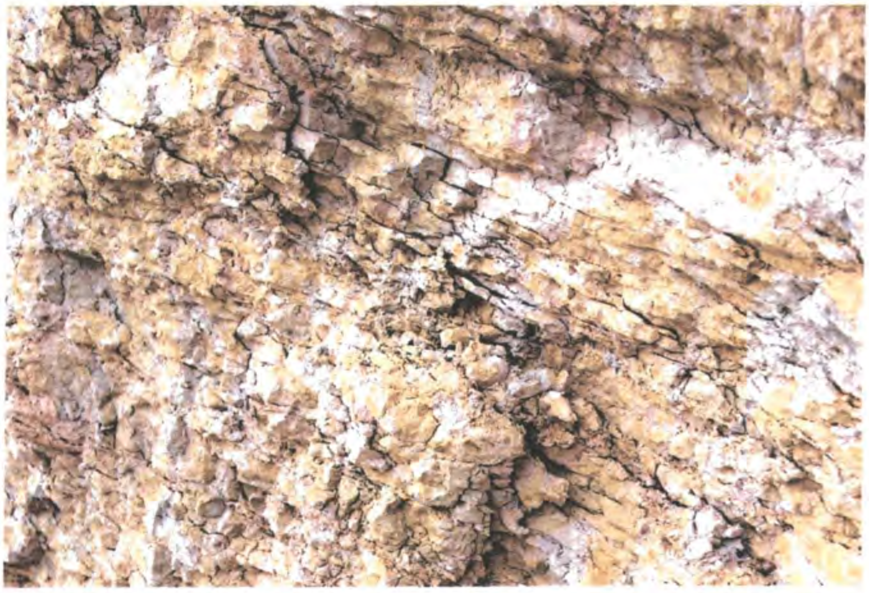


Fig. 3.75. Extreme red-yellow colour mottling in a silty clay bed. From the Middle Campodarbe Fm., near the Monrepos log (off section).

static water column. The parallel-lamination but lack of cross-lamination in the silts indicates that currents did not operate during deposition.

The process that gives this facies its broadly red colouration is haematisation. After the sediment has been laid down (and possibly during diagenesis), iron minerals within the sediment are oxidised, forming a red haematite (Fe_2O_3) coating on the detrital grains (Retallack, 1997). Colour mottling, which was always seen to be associated with bioturbation, occurs when the iron minerals in the fill of the traces are at different oxidation state to those in the rock that host the traces.

Although clays and silts settle out of suspension in a wide range of low energy depositional environments, haematisation almost always occurs in sediments laid down in hot, semi-arid continental environments (Retallack, 1997). This is because the heat and moisture allows the rapid weathering of minerals within the sediments, releasing iron that goes on to oxidise to haematite.

However, the red colouration is not pervasive throughout all the facies of the Lower / Middle Campodarbe Fm. (sections **3.2.16 – 3.2.20**), or even just throughout all the clay and silt beds, as many are yellow-coloured. It seems unreasonable to believe that there are sudden changes in the colour of the clay and silt beds because of abrupt changes in their original composition at deposition; rather it is more likely that the beds have been operated on by differing post-depositional processes. Differing diagenetic processes do not seem to be the answer as on many occasions adjacent beds of clay or silt, that would surely have experienced the same diagenesis, have very different colours (e.g. **Fig. 3.72**).

The post-depositional processes most likely to create vertically banded profiles of differing colours in previously homogeneous sediments, including reddening, is that of soil formation (Kraus, 1999). Red soils are readily created in tropical humid and semi-arid areas today (Retallack, 2001). However, beds of this facies do not have well-developed vertical profiles of different colours; rather many of the colour changes are fairly gradual, although some are abrupt. The best explanation for this is not that a homogenisation processes has occurred within the clays (e.g. repeated wetting and swelling, drying and cracking), as this would make all boundaries diffuse. Rather, it seems most likely that the soil forming processes which created the reddish colours and their gradual variations were not able to go to completion and create abrupt horizons of distinct colours.

Pedogenic processes, which take 2 – 30 thousand years to reach maturity (Kraus, 1999), are most likely to be interrupted by changes in climate or the deposition of fresh sediment. Changing climate does not appear to be the explanation here, as the red horizons reoccur again and again throughout the succession, more frequently than any changes in climate could occur and reoccur. Rather, it seems that fresh deliveries of sediment were arriving regularly, preventing the pedogenic processes from creating mature soils with well-developed vertical stratification.

The deposition of clay and silt grade materials from suspension, and the formation of partially stratified red soils under terrestrial conditions, most commonly occurs on river floodplains. The soils would be formed between floods. Their apparently immature profiles suggest that the floods, which would bring in new sediment and terminate the formation of the existing soil, occurred every few thousand years at least (Kraus, 1999). Channel migration and avulsion could also have contributed to the variations in sediment being supplied to the floodplain. The fact that the soils are red suggests that the climate was hot, and humid to semi-arid.

Jolley (1987) undertook a more detailed analysis of the palaeosols that occur throughout the Campodarbe Group succession in the Jaca Basin. The red or red/brown types with immature profiles discussed here were interpreted as fluvent entisols (Buurman, 1975). A depositional environment of a floodplain with periodic flooding and a fluctuating water table was inferred.

3.2.17 Very fine, colour-mottled sandstones facies

3.2.17.1 Occurrence and description

This is a very common lithofacies, occurring throughout the logged portions of the Lower Campodarbe Fm. and Middle Campodarbe Fm. on almost every log. The best examples of this facies come from the northern basin margin, at: Ligüerre de Ara (134 m – 286 m; Vol.2, p.56 – 57), Bernués (245 m – 384 m; Vol.2, p.99 – 100), and Binacua (321 m – 345 m; **Fig. 3.76**; Vol.2, p.126).

Beds tend to be thin (0.4 – 2 m), and occur singly, although occasionally two or more beds may be amalgamated into a small package. The geometry of beds is highly variable, ranging from planar and laterally extensive (for up to 100 m), to wedge-shaped and laterally inextensive (down to less than 10 m laterally). The most common grainsizes vary from silt up to fine sand, with very fine sand being the most common. The sands are always well sorted, and on rare occasions are normally graded. Parallel-lamination was occasionally observed in this facies; poorly developed tabular and

Very fine, colour-mottled sandstones facies

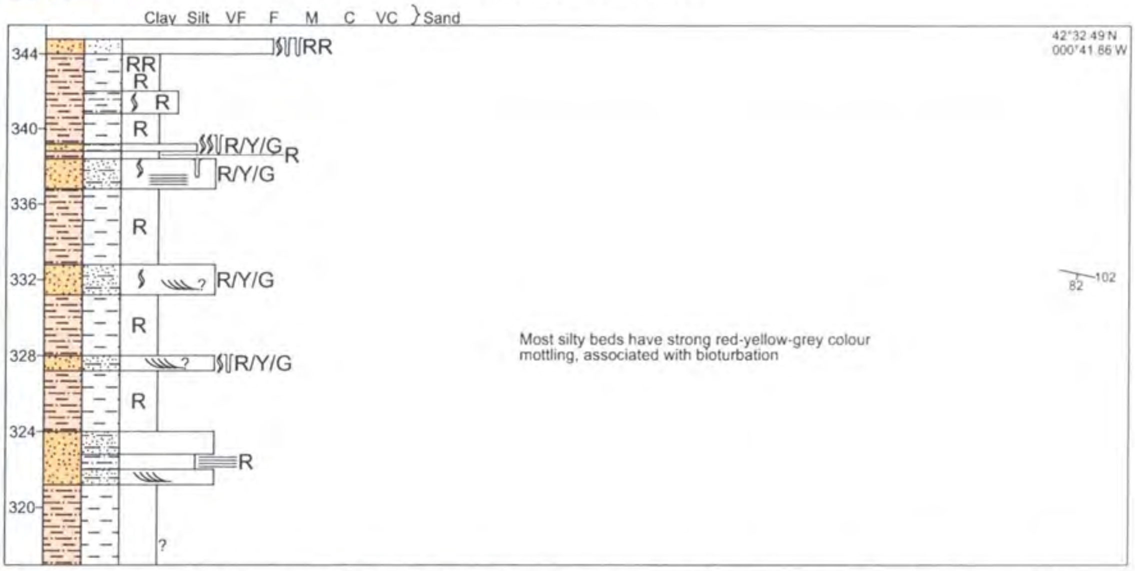


Fig. 3.76. Typical beds of this facies. From the top of the Binacua log (Vol.2, p.126).

Fig. 3.77. Red-yellow-greeny-grey colour mottling. From the lower half of the Bara log (photos '4BA5-6', Vol.2, p.153).

Fig. 3.78. Green (reduced iron) root traces (arrowed) in a red (oxidised iron) host rock. From near to the top of the Navasa log (off section).

trough cross-lamination, and desiccation cracks, are rare but present. Bioturbation of 'moderate bioturbation' levels is very common, and occasionally reached 'high bioturbation' levels (Taylor & Goldring, 1993). Vertical burrows were, however, rare. The only fossils noted were very rare plant debris.

These sandstones come in a distinctive range of yellows, oranges and reds. Colour mottling is very common, with both yellow-grey and red-yellow (with or without grey) types being common (**Fig. 3.77**). Rarely, the colour mottling depicts branching root-like forms, usually green, within a usually red host rock (**Fig. 3.78**).

3.2.17.2 Interpreted depositional processes and environment

The occasional parallel-lamination and rare tabular and trough cross-lamination indicate that this lithofacies was deposited either out of suspension from a relatively static water column, or by very weak unidirectional currents. Because the beds are relatively thin, the depositional process that formed them could not have been particularly long-lived, and also apparently operated over areas of variable lateral extent.

The common orange and red colours indicate that a degree of haematisation occurred in most beds. Bioturbation is also common, and frequently affects the colour of the rock, giving rise to colour mottling. One particularly distinctive form of this is the green, branching root-like traces in a red host rock. These occur because the red host rock contains abundant haematite (oxidised iron), whilst the green of the root traces is caused by reduction of the iron, due to the anaerobic decomposition of the root during early diagenesis (Retallack, 1997). This feature records root penetration, which implies plant growth on the sediment surface. This could only occur if sediment accumulation periodically stopped for a few tens of years or more.

Haematisation is most likely to occur in sediments laid down in hot, semi-arid continental environments (section **3.2.16.2**; Retallack, 1997). The continental environments most commonly associated with receiving small but frequently reoccurring deliveries of well-sorted, very fine sands, deposited by weak currents or out of suspension, is that of a river floodplain. During times of increased river flow (but not flood), sands may be delivered to the floodplain by crevasse splays in the levees of the river channel, creating sandy and silty lobes extending onto the floodplain (O'Brien & Wells, 1986). During times of flood when the levees are overtopped, suspended sediment, including sands, may be deposited on the levees and across the floodplains.

The grainsize of sediments deposited in this way tens to become finer with increasing distance from the main channel (Guccione, 1993). The desiccation cracks indicate that the sediments on the flood plain were able to dry out. The bioturbation and plant colonisation of the sands indicates that between periods of crevasse splaying or flooding, the sediments lying on the floodplain were colonised by plants and animals.

3.2.18 Symmetrically rippled, coloured sandstones facies

3.2.18.1 Occurrence and description

This is this rarest of all the defined lithofacies, only being present in small thicknesses (less than 20 m in total) on two logs from opposite ends of the Jaca Basin: Las Almunias (Upper) (60 m – 96 m; Vol.2, p.147) from the SE corner, and Martes (66 m – 85 m; **Fig. 3.79**; Vol.2, p.134) from the far NW corner. On the former it occurs in the Lower Campodarbe Fm., and on the latter in the Middle Campodarbe Fm.

The beds are always sharp based and can be quite thick (up to 4 m), and are sometimes amalgamated into packages of 2 – 3 beds that may be up to 6 m thick. Limited exposure meant that it was not possible to ascertain their typical lateral extent. Commonly the beds consist of thinly interbedded clays, silts and well-sorted sands, with very fine sand being the most common grainsize.

The feature that distinguishes this lithofacies is its ubiquitous symmetrical ripples (**Fig. 3.80**). These are commonly small – wavelengths of 3 cm or less, amplitudes of 5 mm or less – and not always well developed. The ripple crests were generally straight, although some bifurcations were noted (**Fig. 3.80**). Other depositional structures present are occasional flaser bedding and rare tabular cross-lamination. 'Moderate bioturbation' is very common, with occasional areas of 'high bioturbation' (Taylor & Goldring, 1993), particularly towards the tops of some of the beds (**Fig. 3.81**). No fossil content of any type was noted. This facies exhibits the range of yellow, pink and red colourations typical of beds of the Lower / Middle Campodarbe Fm.

3.2.18.2 Interpreted depositional processes and environment

The key depositional structures in this facies are the symmetrical ripples and flaser bedding. Symmetrical ripples are formed by oscillatory flow in a standing body of water, due to wind-formed waves on the water's surface. The small wavelengths (less

Symmetrically rippled, coloured sandstones facies

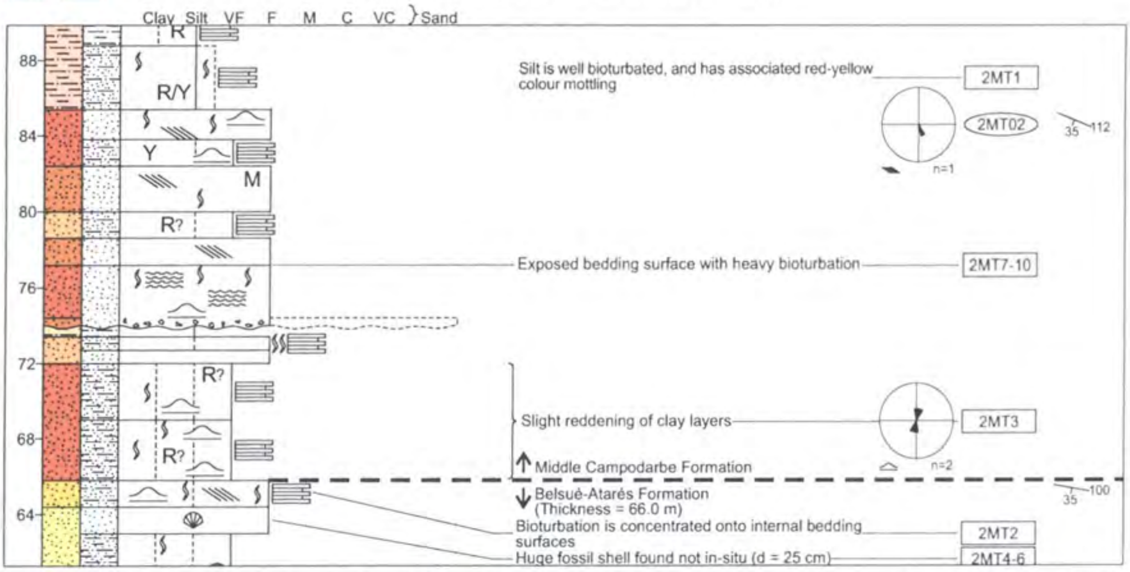


Fig. 3.79. Three beds typical of this facies. From upper half of Martes log (Vol.2, p.134).

Fig. 3.80. Bedding surface featuring very small-scale symmetrical ripples, including a few crest bifurcations (arrowed). From the upper half of the Martes log (photos '2MT7-10', Vol.2, p.134).

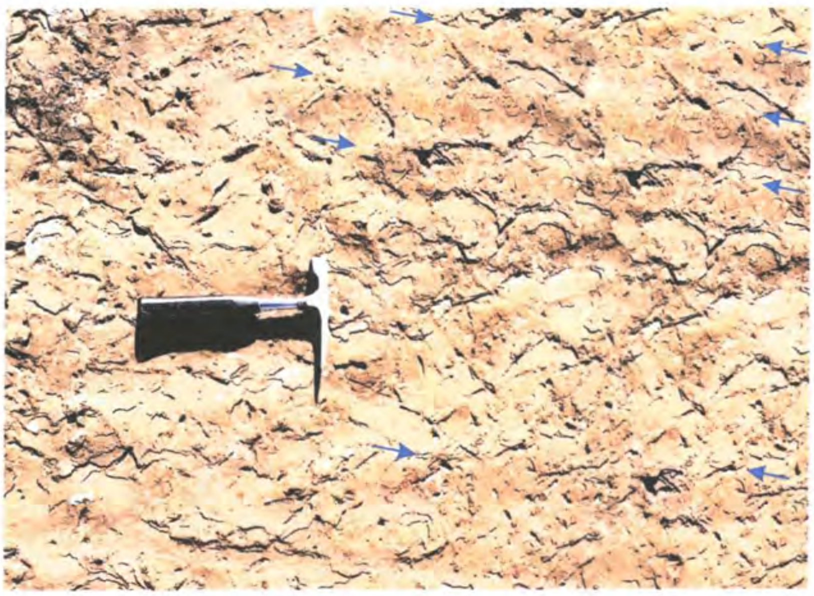


Fig. 3.81. An upper bedding surface with low-amplitude symmetrical ripples (ripple crests are arrowed) and moderate bioturbation. From the upper half of Martes log (photos '2MT7-10', Vol.2, p.134).

than 3 cm) and low wave amplitudes (less than 5 mm), in the generally very fine sands, indicate that the water depth was low (perhaps only a couple of metres) and/or the wave energy was low (Diem, 1985). The flaser bedding implies that the periods of higher wave energy, moving sand and silt around to form ripples, were separated by periods of low or zero wave energy, allowing mud deposition from slack water.

The colours exhibited by this facies – yellow, pinks and reds – indicate that iron minerals in the rock have been weathered and, where reddened, oxidised (forming haematite). These colours suggest that this lithofacies, like all others of the Lower / Middle Campodarbe Fm., were of terrestrial origin. In the Jaca Basin, all lithofacies of unambiguous marine origin, e.g. those that contain un-reworked marine fossils, do not display bright yellow, pink or red colours (sections **3.2.1 – 3.2.11**).

The symmetrical ripples, flaser bedding and sediment colour imply that this facies formed beneath a terrestrial body of water. The thicker beds / packages of this lithofacies (up to 6 m) are likely to have been formed in long-lived non-marine water bodies e.g. lakes. The thinner beds (down to 40 cm) probably result from deposition in more ephemeral water bodies, such as playa lakes or floods on river floodplains. Although there is essentially no minimum water depth in which the symmetrical ripples could have formed (Diem, 1985), the body of water must have had a large enough lateral extent for wind to create waves on its surface – perhaps several tens of metres or more parallel to the wind direction.

3.2.19 Fine, cross-laminated coloured sandstones facies

3.2.19.1 Occurrence and description

This lithofacies is common, being seen throughout the logged portions of the Lower / Middle Campodarbe Fm. on around two out of every three logs. Probably the best examples of it come from the Bara log (179 m – 304 m; **Fig. 3.82**; Vol.2, p.152 – 154).

Beds are usually relatively thin, often being no more than 3 m thick. Most commonly they occur singly, although very rarely they are amalgamated into packages of two beds, which may be up to 5 m thick. The beds are planar to wedge shaped, and tend not to be laterally extensive over more than 20 m. On rare occasions, erosive bases were observed. Grainsizes vary from very fine to medium sand, with fine sand being

Fine, cross-laminated coloured sandstones facies

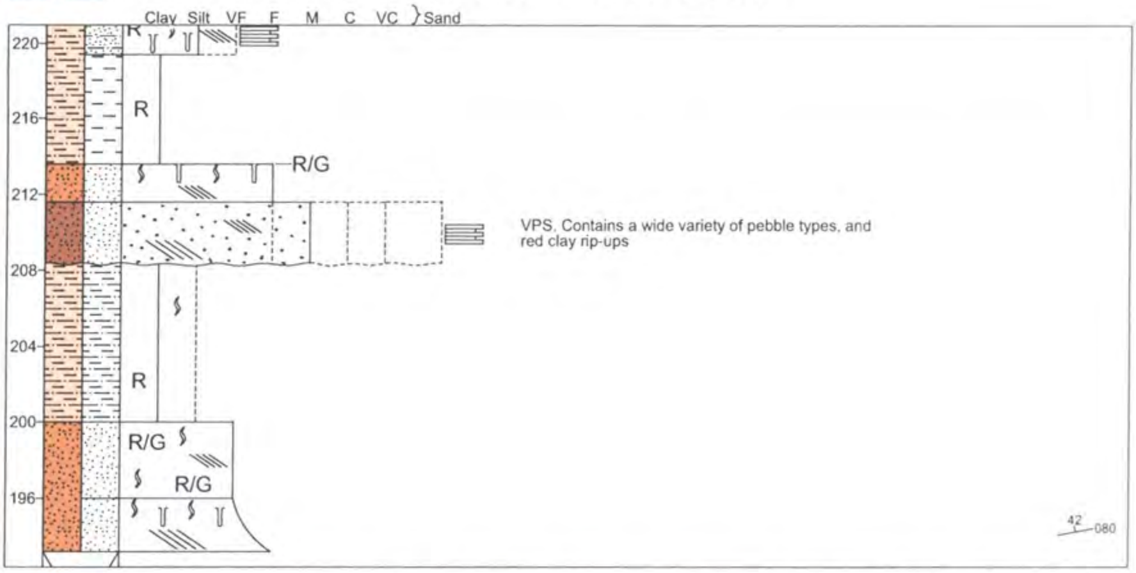


Fig. 3.82. Three beds typical of this facies. From lower half of Bara log (Vol.2, p.153).

Fig. 3.83. Trough cross-lamination. From the top of the Martes log (photos '2MT12-13', Vol.2, p.135).

Fig. 3.84. Burrows extending down from the top of a bed. From close to the top of the Las Almunias (Upper) log (off section).

Fig. 3.85. A large and well-preserved fossilised log, on a bedding surface that also features some clay rip-up clasts (arrowed). From the top of the Martes log (photos '2MT14-15', Vol.2, p.135).

the most common. The sands are moderately sorted, and fining upwards was occasionally observed.

This lithofacies is characterised by the very common occurrence of tabular cross-lamination, and the fairly common occurrence of trough cross-lamination (**Fig. 3.83**). Parallel-lamination was also occasionally seen. Rip-up clasts of clay lithologies are occasionally present, along with a few, rare, quartz pebbles. Both are most common in erosively-based beds, and are usually concentrated towards the base of each bed.

Bioturbation is generally at 'low bioturbation' to 'moderate bioturbation' levels, but occasionally reaches 'high bioturbation' levels on the upper surfaces of some of the beds (**Fig. 3.84**; Taylor & Goldring, 1993). The only fossil content in this lithofacies is very rare plant debris (**Fig. 3.85**).

Beds of this facies normally come in a range of greys to pale yellows, although occasional pale pinks and rare reds were noted on some sections. Occasionally, colour-mottling is associated with the bioturbation: yellow-grey is the most common type, but rarely, shades of red, and very rarely, shades of green, are present (e.g. 626 m – 629 m on the Navasa log; Vol.2, p.96).

3.2.19.2 Interpreted depositional processes and environment

The very common tabular cross-lamination and the fairly common trough cross-lamination that characterise this facies were formed by the migration of straight-crested and curve-crested ripples under the influence of a unidirectional current. The presence of erosive bases and rip-up clasts show that these currents were occasionally strong enough to erode into underlying or surrounding deposits. The occasional fining upwards within beds indicates that sometimes the depositional currents waned in strength.

Bioturbation was often much more concentrated towards the upper surfaces of the beds than within the rest of their volume. The fact that organisms were not able to thoroughly bioturbate the sediments until the depositional process had slowed or ceased suggests that the deposition was relatively rapid process.

The yellow, occasional pink and rare red colours exhibited by this facies indicate that iron minerals within the rock have been weathered and, where reddened, oxidised (forming haematite). These colours suggest that this lithofacies, like all others of the Lower / Middle Campodarbe Fm., were of terrestrial origin. In the Jaca Basin, all lithofacies of unambiguous marine origin, e.g. those that contain un-reworked marine fossils, do not display bright yellow, pink or red colours (sections **3.2.1 – 3.2.11**).

The rapid deposition of relatively thick beds of fine, well-sorted sands (in which bioturbation is most intense in the uppermost portions), by unidirectional currents (cross-laminated) that sometimes waned in strength (fining upwards), in a terrestrial setting (yellow / orange / red colouration) is most commonly associated with the action of fluvial systems (Ramos *et al.*, 1986). The variously shaped beds, from planar to wedge-shaped and laterally inextensive, with or without erosive bases, suggests that this lithofacies was laid down in a number of different sub-environments within the fluvial system – such as: in the main river channel during relatively low velocity flow (less than 0.7 m/s for fine sands; Ashley *et al.*, 1990), in a small channel in a braided river system, or in the proximal parts of a crevasse splay lobe, formed when an almost-flooding river splits the tops of its levees (Leeder, 1974). The only way to determine which of these sub-environments this lithofacies was deposited in is to look at the other lithofacies that it is found in association with (section **3.3**).

Jolley (1987) found abundant fine, bioturbated sandstones in the Campodarbe Group of the Jaca Basin, and interpreted some to have formed in fluvial channels and others to have formed in overbank settings.

3.2.20 Medium, cross-bedded coloured sandstones facies

3.2.20.1 Occurrence and description

This lithofacies is common, appearing in the Lower / Middle Campodarbe Fm. on about one in two logs from the northern basin margin, and on about two in three logs from the southern basin margin. Good examples can be seen on the northern margin at Ligüerre de Ara (121 m – 132 m; **Fig. 3.86**; Vol.2, p.56), and on the southern margin at Pico del Águila (308 m – 330 m; Vol.2, p.201) and Bentué de Rasal (683 m – 692 m; Vol.2, p.222).

This facies forms thick beds – usually not less than 1 m thick, and up to 5 m (**Fig. 3.87**). They almost always occur as single beds, although on very rare occasions two beds may be amalgamated into packages that may be up to 10 m thick. The beds themselves may be planar and laterally extensive (over more than 100 m), but highly variable along their lateral extent (in terms of grainsize, clast content and sedimentary structures), down to laterally inextensive channel-like forms (20 m across or less). Erosive bases are common – but far from ubiquitous.

Medium, cross-bedded coloured sandstones facies

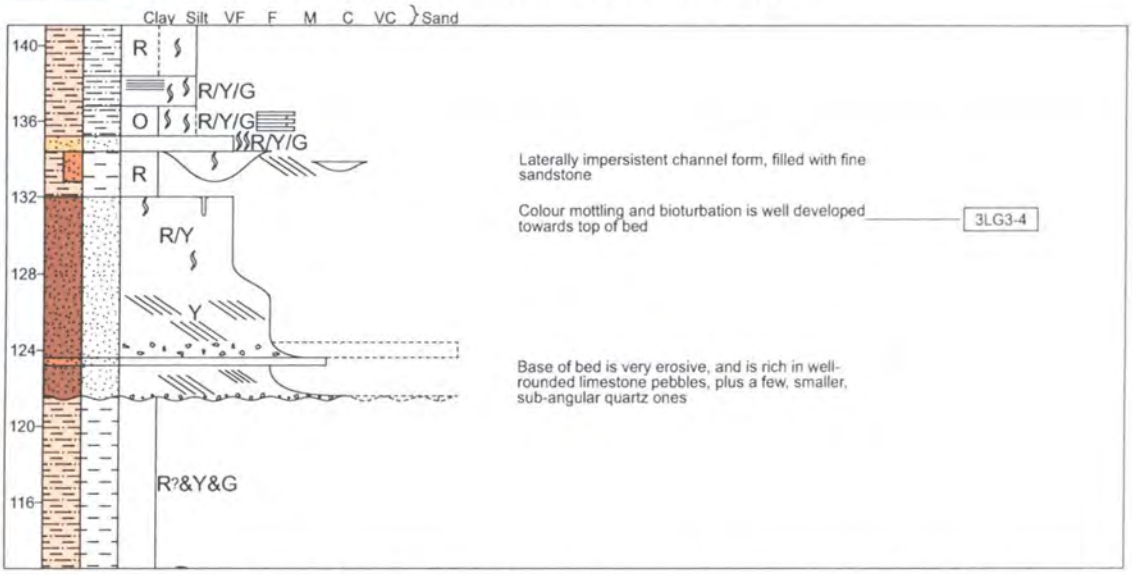


Fig. 3.86. A typical bed of this facies. From middle of Ligüerre de Ara log (Vol.2, p.56).

Fig. 3.87. A thick and fairly laterally extensive bed of this facies. From the Middle Campodarbe Fm. close to the Monrepos log (off section).

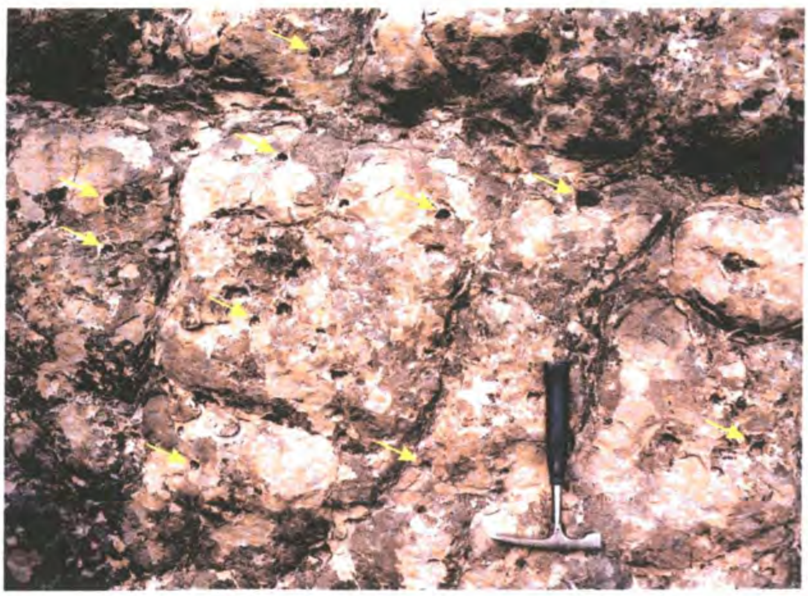


Fig. 3.88. Upper surface of a bed of this facies, featuring red-orange colour mottling and vertical burrows going into it (arrowed). From the middle of the Ligüerre de Ara log (photos '3LG3-4', Vol.2, p.56).

A wide range of grainsizes is commonly associated with this facies – from fine to very coarse sand, with the most common being medium sand. Fining upwards within beds is very common, and is occasionally strongly developed (e.g. a drop in a whole grainsize in a few tens of centimetres). The sands are well sorted, with only the coarsest beds being moderately sorted or occasionally poorly sorted.

Tabular cross-bedding is very common, and trough cross-bedding is fairly common. On a smaller scale, tabular cross-lamination was also fairly common, but trough cross-lamination was only rarely observed. On very rare occasions, load structures were seen at the base of some beds.

Bioturbation is common in this lithofacies. Although sometimes it is evenly distributed throughout beds at 'low bioturbation' to 'moderate bioturbation' levels, fairly commonly it is concentrated in the upper portions of the beds, and particularly on the upper surfaces, reaching 'high bioturbation' levels (Taylor & Goldring, 1993). Possible *Beaconites* traces were identified (R. Goldring, pers. comm., 2003). Although vertical burrows were comparatively rare, they too are often concentrated in the upper portions of beds. No fossils of any sort were observed in this lithofacies.

Clay rip-up clasts, from 4 – 64 mm across, are common. Small pebbles were fairly commonly seen: well-rounded limestones pebbles were the most common; sub-rounded to sub-angular quartz pebbles were also present, but rare. Neither the limestone nor sandstone pebbles were recognised as having originated from rocks presently outcropping in the Jaca Basin, and so are thought to be of extrabasinal origin. Both pebbles and rip-up clast were commonly concentrated at the bases of beds, and especially so in beds with erosive bases.

This facies is normally seen in a range of grey and pale yellow colours in outcrop, although occasionally pinks and reds were also seen. Red-yellow colour mottling was fairly rarely seen, but always associated with bioturbation (**Fig. 3.88**).

3.2.20.2 Interpreted depositional processes and environment

The very common cross-bedding present in this lithofacies records the migration of straight-crested and curve-crested dunes or bars, under the influence of a strong unidirectional current (faster than 0.5 m/s for medium sand; Ashley *et al.*, 1990). The less common and smaller-scale tabular and trough cross-lamination record the migration of straight-crested and curve-crested ripples, respectively, during times of lower flow velocity (less than 0.5 m/s; Ashley *et al.*, 1990). The common occurrence of erosive bases and rip-up clasts indicates that these currents were often strong enough to erode into underlying and surrounding finer sediments. Fining upwards is very common and may reflect the lateral migration of a current (e.g. the lateral migration of a channel), causing the flow strength experienced at a particular location to wane, or simply the waning of flow within a channel.

Bioturbation was often seen to be much more concentrated on the upper surfaces of beds than within the volume of the bed. The fact that organisms did not have time to thoroughly bioturbate the sediments until the depositional process had slowed or ceased suggests that the deposition occurred rapidly.

The presence of extra-basinal pebbles implies that the depositional system responsible for this lithofacies was sourced, at least partly, from outside the Jaca Basin. A long sediment transport path would also explain why the sediments, and particularly the coarser beds, are surprisingly well sorted.

The yellow, occasional pink and rare red colours exhibited indicate that iron minerals within the rock have been weathered and, where reddened, oxidised (forming haematite). These colours suggest that this lithofacies, like all others of the Lower / Middle Campodarbe Fm., were of terrestrial origin. In the Jaca Basin, all lithofacies of unambiguous marine origin, e.g. those that contain un-reworked marine fossils, do not display bright yellow, pink or red colours (sections **3.2.1** – **3.2.11**).

The rapid deposition (bioturbation concentrated on upper surfaces) of thick beds (up to 10 m) of fine to very coarse sands containing extrabasinal pebbles, by strong unidirectional currents (cross-bedded; flow greater than 0.5 m/s) in a terrestrial setting (yellow / orange / red colouration) is most likely to occur in the channels of a fluvial system (Ramos *et al.*, 1986). The very common fining upwards within beds most likely indicates that the channels migrated laterally and/or that the flow within them waned. The clay rip-up clasts suggest that the fluvial system eroded fines-dominated overbank areas, most likely due to lateral migration of the channel. The extrabasinal pebbles imply that the fluvial system was, at least partly, fed from a drainage area outside to the Jaca Basin.

Jolley (1987) undertook a detailed study of the sandstones that belong to the Campodarbe Group of the Jaca Basin. The coarser, cross-bedded units of limited lateral extent were interpreted as the infills of bedload fluvial channels. The fluvial system to which these belonged varied from being stable and sinuous to regularly avulsing, and was interpreted to have been sourced in the Pyrenean axial zone.

3.3 Facies associations and depositional environments

The aim of this project is to understand the way in which the growing structures within the Jaca Basin (**Fig. 1.3**) affected the coeval sedimentation. The effect of the structures is reflected in the depositional environments developed in the basin at the time, and in particular their positioning relative to the growing structures and any changes in the environments through time. The depositional environments recorded in the syntectonic infill of the basin, including their positioning and vertical changes, are discussed for the various sectors of the basin (**Fig. 1.2**) in subsequent chapters (Chapters 4 – 9). However, in order to do this, it is first necessary to identify the depositional environments and determine their nature from the rock record. This was achieved by analysing the lithofacies to define a number of facies associations.

Each facies association was defined by identifying lithofacies that commonly occur interbedded with one another or laterally adjacent to one another. If each lithofacies records the action of a particular depositional process, then each group of lithofacies that commonly occur together – a facies association – records the depositional processes that occurred in a particular depositional environment. **Fig. 3.2** summarises which of the twenty lithofacies make up the twelve defined facies associations, including an indication of whether each was a major (> 10% by volume), minor (1 – 10%), or rare (0.1 – 1%) component. It should be noted that because the infill of the Jaca Basin has been divided into lithofacies rather than facies, many of the lithofacies occur across several different facies associations – because a given depositional process may operate in more than one depositional environment. **Fig. 3.3** provides a visual summary of the different depositional environment that existed in the Jaca Basin, and the various depositional processes (lithofacies) that operated within them.

In this section, the facies associations are presented in a broadly 'distal' to 'proximal' order: the first facies association (section **3.3.1**) was interpreted to represent the offshore parts of a marine basin, whilst the last one (section **3.3.12**) records a fluvial system in a terrestrial setting. The first six facies associations (sections **3.3.1** – **3.3.6**) represent increasingly shallow water depths in a marine basin. The next three (sections **3.3.7** – **3.3.9**) are the product of unusual, locally occurring shallow to marginal marine environments. The final three (sections **3.3.10** – **3.3.12**) were formed by alluvial systems in non-marine settings.

3.3.1 FA1: offshore marine marls

The major component of this facies association is pure marls facies (section **3.2.1**); silty and sandy marls facies is a minor component (section **3.2.2**). Both lithofacies are found in thick, monotonous accumulations, and sometimes grade into one another. A good example of this very commonly occurring facies association can be seen in the lower half of the Bentué de Rasal summary log (**Fig. 3.89**; Vol.2, p.44).

Within these two lithofacies there is very little evidence of current activity, and little if any clastic material above clay-grade is recorded (sections **3.2.1** and **3.2.2**). The calcareous mud that makes up the majority of these two lithofacies originated from planktonic microfauna, and arrived at the seabed by settling out of suspension. Occasionally the sediments on the seabed were bioturbated.

This facies association is interpreted as accumulating in a deep, offshore marine environment, far away from any sources of clastic input and experiencing very little current activity, but with an abundant planktonic microfauna.

3.3.2 FA2: offshore–transition zone marls and sandstones

The major components of this facies association are silty and sandy marls facies (section **3.2.2**) and marly silts and sandstones facies (section **3.2.3**); pure marls facies (section **3.2.1**), very fossiliferous sandy marls and sandstones facies (section **3.2.4**), and fine, well bioturbated sandstones facies (section **3.2.5**) are minor components. The three marly lithofacies tend to form thick, monotonous accumulations, which may grade into one another, with occasional single beds of the two sandy lithofacies occurring within them. A good example of this fairly common facies association makes up the lower half of the Albella summary log (**Fig. 3.90**; Vol.2, p.8).

The pure marls facies, the silty and sandy marls facies, and the marly silts and sandstones facies all record calcareous clay settling out of suspension, with current activity and clastic input varying from zero through to quite significant (sections **3.2.1**, **3.2.2** and **3.2.3**). Evidence of both weak unidirectional currents (probably seabed currents) and oscillatory currents (wave-related i.e. created at depths just above normal wave base) exists. Although *Nummulites* are common throughout this facies association, at times they became extremely abundant – as recorded by the thicker beds of very fossiliferous sandy marls and sandstones facies. The presence of *Nummulites* implies

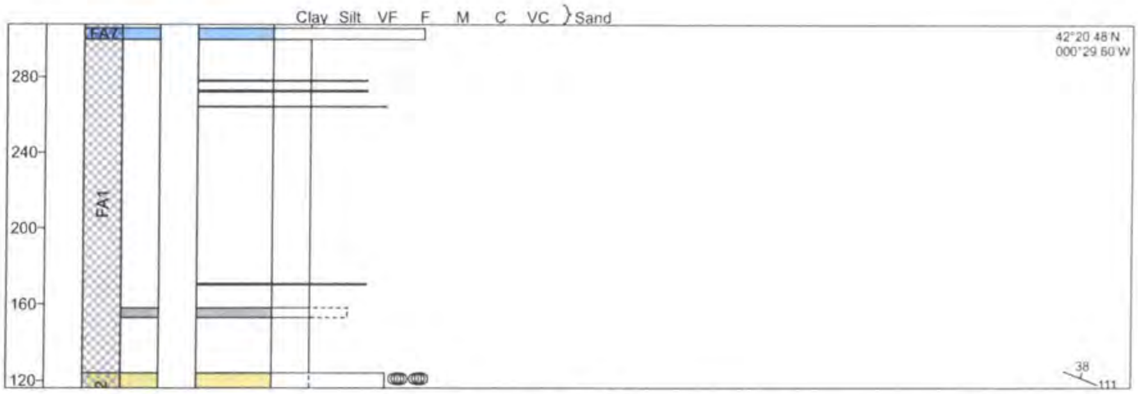


Fig. 3.89. An example of FA1. From lower half of Benué de Rasal summary log (Vol.2, p.44).

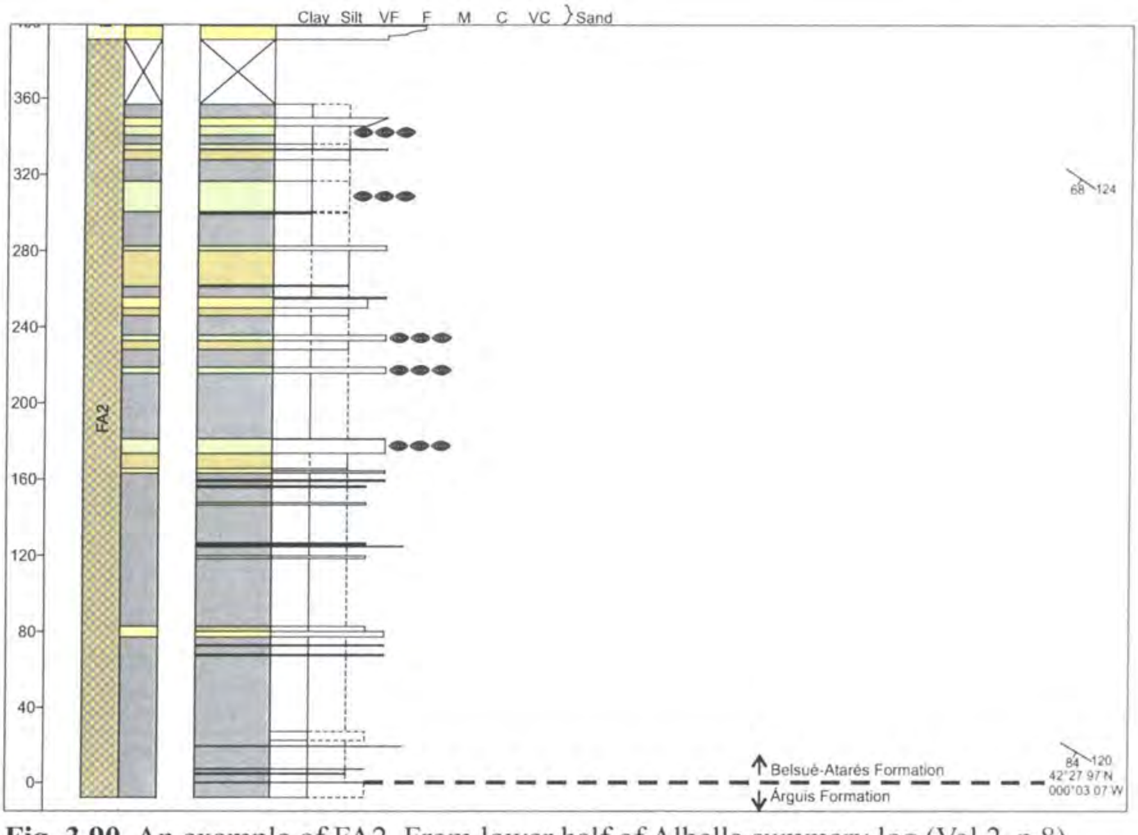


Fig. 3.90. An example of FA2. From lower half of Albella summary log (Vol.2, p.8).

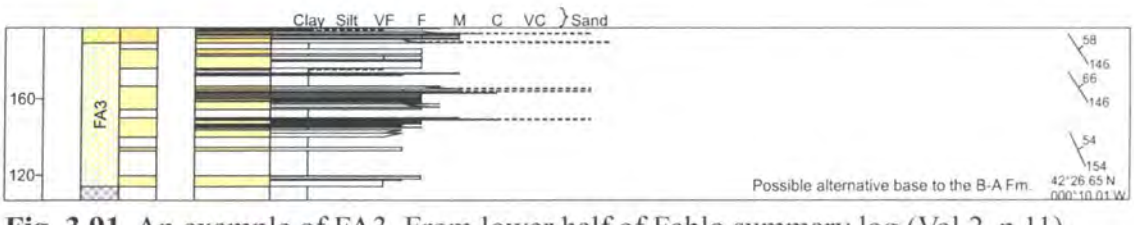


Fig. 3.91. An example of FA3. From lower half of Fablo summary log (Vol.2, p.11).

that the palaeoenvironment was a warm sea, and that water depths were within the photic zone.

Also part of this facies association are thinner beds of very fossiliferous sandy marls and sandstones facies, and fine, well-bioturbated sandstones facies. The concentrations of bioclasts in the former may have been formed by storm-generated currents (section **3.2.4**), although the lack of any hummocky or swaley cross-stratification implies that this would to have been at depths beneath storm wave base. Isolated beds of the latter lithofacies record episodes of transport of sands into deeper areas of the basin, either by storm currents or turbidity currents (section **3.2.5**).

This facies association is interpreted as accumulating in a fairly deep marine environment, dominated by calcareous clays settling out of suspension, but with a significant amount of clastic sediment coming from a relatively distant source. Water depths were largely below normal wave base, but within the photic zone, which would place this environment in the offshore–transition zone. Probable storms currents and/or turbidity currents occasionally delivered sands and concentrations of bioclasts.

3.3.3 FA3: lower shoreface sandstones

The major components of this facies association are pure marls facies (section **3.2.1**) and fine, well bioturbated sandstones facies (section **3.2.5**); silty and sandy marls facies (section **3.2.2**) is a minor component. The two marly lithofacies tend to form thick, monotonous accumulations, with the sandstones present as thinner interbeds, usually singly but sometimes amalgamated into packages of 2 – 4 beds. A good example of this commonly occurring facies association can be seen in the lower half of the Fablo summary log (**Fig. 3.91**; Vol.2, p.11).

The two marly lithofacies were formed in a relatively deep, offshore marine environment, experiencing very little clastic input and current activity, but with an abundant planktonic microfauna (sections **3.2.1** and **3.2.2**). Interbedded within these are beds of fine, well bioturbated sandstones facies that, where thin and isolated, record deposition by storm currents or turbidity currents in offshore–transition areas beneath storm wave base (section **3.2.5**). Up section, these beds tend to become thicker, are more likely to be amalgamated into packages and occasionally contain symmetrical ripples. These changes record increased supply of sands and deposition at or just above normal wave base, in the lower shoreface zone.

This facies association is interpreted as being the product of background marl deposition, sand supply (initially by episodic storm and turbidity currents, but grading up into more frequent sand delivery) and wave reworking in the lower shoreface zone.

3.3.4 FA4: upper shoreface and delta front sandstones

The major components of this facies association are pure marls facies (section **3.2.1**), fine, well bioturbated sandstones facies (section **3.2.5**), and medium, cross-laminated sandstones facies (section **3.2.6**). The marly lithofacies tends to form thick, monotonous accumulations. The two sandy lithofacies tend to form thinner beds, which may be isolated within the marls, interbedded with one another, or amalgamated into packages of 3 – 5 beds. A good example of this common facies association can be seen in the middle of the San Julián de Basa summary log (**Fig. 3.92**; Vol.2, p.14).

The pure marls facies is a product of the background settling of calcareous clays from suspension (section **3.2.1**). The fine, well-bioturbated sandstones facies records sand deposition at water depths around normal wave base via both episodic and more continuous processes (section **3.2.5**), and perhaps also the deposition of fine sandstones in low energy settings at shallower water depths.

The medium, cross-laminated sandstones facies records the action of fairly high-energy, unidirectional currents (section **3.2.7**). This lithofacies could be formed in two different depositional environments – the upper shoreface of a siliciclastic coast or on a delta front. Some beds of this lithofacies are rich in small marl rip-up clasts and extrabasinal pebbles which, along with the common marine fossils, point towards a fluvial sediment source but a marine depositional environment. Thus these beds were probably laid down as distributary mouth bars on a delta front. Beds without clasts are more likely to have originated on the upper shoreface, away from any fluvial input.

This facies association is interpreted as being deposited in the lower and upper shoreface zones, and on a delta front. Wave-rippled fine sands of the lower shoreface (or presumably, lower delta front) grade up into medium, cross-laminated sands of the upper shoreface or delta front.

3.3.5 FA5: proximal delta front channelised sandstones

The major components of this facies association are medium cross-laminated sandstones facies (section **3.2.7**) and coarse, cross-bedded sandstones facies (section

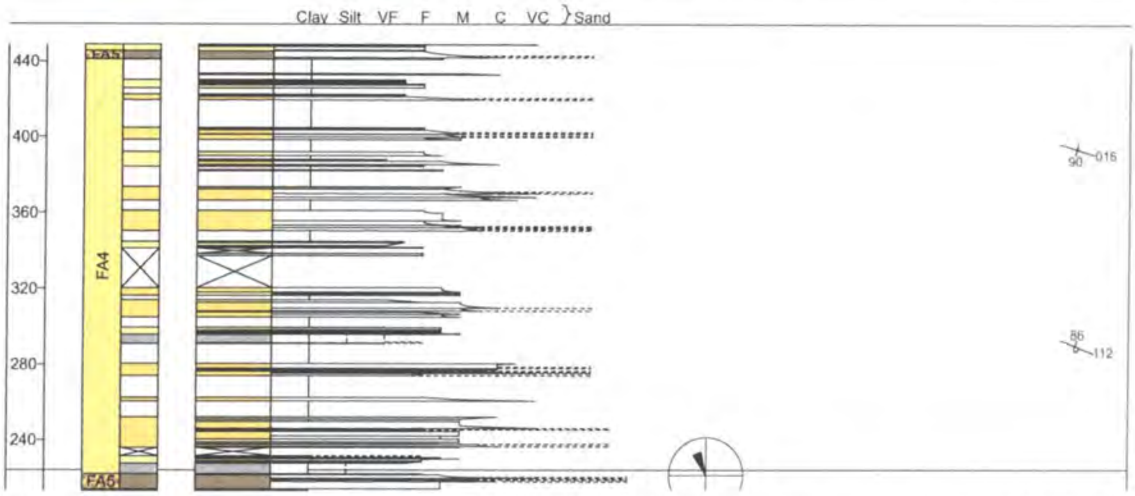


Fig. 3.92. An example of FA4. From middle of San Julián de Basa summary log (Vol.2, p.14).

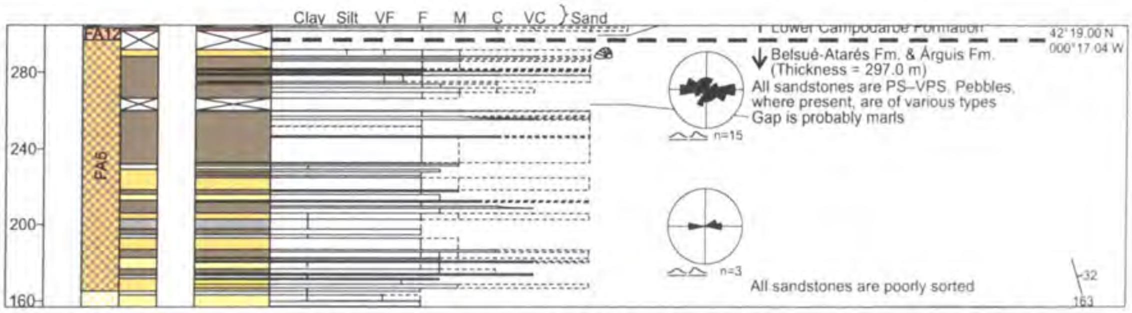


Fig. 3.93. An example of FA5. From upper half of Gabardiella summary log (Vol.2, p.35).

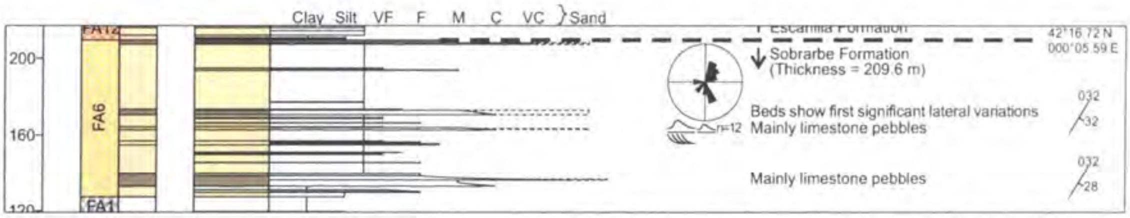


Fig. 3.94. An example of FA6. From upper half of Eripol summary log (Vol.2, p.28).

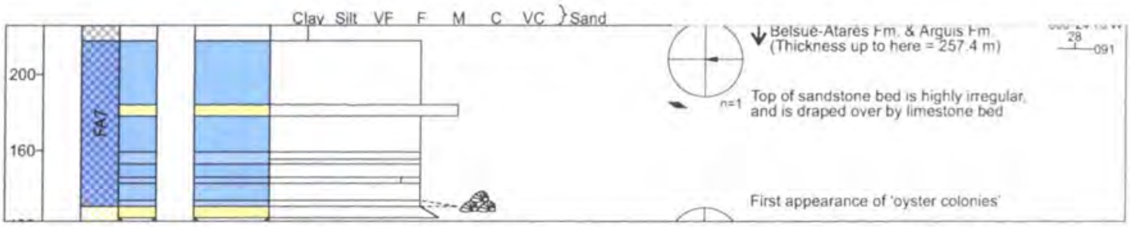


Fig. 3.95. An example of FA7. From middle of Pico del Águila summary log (Vol.2, p.41).

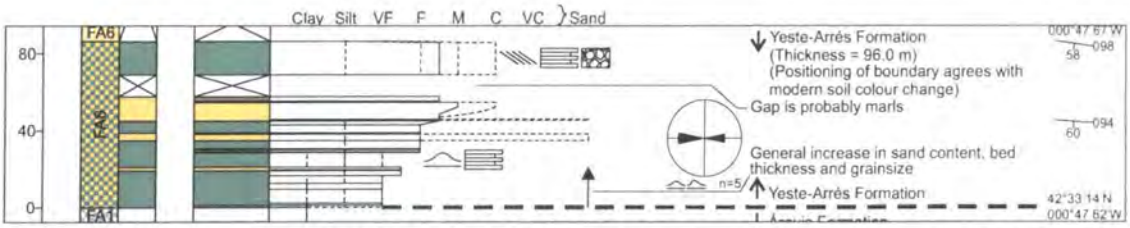


Fig. 3.96. An example of FA8. From lower half of Puente La Reina summary log (Vol.2, p.22).

3.2.8); pure marls facies (section **3.2.1**) is a minor component. The two sandy lithofacies tend to either be interbedded with one another, or to occur in amalgamated packages of 2 – 5 beds, separated by thin beds of pure marls facies. A good example of this fairly commonly occurring facies association can be seen in the upper half of the Gabardiella summary log (**Fig. 3.93**; Vol.2, p.35).

The medium, cross-laminated sandstone facies was deposited in either the upper shoreface of a siliciclastic coast or – more likely in this facies association – in mouth bars, on a delta front (section **3.2.7**). As previously, the pure marls facies records the background settling of calcareous clays out of suspension (section **3.2.1**), that seemingly occurs across nearly all of the marine facies associations (and hence at most water depths and in most marine environments).

The coarse, cross-bedded sandstones facies is most likely to have formed on the most proximal parts of a delta front (section **3.2.8**). The coarse, poorly sorted extrabasinal pebble- and rip-up clast-rich sands, which were occasionally formed into beds of channel-like shape, were probably laid down in subaqueous channels on the delta front or as bars at the mouths of the channels. Channel migration and gradual abandonment gave rise to the normally graded character of many beds.

This facies association is interpreted to have been deposited in a proximal delta front environment, primarily in subaqueous channels and mouth bars, but with continued marl sedimentation in the areas in between.

3.3.6 FA6: marginal marine clays and sandstones

The major component of this facies association is grey and yellow clays and silts facies (section **3.2.15**); fine, well bioturbated sandstones facies (section **3.2.5**), medium, cross-laminated sandstones facies (section **3.2.7**), and coarse, cross-bedded sandstones facies (section **3.2.8**) are all minor components. Single beds or small, amalgamated packages of the three sandy lithofacies tend to be isolated within thicker, fairly monotonous packages of the grey and yellow clays and silts facies. A good example of this fairly common facies association can be seen in the upper half of the Eripol summary log (**Fig. 3.94**; Vol.2, p.28).

The yellow clays and silts are given their colour by the oxidation / hydration of iron-bearing minerals deposited out of suspension with the clays (section **3.2.15**). The colour trend within the clays tends to correlate with the trend in the facies associations: if there is a shallowing upwards trend in the facies associations on a log, then the clays and silts in this facies association tend to become increasingly yellow upwards. The yellow colouration is thought to be associated with shallowing water depths in this way because the yellowy weathered iron mineral are dense, settle out of suspension quickly, and so do not make it far down the depositional system into deeper waters (section **3.2.15**).

Although this facies association does not contain any features that are truly diagnostic of the depositional environment that it represents, from its spatial relationships with other facies associations that do contain diagnostic features, it can be inferred that this facies association was formed in a very shallow to marginal marine setting: generally, this facies association gradationally overlies a shallow marine facies association (FA4 or FA5), and gradationally underlies a non-marine facies association (FA11 or FA12), as seen in the uppermost portions of the Belsué log (Vol.2, p.39). Clay can only settle out of suspension in very low energy conditions, meaning that if deposition did occur in a shallow to marginal marine setting, then the environment must have been protected from the energy of the sea. Possible protected environments include coastal lagoons, mud-dominated tidal flats and interdistributary bays on a delta top.

The three sandy lithofacies are the products of marine sediment supply and deposition processes of varying energy (sections **3.2.5** – **3.2.8**) – though not necessarily varying water depth, as environmental energy does not necessarily equate to marine water depth. If the grey and yellow clays and silts facies formed in lagoons, mud-dominated tidal flats and/or interdistributary bays on a delta top, then these sandy lithofacies could represent channels on a tidal flat, subaqueous channels on the delta front, and/or crevasse splays from either of these types of channels.

This facies association is interpreted as being a product of sedimentation in shallow to marginal marine conditions, in a number of similar but distinct depositional environments: coastal lagoons, mud-dominated tidal flats and/or interdistributary bays on a delta top. It also includes evidence of occasional channelised sand delivery.

3.3.7 FA7: carbonate ramp limestones

The major components of this facies association are bioclastic limestones facies (section **3.2.9**), sandy bioclastic limestones facies (section **3.2.10**), and coral limestones facies (section **3.2.11**). These may occur singly as thin or thick beds (0.4 – 20 m), or may be interbedded with one another. Probably the best example of this fairly rarely occurring facies association can be seen in the middle of the Pico del Águila summary log (**Fig. 3.95**; p.41).

The carbonate mud that comprises the bioclastic limestones facies was deposited by settling out of suspension, in a necessarily low energy environment (section **3.2.9**). However, some of the fossils in this lithofacies, such as the *Nummulites*, only occur in the photic zone of open marine areas, and not in other low energy environments such as marginal marine lagoons or deep-water areas beneath the photic zone. Thus, this lithofacies probably formed in a low energy, fairly shallow marine setting, either below normal wave base or protected from wave energy. The sandy bioclastic limestones facies probably formed in more-or-less the same environment, except with a small but significant supply of clastic material (section **3.2.10**). In terms of the classic carbonate ramp model (Tucker & Wright, 1990), these two lithofacies would be expected to have formed in the mid-ramp and outer ramp areas.

The coral limestones facies records the growth of corals reefs (section **3.2.11**). Modern reefs only grow in conditions of warm, normal salinity water, very low turbidity, and at water depths no greater than the base of the photic zone (less than 100 m). The corals observed in this lithofacies have either low or high wave-energy growth forms. This suggests that reef formation occurred around normal wave base, or that conditions varied. However, both growth forms were 'erect' in nature, which is a type of growth that is adapted to prevent smothering in conditions of high sedimentation. On a carbonate ramp model, this lithofacies would be deposited in the inner ramp and upper mid-ramp areas.

This facies association is the product of sedimentation on a carbonate ramp in a warm, normal salinity sea, with low turbidity, occasional sand input, and variable but generally low wave energy. Coral reef formation occurred in the inner ramp and upper mid-ramp areas, whilst carbonate mud built up in the low energy conditions of the mid-ramp and outer ramp areas.

3.3.8 FA8: tidal flat sandstones

The major components of this facies association are medium, cross-laminated sandstones facies (section **3.2.7**), and parallel-laminated sandstones facies (section **3.2.12**). These two lithofacies occur both as single beds that are interbedded with one another, and as amalgamated packages that, in the case of the latter facies, may be up to

10 beds thick. A good example of this rare facies association is in the lower half of the Puente La Reina summary log (**Fig. 3.96**; Vol.2, p.22).

The parallel-laminated sandstones facies consists of ubiquitous parallel-laminated to thinly bedded sandstones (5 mm – 10 cm lamina / bed thickness), thought to represent annual (or longer) cycles in sediment supply (section **3.2.12**). Also present is abundant evidence of unidirectional and bi-directional currents, suggesting that wave, current and tide energy were important. This lithofacies is thought to have been deposited on a sand-dominated tidal flat, mainly in the inter-tidal zone, but with some more sustained periods of subaerial exposure in its uppermost portions, forming desiccation cracks.

The medium, cross-laminated sandstones facies was deposited by unidirectional currents, with some evidence of erosion of underlying fines, and channelisation (section **3.2.7**). In a tidal flat setting, this lithofacies is most likely to represent tidal channels on the flat, and perhaps also current-generated sand bedforms in the lower tidal flat zone.

This facies association was deposited on a sand-dominated tidal flat, which experienced annual (or longer) cycles in sediment supply. Tidal channels existed on the flat, and its uppermost portions experienced some prolonged periods of subaerial exposure.

3.3.9 FA9: fan delta front conglomerates

The major components of this facies association are pure marls facies (section **3.2.1**), and clast-supported conglomerates facies (section **3.2.14**); medium, cross-laminated sandstones facies (section **3.2.7**) and coarse, cross-bedded sandstones facies (section **3.2.8**) are minor components. Each lithofacies tends to form up to 10-m-thick packages, which are intercalated with one another. The only two recorded examples of this facies association can be seen near the tops of the Yebra de Basa summary log (**Fig. 3.97**; Vol.2, p.13) and the San Julián de Basa summary log (Vol.2, p.14).

The marine microfossil content of the pure marls facies (Sztràkos & Castelltort, 2001; Castelltort *et al.*, 2003), and the un-reworked marine fossil content of medium, cross-laminated sandstones facies (section **3.2.7**) and the coarse, cross-bedded sandstones facies (section **3.2.8**) indicate that this facies association was formed in a marine setting. Thus, although the clast-supported, internally massive conglomerates of the clast-supported conglomerates facies are most likely to be associated with an alluvial fan (section **3.2.14**), it seems as though they were deposited in a sea as a fan

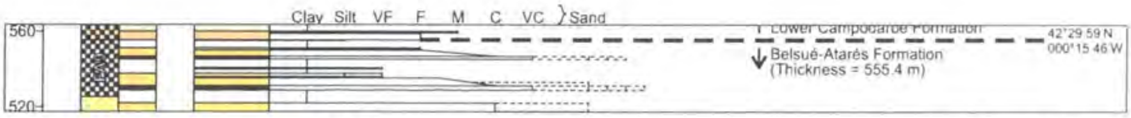


Fig. 3.97. An example of FA9. From top of Yebra de Basa summary log (Vol.2, p.13).

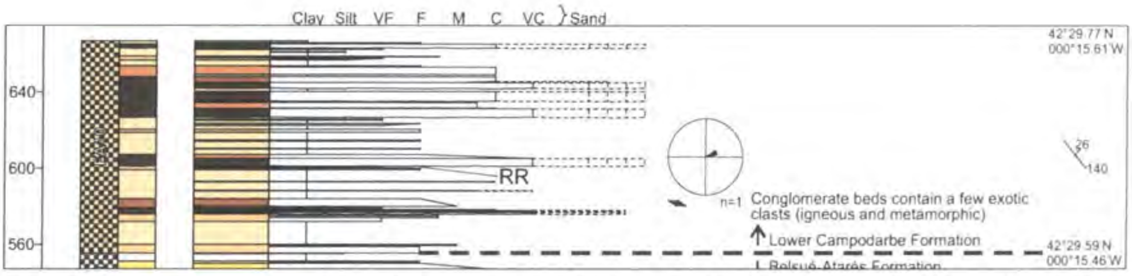


Fig. 3.98. An example of FA10. From top of Yebra de Basa summary log (Vol.2, p.13).

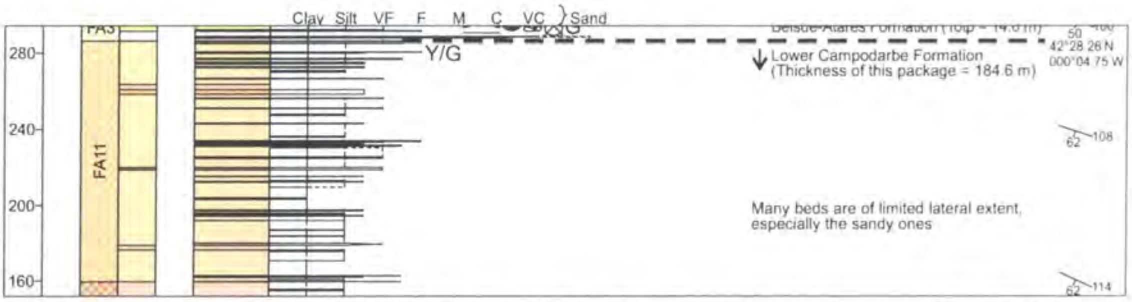


Fig. 3.99. An example of FA11. From upper half of Ligüerre de Ara summary log (Vol.2, p.9).

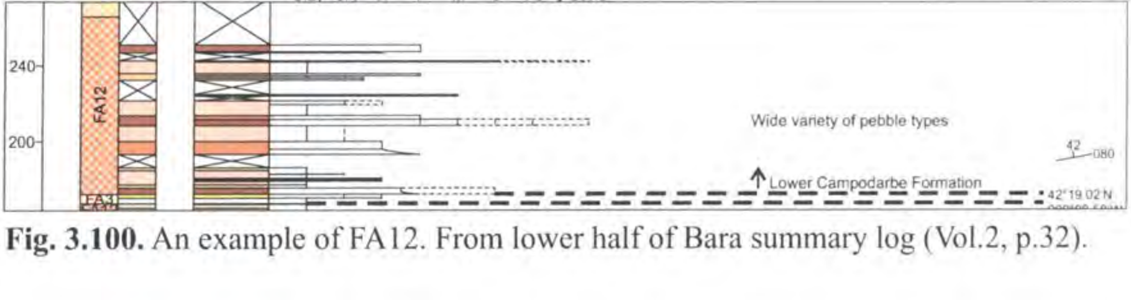


Fig. 3.100. An example of FA12. From lower half of Bara summary log (Vol.2, p.32).

delta, rather than subaerially. The laterally extensive (over hundreds of metres) beds of conglomerate result from unconfined, gravity-driven grain flows of conglomeratic material down the steep front of the fan delta. Although there was no evidence of reworking of the conglomerates by marine processes, the beds of other lithofacies between the conglomerates in this facies association indicate that the transport of conglomeratic material down the fan delta front was episodic. The presence of pebbles of extrabasinal origin in the conglomerates suggests an extrabasinal origin for the system that fed the fan delta (some pebbles came from rocks only found in the high Pyrenees; Jones, 1997).

Pure marls facies records the background settling out of suspension of calcareous clays (section **3.2.1**). Medium, cross-laminated sandstones facies is the product of the unidirectional causing the formation and migration of asymmetrical ripples in sands (section **3.2.7**). Coarse, cross-bedded sandstones facies records stronger unidirectional currents causing the formation and migration of dunes in coarser sands (section **3.2.8**). These three lithofacies are also found together in FA5 (section **3.3.5**), where they are interpreted as having been deposited in a proximal delta front environment. In FA5, the sandy lithofacies are thought to have formed as bars at the mouths of the deltaic distributary channels and in subaqueous deltaic channels, whilst the marls seem to represent suspension settling in the areas between the bars and channels. Therefore, because these three lithofacies are also present together in this facies association, it seems likely that the depositional processes and environment that they represent are essentially the same. Thus, the only real difference between this facies association that of the proximal delta front (FA5) is that the source of the sediment was an alluvial fan rather than a river, and the sediment provided to the delta front also included episodic flows of clast-supported conglomerates.

This facies association is interpreted as being deposited on the proximal parts of a fan delta, where an area of mouth bars and subaqueous channels was occasionally washed over by unconfined gravity-driven grain flows of conglomerate, sourced from a terrestrial alluvial fan. In between the bars and channels, and the episodes of conglomerate delivery, background marl sedimentation occurred.

3.3.10 FA10: alluvial fan conglomerates

The major components of this facies association are clast-supported conglomerates facies (section **3.2.14**), and grey and yellow clays and silts facies (section

3.2.15); very fine, colour-mottled sandstones facies (section **3.2.17**), fine, cross-laminated coloured sandstones facies (section **3.2.19**), and medium, cross-bedded coloured sandstones facies (section **3.2.20**) are all minor components. The sandstones and conglomerates tend to form amalgamated packages of several beds of the same facies, or to be interbedded with one another. Between these lie relatively thick (up to 12 m), monotonous beds of grey and yellow clays and silts facies. The only recorded example of this facies association can be seen at the top of the Yebra de Basa summary log (**Fig. 3.98**; Vol.2, p.13).

In this facies association, all lithofacies except the clast-supported conglomerates facies are readily interpreted as being non-marine, on the basis of their colour (bright yellows, oranges and reds), the presence of palaeosols, and their complete lack of marine fossils (Puigdefàbregas, 1975; Jolley, 1987). Thus it seems reasonable to assume that the clast-supported conglomerates facies, which is intercalated with the other clearly non-marine lithofacies in this facies association and does not contain marine fossils, is also of non-marine origin.

The laterally extensive beds (over hundreds of metres) of clast-supported, internally massive conglomerates are interpreted as having been deposited by unconfined sheet floods on an alluvial fan (section **3.2.14**). The presence of pebbles that are not of Jaca Basin lithologies in the conglomerates suggests an extrabasinal origin for the system that fed the alluvial fan (some pebbles came from rocks only found in the Pyrenean axial zone; Jones, 1997). The beds of other lithofacies between the conglomerates record environmental conditions on the surface of the fan between the episodic sheetflood events.

The cross-bedded, and often laterally inextensive (< 20 m) and erosively-based beds of the medium, cross-bedded coloured sandstones facies are thought to be the product of fluvial channels, in which two- and three-dimensional dunes and bars migrated (section **3.2.20**). Fining upwards and clay rip-up clasts suggest that the channels migrated laterally. Again, the presence of extra-basinal pebbles implies that the fluvial system was, at least partly, fed by a drainage basin external to the Jaca Basin. In the alluvial fan setting identified above, the channels could represent the normal fluvial activity on the surface of the fan, between episodes of sheet-flooding.

The fine, cross-laminated coloured sandstones facies could be deposited in a number of different sub-environments within this fluvial system (section **3.2.19**), such as in a river channel due to a fall in flow velocity, or in the proximal parts of a crevasse splay lobe. The very fine, colour-mottled sandstones facies is thought to have been deposited in the distal parts of crevasse splay lobes (section **3.2.17**), and contains abundant evidence of plant colonisation of the inter-channel areas between flooding / crevasse splaying events. All three of the sandy lithofacies described above commonly have a red colouration, due to haematisation, and this implies that their deposition most likely occurred in a hot, semi-arid continental environment (Tucker, 1996). Finally, grey and yellow clays and silts facies records the settling of clays out of suspension, accompanied by varying amounts of weathered yellow iron minerals, on areas of a river floodplain unaffected by crevasse splay events or soil forming processes (section **3.2.15**).

This facies association is interpreted as being the product of sedimentation on the surface of an alluvial fan, which consists of a laterally-migrating fluvial system (partially sourced from outside the Jaca Basin) and associated floodplains, but which is periodically swept by large-scale, unconfined sheet floods bringing abundant conglomeratic material down from the apex of the fan. The environment was probably hot, semi-arid continental.

3.3.11 FA11: fluvial sandstones and floodplain fines

The major components of this facies association are grey and yellow clays and silts facies (section **3.2.15**) and very fine, colour-mottled sandstones facies (section **3.2.17**); fine, cross-laminated coloured sandstones facies (section **3.2.19**) and medium, cross-bedded coloured sandstones facies (section **3.2.20**) are minor components. The sandy lithofacies tend to form single beds or relatively thin amalgamated packages (up to 10 m thick), separated by usually thicker beds of grey and yellow clays and silts facies (up to 40 m thick). A good example of this commonly occurring facies association can be seen in the upper half of the Ligüerre de Ara summary log (**Fig. 3.99**; Vol.2, p.9).

The cross-bedded, and often laterally inextensive (< 20 m) and erosively-based beds of the medium, cross-bedded coloured sandstones facies are thought to be the product of fluvial channels, in which two- and three-dimensional dunes and bars migrated (section **3.2.20**). Fining upwards within beds and clay rip-up clasts suggest that the channels migrated laterally. Common pebbles of non-Jaca Basin lithologies imply that the fluvial system was at least partly sourced from outside the basin.

Fine, cross-laminated coloured sandstones facies could be deposited in a number of different sub-environments in a fluvial system (section **3.2.19**), such as in a river channel due to a fall in flow velocity, or in the proximal parts of a crevasse splay lobe. Very fine, colour-mottled sandstones facies is thought to have been deposited in the distal parts of crevasse splay lobes on a floodplain (section **3.2.17**), and contains evidence of some plant colonisation between flooding / crevasse splay events. Grey and yellow clays and silts facies is the product of the settling out of suspension of clays, silts and weathered iron-bearing minerals, onto areas of a floodplain unaffected by crevasse splays or soil-forming processes (section **3.2.15**). The lack of soil development within this lithofacies suggests that channel migration, avulsion, flooding or crevasse splaying events affected the floodplains regularly (every hundred years or less), preventing vegetation growth from producing well-developed soil profiles (Kraus, 1999).

This facies association is interpreted as being deposited by a fluvial system consisting of laterally migrating channels, partially sourced from outside the Jaca Basin. This system was surrounded by floodplains that were dominated by clay and silt sedimentation. Regular flooding /crevasse splay / channel movement events meant that plant colonisation was limited and soil development did not occur.

3.3.12 FA12: fluvial sandstones and red soils

The major component of this facies association is brightly coloured clays and silts facies (section **3.2.16**); very fine, colour-mottled sandstones facies (section **3.2.17**), fine, cross-laminated coloured sandstones facies (section **3.2.19**) and medium, cross-bedded coloured sandstones facies (section **3.2.20**) are all minor components. The sandy lithofacies tend to be represented by single beds or relatively thin amalgamated packages (up to 10 m thick), separated by usually thicker beds of brightly coloured clays and silts facies (up to 40 m thick). A good example of this fairly commonly occurring facies association can be seen in the lower half of the Bara summary log (**Fig. 3.100**; Vol.2, p.32).

The cross-bedded, and often laterally inextensive (< 20 m) and erosively-based beds of the medium, cross-bedded coloured sandstones facies are thought to be the product of fluvial channels, in which two- and three-dimensional dunes and bars migrated (section **3.2.20**). Fine, cross-laminated coloured sandstones facies could represent a number of different sub-environments within a fluvial system (section **3.2.19**), such as the proximal parts of a crevasse splay lobe. Very fine, colour-mottled sandstones facies was probably deposited as the distal parts of crevasse splay lobes (section **3.2.17**), and contains abundant evidence of plant colonisation between flooding / crevasse splaying events.

The brightly coloured clays and silts facies is often reddish, because of haematisation – a process normally associated with sediments laid down in hot, semi-arid continental environments (section **3.2.16**). The precise shade of the clays and silts often varies vertically on a metre-scale, sometimes sharply but often gradually. This is not thought to be due to variations in original composition or diagenesis of the clays and silts, but because they have undergone soil-forming (pedogenic) processes post-deposition. Regular interruptions to the pedogenic processes (which take 2 – 30 thousand years to reach maturity; Kraus, 1999) are thought to have caused the diffuse-striped vertical profiles, as a fully mature profile tends to consists of sharply-bounded colour bands (Retallack, 1997). The interruptions probably occurred because of the delivery of new sediments by flooding or crevasse splaying, which would swamp the vegetation colonised-surfaces and put an end to the development of the existing soil profile. Regular clay and silt sedimentation, followed by soil formation, is a common feature of river floodplains.

This facies association is very similar to FA11 (section **3.3.11**), except that the grey and yellow clays and silts facies are here replaced by brightly coloured clays and silts facies i.e. extensive soil formation was able to occur in this facies association, but not FA11. Red soils may have been unable to form in FA11 because of too-regular flooding of the floodplain, regularly migrating or avulsing fluvial channels, or perhaps due to unsuitable climatic conditions.

This facies association is interpreted as being deposited by a fluvial system of laterally migrating channels. The surrounding floodplains experienced periodic crevasse splay and flooding events, with red soil formation in between. The climate was most likely to be hot, semi-arid continental.

3.4 Conclusions

By analysing the lithological characteristics of each bed on all graphic logs through the Belsué-Atarés Fm. (plus parts of the underlying Árguis Fm. and overlying Lower / Middle Campodarbe Fm.), twenty lithofacies have been identified and described. Beds within each lithofacies have very similar sedimentological characteristics, and so are interpreted as having been formed by similar depositional processes, thought not necessarily in the same depositional environment. Lithofacies that commonly occur interbedded with or adjacent to one another have been grouped into twelve facies associations. Each facies association represents the geological record of a particular depositional environment. The boundaries between the different facies associations tend to be gradational rather than sharp, reflecting a gradual progradation of depositional systems, instead of any rapid changes or periods of non-deposition.

The range of depositional environments interpreted from the facies associations, in the 'distal' / marine to 'proximal' / non-marine order that they were presented in this chapter, are: offshore marine (FA1), offshore–transition zone (FA2), lower shoreface (FA3), upper shoreface and delta front (FA4), proximal delta front (FA5), marginal marine (FA6), carbonate ramp (FA7), tidal flat (FA8), fan delta front (FA9), alluvial fan (FA10), fluvial system with floodplains (FA11), and fluvial system with red soils (FA12). These are also summarised visually on **Fig. 3.3**.

A number of trends in the facies associations are common to many of the logs. For example, background marl sedimentation, via the settling out of calcareous clays from suspension in a marine water column, occurs in almost all of the normal marine depositional environments noted (FA1 – FA5 and FA9), irrespective of water depth and other processes occurring. Also, the succession of facies associations on most of the logs describes an overall shallowing upwards trend, typically beginning with the relatively deep marine marls of the Árguis Fm. (FA1 – FA2). These give way to the coarsening-upwards sandstones, and limestones, of the Belsué-Atarés Fm. (FA3 – FA9). Finally, the logs end with the non-marine sands, gravels and fines of the Lower / Middle Campodarbe Fm. (FA10 – FA12).

Understanding the controlling effects that actively growing tectonic structures within the Jaca Basin (**Fig. 1.3**) had on the coeval intrabasinal depositional processes and environments is the primary aim of this thesis. To address this, the spatial distribution of the different facies associations (depositional environments) within the basin, and the changes in this distribution through time, will be the principal focus of Chapters 4 – 9.

The next chapter, Chapter 4, focuses on the easternmost end of the northern margin of the Jaca Basin. In this area, the Belsué-Atarés Fm. – Lower Campodarbe Fm. boundary progrades and retrogrades by a few kilometres along the basin axis, several times, suggesting the existence of an allocyclic control on basinal sedimentation.

Chapter 4:
Far NE Jaca Basin

4. Far NE Jaca Basin

Contents

4. Far NE Jaca Basin

4.1 Introduction

It is well documented that growth structures can have a profound effect on the syntectonic infill of a basin (e.g. Casas-Sainz *et al.*, 2002; Rafini & Mercier, 2002; López-Blanco, 2002; Sohn & Son, 2004). The Jaca Basin contains abundant growth structures: the northern margin features two, kilometre-scale, ENE–WSW-trending growth anticlines, whereas the southern margin has eight N–S anticlines of similar scale (**Fig. 1.3**; Millán *et al.*, 1994). These structures grew whilst the Belsué-Atarés Fm. was being deposited (Puigdefàbregas, 1975; Castelltort *et al.*, 2003; chapters 5 – 9 of this work). The problem this poses when studying the Belsué-Atarés Fm. is that all of its outcrops are located along the northern and southern basin margins, and so during deposition were always in the immediate vicinity of one or more of the growing folds. This means that all the lithologies and facies exposed in all Belsué-Atarés Fm. outcrops will, to some extent, have been controlled by the nearby kilometre-scale structures.

There is however one exception. The Far NE Jaca Basin sector, at the very eastern end of the northern margin of the basin, contains multiple hundred-metre-thick exposures of the Belsué-Atarés Fm., yet there are no known growth structures in the vicinity. Thus the facies and lithologies observed in this area should represent what Belsué-Atarés Fm. sedimentation was like without any local tectonic influence. This area should therefore provide an important calibration point for determining the controlling effect that the growth anticlines had on the Belsué-Atarés Fm. across the rest of the basin.

The aims of this chapter are to use basic sedimentological observations, such as those of facies and facies associations, palaeocurrents and sediment provenance (section **4.2**), to gain a thorough understanding of the mode of deposition of the Belsué-Atarés Fm. in the absence of growing structures (section **4.3**).

4.2 Graphic logs of the Far NE Jaca Basin sector

This sector of the field area covers a fairly small 8-km-long section at the very eastern end of the northern margin of the Jaca Basin (**Fig. 4.1**), situated around 20 km east of the small town of Sabiñánigo. In this area, the northern margin of the basin is

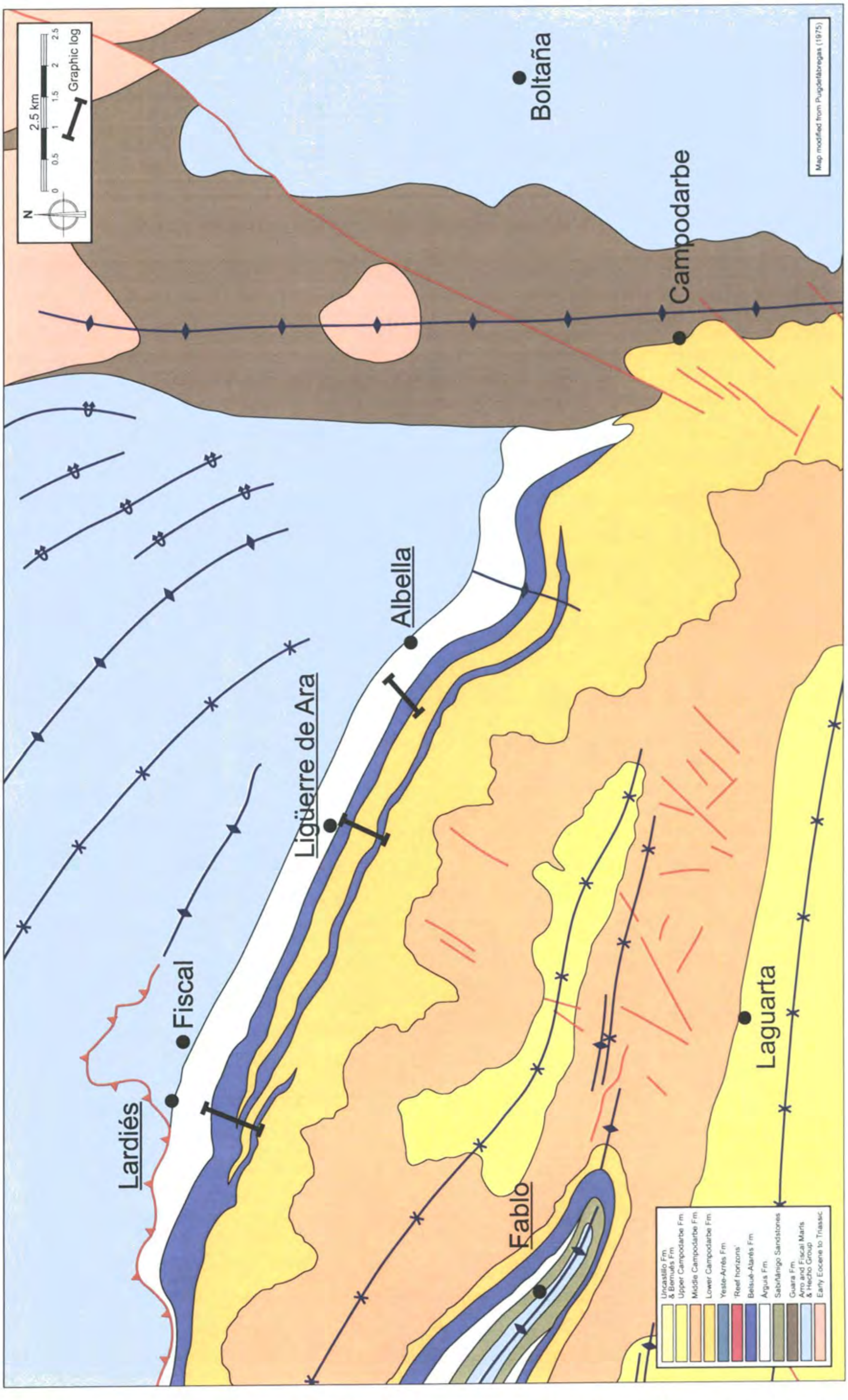


Fig. 4.1. Geological map of the Far NE Jaca Basin, indicating the positions of the three graphic logs.

defined by a series of WNW–ESE-trending thrusts and folds. Three graphic logs were completed – their locations are indicated on **Fig. 4.1**. Each log, in both summary and original full-scale version, is reproduced in the appendices in Vol.2.

Log name	Summary log	Original log
Albella	Vol.2, p.8	Vol.2, p.49 – 54
Ligüerre de Ara	Vol.2, p.9	Vol.2, p.55 – 58
Lardiés	Vol.2, p.10	Vol.2, p.59 – 65

This part of the Jaca Basin has not been studied in detail since the basin-wide mapping of Puigdefàbregas (1975). This mapping not only revealed that this part of the basin is one of the few that is free of major structures, but also found highly unusual 'interfingering' between the marine Belsué-Atarés Fm. and the non-marine Lower Campodarbe Fm. (**Fig. 4.1**). Each 'finger' is around 10 km long and several hundred metres thick. This pattern in the stratigraphy is suggestive of a number of marine transgressions and regressions. As this area has not previously been studied in detail, the cause of these large-scale cycles is unknown, but most probably relates to variations in either relative sea-level or sediment supply. It is likely that the cause of these cycles influenced the deposition of contemporaneous sediments of the Belsué-Atarés Fm. across the rest of the Jaca Basin. It therefore seems best to first study the cycles in this area, where the otherwise common intrabasinal growth structures are absent.

The following sections of this chapter are based upon the data collected during the course of this project. In this section, section **4.2**, the sedimentological data from the Belsué-Atarés Fm., including facies and facies associations, palaeocurrents, and sediment compositions, are described and interpreted. The interpretation of these fundamentals is then applied, in section **4.3**, to analyse the sedimentary cycles and to shed light on the structural configuration of the Jaca Basin during Belsué-Atarés Fm. times.

4.2.1 Facies, facies associations and facies architecture

The three logs undertaken in this sector (see **Fig. 4.1** for their locations) record a very diverse range of facies and facies associations. The most easterly log, located at Albella (Vol.2, p.8 & p.49 – 54), includes the uppermost 390 m of the Árguis Fm. These beds are dominated by silty and sandy marls facies (section **3.2.2**), marly silts and sandstones facies (section **3.2.3**), and an unusually large amount of very fossiliferous sandy marls and sandstones facies (section **3.2.4**), compared to other sections in the basin. Beds of the latter are up to 16 m thick and extremely rich in *Nummulites*, with some beds being composed of very little else (Vol.2, p.50 – 52). The three dominant lithofacies together make up the offshore–transition zone marls and sandstones facies association (FA2; section **3.3.2**). Overlying the Árguis Fm. is just less than 140 m of Belsué-Atarés Fm., consisting first of lower shoreface sandstones (FA3; section **3.3.3**), then upper shoreface and delta front sandstones (FA4; section **3.3.4**), and finally an unusually thick 82 m of marginal marine clays and sandstones (FA6; section **3.3.6**). The vast majority of the latter are grey and yellow clays and silts facies (section **3.2.15**), with very few sand-grade interbeds. Lying on top of the Belsué-Atarés Fm., with a gradational contact that stretches over a few tens of metres, is the Lower Campodarbe Fm. This initially consists of fluvial sandstones and floodplain fines (FA11; section **3.3.11**), but within about 30 m of the contact the relatively thick beds of fines become reddened in colour (Vol.2, p.54), indicating a change to fluvial sandstones and red soils (FA12; section **3.3.12**).

Moving just over 2 km westwards, the next log encountered is at Ligüerre de Ara (Vol.2, p.9 & p.55 – 58). This log has much in common with the nearby Albella log, although the Árguis Fm. was not exposed at Ligüerre de Ara. Here, the Belsué-Atarés Fm. consists of lower shoreface sandstones (FA3), which are again overlain by an unusually thick 80 m of marginal marine clays and sandstones (FA6). Above this lie fluvial sandstone and floodplain fines (FA11) of the Lower Campodarbe Fm., and then fluvial sandstones and red soils (FA12), just like at Albella. However, after nearly 50 m of these, FA11 returns. Then, after a total of nearly 185 m of terrestrial Lower Campodarbe Fm., the first reappearance of the marine Belsué-Atarés Fm. is encountered (Vol.2, p.57 – 58). The Belsué-Atarés Fm. package is 14-m-thick and composed of pure marls facies (section **3.2.1**) interbedded with sandstones bearing marine fossils such as *Nummulites* and oysters. After a further 24 m of the Lower Campodarbe Fm., a second 6.4-m-thick package of Belsué-Atarés Fm. is present (Vol.2, p.58). This consists of pure marls facies and silty and sandy marls facies (section **3.2.2**). Above this, deposition of FA11 of the Lower Campodarbe Fm. is resumed, with no further incursions of the Belsué-Atarés Fm. In all cases, the boundaries between the Belsué-Atarés Fm. and Lower Campodarbe Fm. (i.e. the transgressive or regressive surfaces) are marked by a gradual colour change from grey to yellow in the clay-grade sediments (stretching over metres to tens of metres), and not by the presence of any particular facies.

At the western end of this sector, around 6 km from Ligüerre de Ara, lies the Lardiés log (Vol.2, p.10 & p.59 – 65). This section begins with around 80 m of offshore–transition zone marls and sandstones (FA2) of the uppermost Árguis Fm. Above is nearly 100 m of marl-dominated Belsué-Atarés Fm., composed of a further package of FA2 and lower shoreface sandstones (FA3). On top lies a 42-m-thick package of Lower Campodarbe Fm. (Vol.2, p.60 – 61), consisting of fluvial sandstones and floodplain fines (FA12), dominated by brightly coloured clays and silts facies (section **3.2.16**). Above this, the first reappearance of the Belsué-Atarés Fm. is represented by a 215.6-m-thick package of marginal marine clays and sandstones (FA6) and upper shoreface and delta front sandstones (FA4). Further up the section, the fluvial sandstones and floodplain fines (FA11) of the Lower Campodarbe Fm. return for 31.2 m (Vol.2, p.63), before the Belsué-Atarés Fm. makes a second reappearance with a 225.6-m-thick package consisting of alternations between offshore marine marls (FA1) and marginal marine clays and sandstones (FA6). The final influx of the Lower Campodarbe Fm. is represented by further fluvial sandstones and floodplain fines (FA11). As was the case at Ligüerre de Ara, the boundaries between the Belsué-Atarés Fm. and Lower Campodarbe Fm. sediments are marked only by gradual colour changes in clays.

The environments of deposition recorded in the Belsué-Atarés Fm. of the Far NE Jaca Basin sector are offshore marine (represented by FA1), offshore–transition zone (FA2), lower shoreface (FA3), upper shoreface and delta front (FA4), and marginal marine (FA6). Together these represent an almost complete spectrum of deltaic infill of a marine sedimentary basin, with the different environments representing different water depths and/or levels of clastic sediment input. The only major marine depositional environment not noted was the proximal delta front (FA5), which is however well developed in other areas of the Jaca Basin. The marginal marine deposits (FA6) were unusually thickly developed on all logs across the sector, when compared to other parts of the basin.

Thus, this corner of the Jaca Basin was infilled by a deltaic system. The presence of unusually thick marginal marine deposits and the absence of the most proximal deltaic facies association implies that the delta was however focused somewhat away from the area. Once the Belsué-Atarés Fm. deltaics had infilled all the marine accommodation space, the fluvial Lower Campodarbe Fm. was able to prograde across the region.

4.2.2 Palaeocurrents

Unfortunately the fines-dominated sections in this part of the Jaca Basin offered relatively few opportunities for taking palaeocurrent readings. However, some sandstones yielded readings from symmetrical and asymmetrical ripples and groove casts on bed bases (**Fig. 4.2**; note that the symbols on the rose diagrams indicate the types of structures that the readings came from; for a key to the symbols, see Vol.2, p.3 – 4). The readings taken indicated predominantly north-directed unidirectional flow at Ligüerre de Ara, and bi-directional NE–SW- to NNE–SSW-directed wave rippling at Lardiés. The section at Albella yielded only one palaeocurrent reading.

The palaeocurrent readings mostly came from lithofacies and facies associations that are thought to have been deposited in shallow marine environments. Although palaeocurrents in such settings frequently have variable directions, the currents are more likely to be directed normal to the shoreline than parallel to it (Reading & Collinson, 1996). In the shoreface zone (i.e. at water depths above wave base), common landward-directed asymmetrical ripples result from the stronger land-directed surge that occurs when wind-formed oscillatory flow in the water column reaches the shallow water of the shoreline. The unidirectional and bi-directional palaeocurrents in Belsué-Atarés Fm. of this sector would therefore indicate a shoreline that was orientated between W–E and NW–SE. This would seem to closely tie in with the WNW–ESE-directed thrusts and related folds that define the present-day northern basin margin (**Fig. 1.3**). Thus, it seems that the northern margin thrusts and folds had formed, or at least partly formed, before the deposition of the portion of Belsué-Atarés Fm. in which the palaeocurrent readings were found.

4.2.3 Sediment composition

During the logging process, samples were collected from several fine–medium sandstone beds on each log. These were then thin-sectioned, and their composition analysed by point-counting the different grain types under a microscope. The aim was to see if there were any major compositional differences between or within the logs, which could represent differing source areas or changes in a given source area.

Fig. 4.3 shows the results of this process for Albella, Ligüerre de Ara and Lardiés. The composition of all of them is fairly similar – there are no obvious lateral discontinuities or vertical trends. It is therefore inferred that the sediments probably

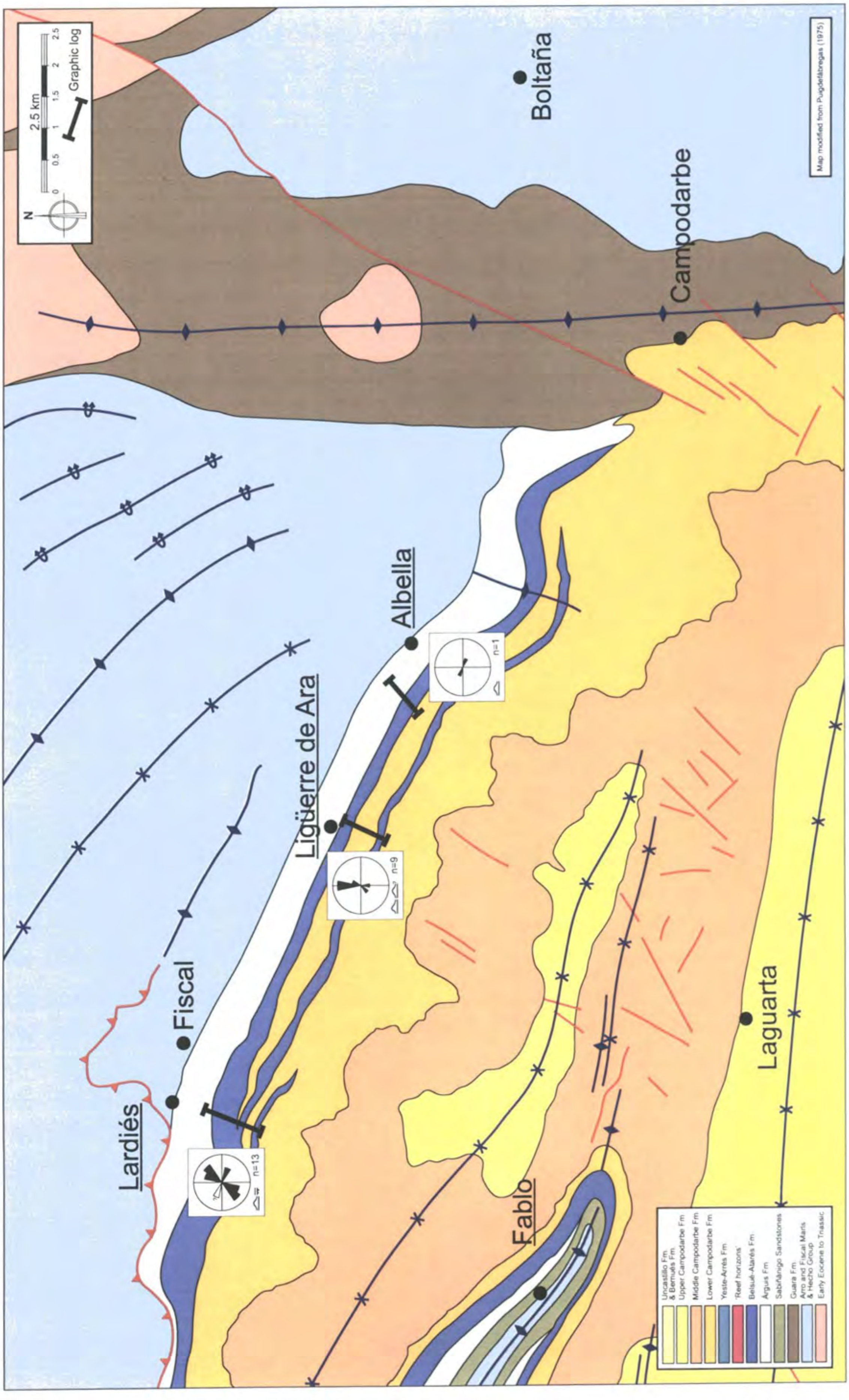


Fig. 4.2. Geological map of the Far NE Jaca Basin, with palaeocurrent rose diagrams for each log.

came from the same source area or areas, which also continued to yield more-or-less the same grain types throughout the deposition of the Belsué-Atarés Fm. There is however a fair degree of variability evident in the data, with no obvious 'average' composition. This could reflect limited variations within the source area or areas, or perhaps preferential sorting of the different grains by the varying depositional processes that operated within the Jaca Basin.

Each of the samples contains a few percent of a number of different 'exotic' grains, such as polycrystalline quartz grains, feldspars, opaque iron minerals, muscovite and chloritised biotite. Grains such as these must have originally come from igneous or metamorphic rocks, which in northern Spain are only found in the Pyrenean axial zone (Jones, 1997). Thus, the Belsué-Atarés Fm. in this area was fed sediments that originated, at least partly, in the high Pyrenees.

4.3 Correlation, interpretation and discussion

Section **4.2** covered the fundamental aspects of the marine growth strata of the Far NE Jaca Basin sector. This section, section **4.3**, takes these fundamentals and builds upon them, aiming towards fully understanding the mode of deposition of the Belsué-Atarés Fm. in an area apparently unaffected by growth structures.

This begins with a description and discussion of the good correlation that exists between the three graphic logs (section **4.3.1**). From this correlation, two multiple hundred-metre-scale sedimentary cycles can be identified within the strata (section **4.3.2**). The correlation also underlines the fact that all the logged sections were fines-dominated – something which can largely be ascribed to the influence of the nearby basin-scale Boltaña anticline (section **4.3.3**).

4.3.1 Correlation between graphic logs

Fig. 4.4 is a WNW–ESE-orientated correlation panel covering all three graphic logs. No palaeomagnetic or biostratigraphic dating has been undertaken in this area, so the correlation had to be constructed purely on the basis of facies. The Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary was used to determine the relative vertical positions of the logs. This contact is often sharp and always distinctive, and has been shown by Hogan & Burbank (1996) to have formed more or less synchronously across other parts of the Jaca Basin. However, because of the interfingering between the

Belsué-Atarés Fm. and Lower Campodarbe Fm. in this sector, it is clear that this boundary did not form synchronously here. This meant that the relative vertical positions of the logs on the correlation panel could not simply be determined by 'hanging' them from the base of the Lower Campodarbe Fm. Instead, the mapping of Puigdefàbregas (1975; **Fig. 4.1**) was used to determine which 'fingers' of each formation were which between logs. Then, the purely stylistic and geologically meaningless convention that progradations of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary should be 'instantaneous' (i.e. drawn as close to horizontal as possible), whilst any retrogradations should be 'diachronous' (i.e. drawn diagonally up to the ESE) was applied.

The implication of this is that the correlation panel is wholly stylistic, and while the vertical scale may be sediment thickness, this has no direct relationship to time. The formation boundaries and other lines of correlation noted merely indicate areas of the same facies association (depositional environment) on adjacent logs. These boundary surfaces and lines are most likely to be diachronous, so are not necessarily key surfaces of any sort.

Once the relative vertical positions of the logs had been determined, it could be seen that a good correlation exists between them. Both the Lardiés and Albella logs begin with offshore–transition zone marls and sandstones (FA2) of the Árguis Fm., which are overlain by the more sand-rich Belsué-Atarés Fm. In the east at Ligüerre de Ara and Albella, the Belsué-Atarés Fm. is 100 – 140-m-thick, the upper two-thirds of which is composed of marginal marine clays and sandstones (FA6). To the west, the correlative Belsué-Atarés Fm. package is around 90 m thick, but composed of the more distal offshore–transition zone marls and sandstones (FA2) and lower shoreface sandstones (FA3). In all logs this package of Belsué-Atarés Fm. is overlain by the Lower Campodarbe Fm., represented by 40 – 50 m of fluvial sandstones and red soils (FA12), with or without a small thickness of fluvial sandstones and floodplain fines (FA11) at its base.

This initial finger of Lower Campodarbe Fm. is, in the westernmost log at Lardiés, immediately overlain by nearly 220 m of marginal marine clays and sandstones (FA6) and upper shoreface and delta front sandstones (FA4) of the Belsué-Atarés Fm. Moving eastwards, this package of Belsué-Atarés Fm. thins markedly, so that only 6 km away at Ligüerre de Ara, it is represented by just two 5 – 15-m-thick packages, the rest being fluvial sandstones and floodplain fines of the Lower Campodarbe Fm. (FA11). This finger of Belsué-Atarés Fm. is not present in the easternmost log at Albella, which implies that the marine transgression it represents did not reach this far eastwards.

Back in the west at Lardiés, 30 m of FA11 of the Lower Campodarbe Fm. is overlain by a further 230 m of Belsué-Atarés Fm., heavily dominated by grey marls and yellow clays. This package of Belsué-Atarés Fm. is not represented further eastwards at Ligüerre de Ara or Albella. The Lardiés log ends with a final return to fluvial sandstones and floodplain fines (FA11) of the Lower Campodarbe Fm.

4.3.2 Sedimentary cycles

The WNW–ESE-directed back-and-forth movement of the marine–non-marine Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary recorded in this sector (**Fig. 4.4**) defines two transgressive–regressive cycles, above the initial regression of the boundary. In order to understand the mechanism responsible for their creation, it is first important to establish the length of time that each cycle represents. This is not a straightforward task however as no work on dating has been undertaken in the immediate area. However, palaeomagnetic dating in other parts of the basin may be of use. Roughly 10 km to the west of this sector at Yebra de Basa (Chapter 5), Hogan & Burbank (1996) showed that the base of the Sabiñánigo Sandstones to the base of the 'Santa Orosia fan delta' represented a stratigraphic thickness of 1115 m and a time span of 3.0 Myr, giving an average sediment accumulation rate of 0.37 mm/yr. 30 km to the SW of this sector at Árguis (Chapter 9), Pueyo *et al.* (2002) showed that the base of the Árguis Fm. to the base of the Lower Campodarbe Fm. represented a thickness of 1255 m and a time gap of 4.9 Myr, giving a rate of 0.26 mm/yr. Also in the Árguis area, Castelltort *et al.* (2003) used a combination of palaeomagnetic dating and estimated palaeobathymetries from facies analysis to suggest an average rate of about 0.2 mm/yr.

The average of the rates suggested by these three studies is 0.28 mm/yr. The range of depositional environments in the Belsué-Atarés Fm. of this sector the Jaca Basin is similar to those that the above-cited palaeomagnetic studies focused on. It seems reasonable to assume that, in the case of a subsidence-dominated basin such as Jaca Basin during its marine phase, the sedimentation rate across most parts of the basin with similar depositional environments was fairly constant. Thus, taking the thicknesses from the Lardiés log, the lower transgressive–regressive cycle is 257.6 m thick and so represents 0.92 Myr, whilst the upper cycle is 256.8 m thick and so also represents 0.92 Myr. Although the sedimentation rate used in these calculations may not be completely representative, it is still reasonable to say that the transgressive–regressive cycles had a repeat time of the order of 1 Myr.

The Ligüerre de Ara log also features a higher-order (shorter and thinner) transgressive–regressive cycle towards its top (Vol.2, p.58). This is 26.8 m thick, and so was around 96 kyr long. It is likely that there are other 100-kyr-order cycles preserved in the stratigraphy, but the highly distinctive nature of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary and its convenient lateral positioning around the Ligüerre de Ara log at the time of the cycle has made this one particularly easy to identify.

1-Myr-order and 100-kyr-order transgressive–regressive cycles may be caused by cyclical changes in one or more of the following: eustatic sea-level, regional subsidence rates, local tectonic deformation, and sediment supply / climate. The fact that the two 1-Myr-order cycles apparently have very similar repeat times suggests that only one of the above parameters varied (or, less likely, that two or more of the parameters varied in phase). Correlation with a eustatic sea-level curve is unfortunately not possible due to the lack of accurate dating in the area, although it is known that there were a number of sufficiently long-lived rises and falls in eustatic sea-level whilst the Belsué-Atarés Fm. and Lower Campodarbe Fm. were being deposited (Haq *et al.*, 1987; **Fig. 2.20**). It is also conceivable that episodic movement on the thrust that lay under the Jaca Basin or on structures to the north could cause local or regional scale uplift events, or variations in the rate of sediment supply. Climatic cycles, perhaps driven by orbital forcing, could be responsible for affecting the sediment supply rate, causing the 100-kyr-year order cycles. In a similar geological setting in the nearby Tremp–Graus Basin (for location see **Fig. 2.17**), Nijman (1998) showed that climatic cycles induced by orbital forcing caused a 100-kyr cyclicity in the Middle Eocene Montanyana Group.

However, determining the mechanism behind sedimentary cycles is a very involved process, which at the very least requires in-depth dating and sequence stratigraphic analysis, and perhaps three-dimensional computer modelling (e.g. Clevis *et al.*, 2004). These methods are far beyond the scope of this project – though are an obvious area for future work.

4.3.3 Influence of the Boltaña anticline

The Boltaña anticline is a 26-km-long, 4-km-across fold that lies at the eastern end of this sector of the basin (**Fig. 4.1**), and defines the boundary between the Jaca Basin and the Aínsa Basin to the east (Bentham *et al.*, 1992; **Fig. 2.17**). On the southern side of the Pyrenees, the sedimentary systems generally developed first in the east, and then prograded westwards (Chapter 2; Puigdefàbregas *et al.*, 1992). This is true of the Aínsa Basin, which had already undergone the transition from deltaic to fluvial sedimentation around the time that deltaic sediment was just being initiated in the Jaca Basin (Bentham *et al*, 1992; **Fig. 2.20**).

There has been considerable interest into the question of how the sediments that make up the Belsué-Atarés Fm. entered the Jaca Basin. Entry points that have already been suggested are from a point source through the central northern basin margin ('Santa Orosia fan delta' of Hogan & Burbank (1996) – see Chapter 5), from the SE corner of the basin (Nocito and Rodellar palaeovalleys implied by Dreyer *et al.*, 1999 – see Chapter 8), and from across the Boltaña anticline (Fig. 12(b) of Bentham *et al.*, 1992). It is of course quite likely that more than one sediment input point was operational during the deposition of the Belsué-Atarés Fm.

The nature of the sediments of the Belsué-Atarés Fm. in this sector indicates that the latter hypothesis – across the Boltaña anticline – is very unlikely. This is because of the strong dominance of marls and clays over sands, and the complete lack of development of proximal delta front channelised sandstones (FA5). The Lower Campodarbe Fm. is also unusually clay-rich and sand-poor. The fine nature of the sediments implies that rather than this part of the Jaca Basin being close to a sediment input point, it was instead in a 'protected' position, with much suspension settling of clays-grade sediments and only fairly limited influence from proximal deltaic or fluvial systems. The Belsué-Atarés Fm. close to of the other two possible basinal sediment input points contains a much greater proportion of sands (Chapter 5 & Chapter 8).

Thus, it seems that the Boltaña anticline acted as a barrier, preventing sand-carrying westward-prograding depositional systems entering the Jaca Basin across its eastern margin. This allowed mainly distal, fines-dominated sedimentation to occur in the Far NE Jaca Basin sector. Other evidence for the Boltaña anticline acting as a barrier comes from the fact that it is known to have deflected depositional systems that existed to its east before, during and after the deposition of the Belsué-Atarés Fm. (Jolley, 1987; Bentham *et al.*, 1992; Jones, 1997; Dreyer *et al.*, 1999).

4.4 Conclusions

The Belsué-Atarés Fm. in this sector of the Jaca Basin was deposited in a range of depositional environments, from offshore marine to upper shoreface, delta front and marginal marine settings. The presence of 'exotic' minerals such as chloritised biotite within the sandstones indicates at least partial sourcing of sediments from the Pyrenean axial zone. The Belsué-Atarés Fm. was however much poorer in sands and much richer in marls and clays than it is in almost any other parts of the basin. This was taken as evidence that this area was protected from major basinal sediment input points during Belsué-Atarés Fm. times. The structures thought to be responsible for this protection were the WNW–ESE-trending thrusts and related folds that define the present-day northern basin margin, and the basin-scale, N–S-orientated Boltaña anticline that defines the eastern basin margin. In order for the northern and eastern basin margins to act as barriers to depositional systems, the structures that define them must have been at least part-formed and actively uplifting during Belsué-Atarés Fm. times.

Two approximately 250-m-thick, 10-km-long transgressive–regressive cycles in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary were observed. Using an average sedimentation rate calculated for the Belsué-Atarés Fm. in other parts of the basin, these were found to have a repeat time of close to 1 Myr. A smaller-scale, higher order cycle of close to 25 m thickness and 100 kyr repeat time was observed at Ligüerre de Ara. The cause of both these orders of cycles was variations in eustatic sea-level, regional subsidence rates, local tectonic deformation, sediment supply and/or climate.

4.5 Key Points

1. Sedimentary infill of the basin:

- The most proximal facies of the Jaca Basin axial deltaic system were not deposited in this part of the basin.
- The Jaca Basin axial system was partly sourced in the Pyrenean axial zone.

2. Structural configuration of the basin:

- The northern margin of the Jaca Basin was structurally defined by actively uplifting, WNW–ESE-trending thrusts and related folds during Belsué-Atarés Fm. times.
- The eastern margin of the basin was structurally defined by an actively uplifting Boltaña anticline during Belsué-Atarés Fm. times.

3. Influence of intrabasinal growth structures:

- Intrabasinal growth structures were not present in this sector the basin.

4. Effect of sea-level changes:

- Transgressive–regressive cycles in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary, with a length of about 10 km, a thickness of approximately 250 m, and a repeat time of around 1 Myr, were recorded.
- Higher order transgressive–regressive cycles in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary, with a thickness of approximately 25 m and a repeat time of around 100 kyr, were observed at Ligüerre de Ara.

The next chapter, Chapter 5, discusses the northern basin margin further to the west, where a major coarse-grained depositional system, sourced in the Pyrenean axial zone, was able to gain entry into the basin. Once in the basin, the coarse-grained system interacted with the axial depositional system and a major kilometre-scale growth anticline.

Chapter 5:

NE Jaca Basin

5. NE Jaca Basin

Contents

5. NE Jaca Basin

5.1 Introduction

The northern margin of the Jaca Basin, along which approximately half of the Belsué-Atarés Fm. outcrops occur, has received only very little attention from geologists. One part of the margin has however been mentioned a few times in previously published literature – because it contains an unusual feature of particular interest. That feature is the Santa Orosia fan delta, and the area in which it lies is the focus of this chapter – the NE Jaca Basin sector.

Fan delta systems frequently make an important contribution of coarse, poorly sorted, pebbly sediments to sedimentary basins in many tectonically active settings (Nemec & Steel, 1988). However, most of the examples of fan deltas described in the literature come from areas dominated by extensional tectonics (e.g. Purvis & Robertson, 2005; Sohn & Son, 2004). Few come from compressional settings (e.g. Marzo & Anadón, 1988; López-Blanco, 1993), and even fewer come from actively deforming, thrust-top settings. Thus, the Santa Orosia fan delta provides an extremely valuable opportunity to study the effects that local-scale and regional-scale compressional tectonic deformation may have on a coarse-grained, point-sourced, marine depositional system.

Understanding the way in which the fan delta system competes with the other depositional systems in the receiving basin, for example, the large-scale axial system of a foreland basin, is of critical importance because the nature of the fan delta sedimentation tends to be dramatically different to that of the other systems. Recent computational work by Clevis *et al.* (2004) has suggested some ways in which the various systems may compete under differing tectonic and sea-level conditions, but these have yet to be tested in the field. It is hoped that the facies relationships described in this chapter should shed further light on this.

The Santa Orosia fan delta is a unique feature in the Belsué-Atarés Fm. of the Jaca Basin. However, it is not presently known why it formed where it has. It is likely that the answer is related to the folds and thrust that outcrop just to the NE of the conglomerates, although nothing is immediately obvious from geological maps (Puigdefàbregas, 1975). If the reason for the location of the Santa Orosia fan delta can be determined by this work, then this would be of great importance for understanding the structural development of the Jaca Basin, and for the entry of fan deltas into compressional basins in general.

The aims of this chapter are to determine the configuration of the northern basin during Belsué-Atarés Fm. times and so help explain the location of the Santa Orosia fan delta, to understand how the fan delta interacted with the basinal depositional systems, and to determine what role sea-level fluctuations and local tectonics played. These aims will be achieved with the use of basic sedimentological observations, such as those of facies and facies associations, palaeocurrents and sediment provenance (section **5.2**), and the construction of correlation panels and models of sedimentation (section **5.3**).

5.2 Graphic logs of the NE Jaca Basin sector

This sector of the field area lies to the south-east of the town of Sabiñánigo and south-west of the village of Fiscal (**Fig. 5.1**). It covers part of the northern basin margin, which here is defined by two WNW–ESE-trending, kilometre-scale, thrust-related anticlines. Four graphic logs were completed through the Belsué-Atarés Fm., each beginning in the Árguis Fm. and ending in the Lower Campodarbe Fm. The locations of the logs are indicated on **Fig. 5.1**, and each is also reproduced, in both summary and original full-scale version, in the appendices in Vol.2.

Log name	Summary log	Original log
Fablo	Vol.2, p.11	Vol.2, p.66 – 70
Fanlillo	Vol.2, p.12	Vol.2, p.71 – 75
Yebra de Basa	Vol.2, p.13	Vol.2, p.76 – 82
San Julián de Basa	Vol.2, p.14	Vol.2, p.83 – 89

The crest of more southerly of the WNW-ESE-trending basin-defining structures divides the more northerly three logs (Fablo, Fanlillo and Yebra de Basa) from the more southerly one (San Julián de Basa).

This part of the Jaca Basin is very poorly covered in the literature – since it was first mapped by Puigdefàbregas (1975), it has only ever been specifically referred to by Hogan & Burbank (1996). These authors were the first to refer to conglomerates that lie to the northeast of Yebra de Basa as the 'Santa Orosia fan' and the 'Santa Orosia fan delta'. Their principal work in this part of the basin was a palaeomagnetic study at Yebra de Basa, which began in the 'Arro and Fiscal Marls & Hecho Group', and ended

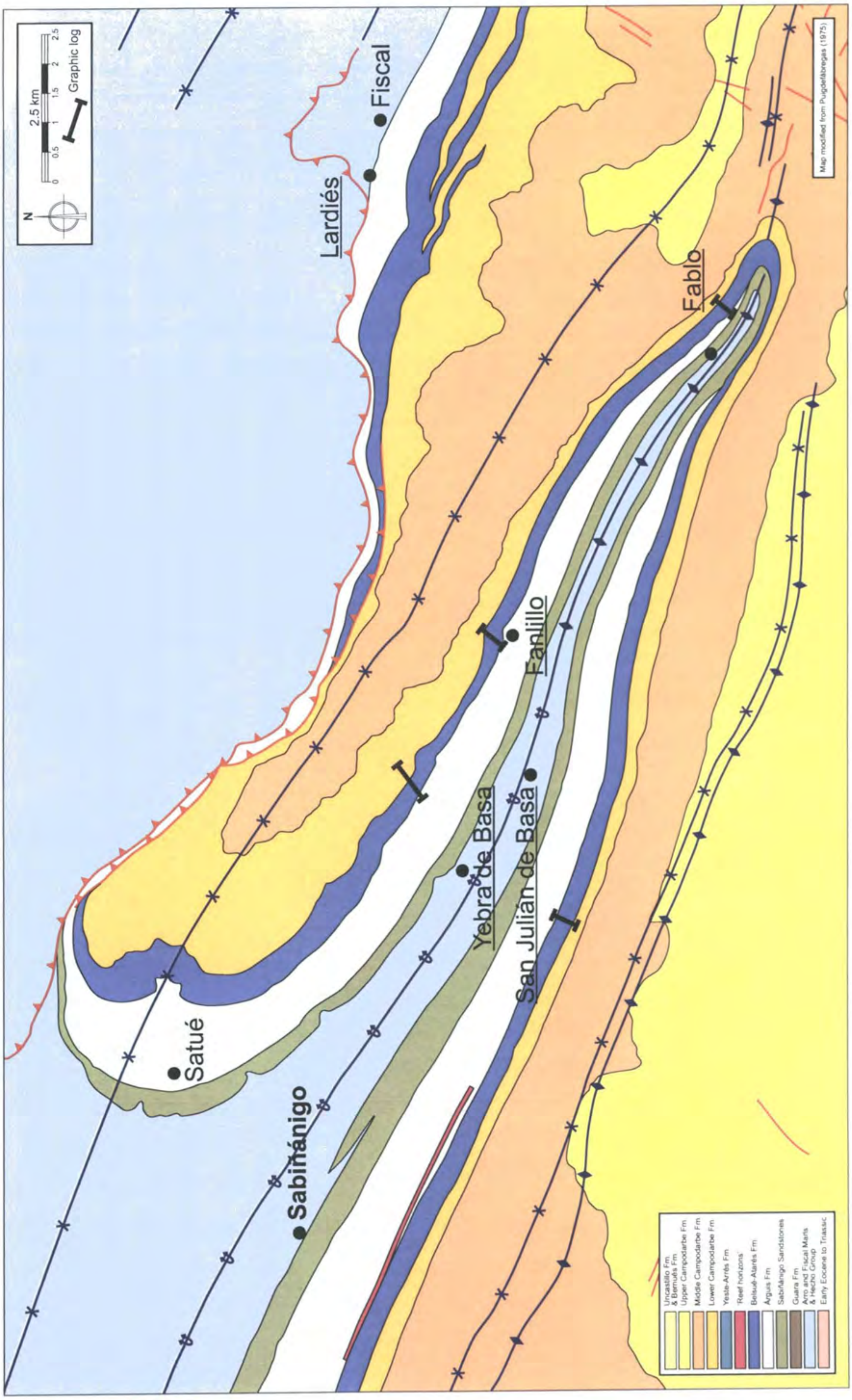


Fig. 5.1. Geological map of the NE Jaca Basin, indicating the positions of the four graphic logs.

in the Middle Campodarbe Fm. (**Fig. 5.1**). Unfortunately their resulting palaeomagnetic section consisted of almost all normal polarity samples, and was therefore not easy to reliably correlate with sections undertaken in other parts of the basin, or the magnetic polarity time scale (**Fig. 5.2**). Nevertheless, the authors suggested some absolute age dates for various important boundaries in the Yebra de Basa section. They stated that the turbiditic deposition terminated at 40.0 Ma (i.e. top of 'Arro and Fiscal Marls & Hecho Group' / base of Sabiñánigo Sandstones), and that "the Santa Orosia fan delta prograded southwards across the Belsué-Atarés delta at ~37.0 Ma". Correlation with their other palaeomagnetic sections implies a date of 37.5 Ma for the base of the Belsué-Atarés Fm., as they define it, at Yebra de Basa.

It is however important to note that there has never been a clear definition for the base of the Belsué-Atarés Fm., because of the gradational nature of the contact with the underlying Árguis Fm. The definition used in this work is that the base of the Belsué-Atarés Fm. lies at the base of the first sand-dominated facies association (FA3 or greater; section **3.3.3**) that is not immediately overlain by thick (> 50 m) marly facies associations (FA1 or FA2; sections **3.3.1 – 3.3.2**), and is traceable into adjacent logs. This criterion was chosen as it provides a laterally persistent and recognisable boundary in the field, and is primarily based on observations of lithology, rather than any interpretation of depositional environment. Hogan & Burbank (1996) placed the formation boundary almost 200 m higher on their Yebra de Basa section, coinciding with the base of the first unambiguously deltaic facies association (FA5; section **3.3.5**).

5.2.1 Facies, facies associations and facies architecture

All four logs display a broadly similar trend throughout their thickness: each begins with thick offshore marine marls (FA1; section **3.3.1**), and ends with an abrupt transition to either alluvial fan conglomerates (FA10; section **3.3.10**), fluvial sandstones and floodplain fines (FA11; section **3.3.11**), or fluvial sandstones and red soils (FA12; section **3.3.12**). In between, lower shoreface sandstones (FA3; section **3.3.3**) are overlain first by upper shoreface and delta front sandstones (FA4; section **3.3.4**), and then by proximal delta front channelised sandstones (FA5; section **3.3.5**). Fan delta front conglomerates (FA9; section **3.3.9**) feature on the Yebra de Basa log, and to a lesser extent, on the San Julián de Basa log. Thus each of the logs describes a broadly shallowing upwards or progradational trend. There are however numerous small-scale

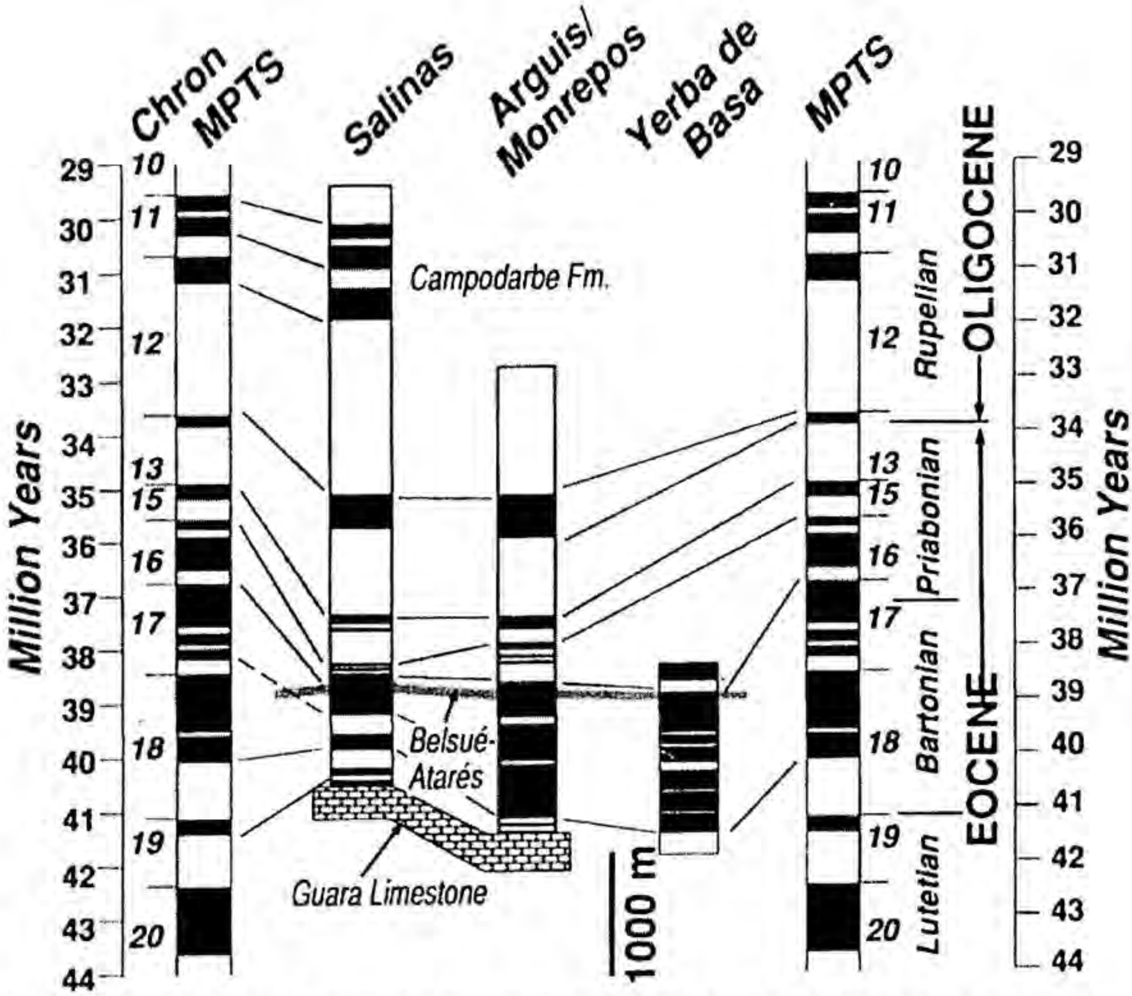


Fig. 5.2. Correlation of magnetic sections from across the Jaca Basin with the magnetic polarity time scale of Cande & Kent (1992). (From Hogan & Burbank, 1996.)

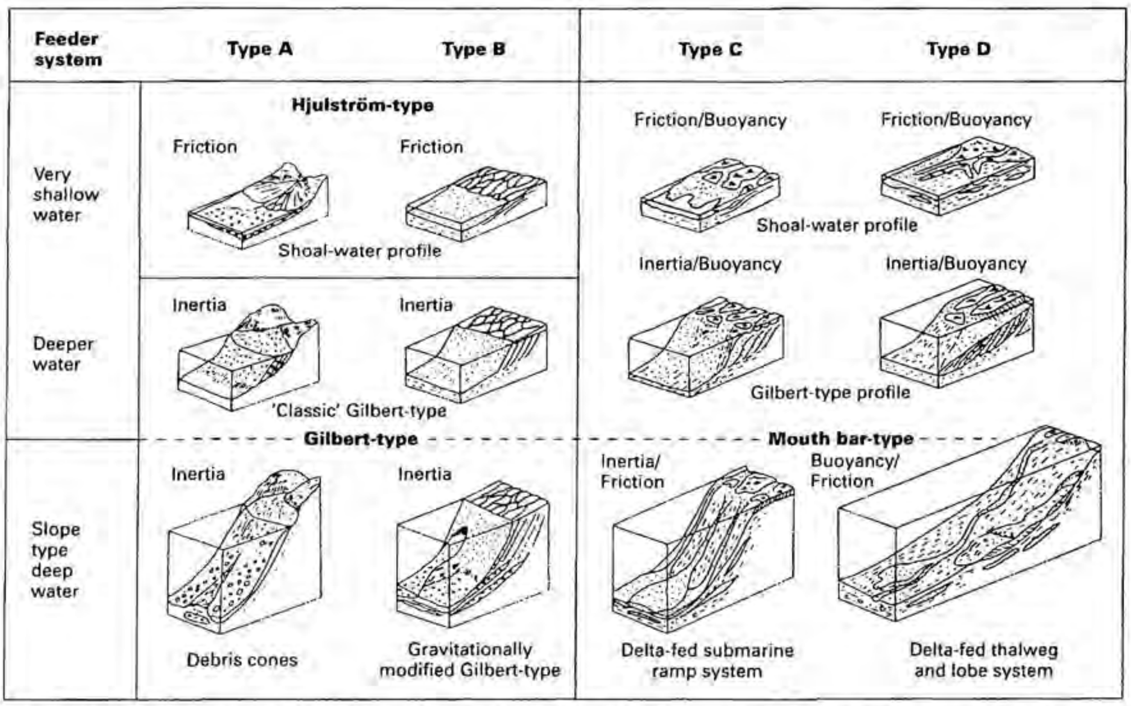


Fig. 5.3. A delta classification scheme based on feeder system type and water depth (Postma, 1990). (From Reading & Collinson, 1996.)

reversals to this trend, where deeper water / more distal facies associations overlie shallower / more proximal ones.

The Fablo log (Vol.2, p.10 & p.66 – 70), the most easterly log in this sector, is notable for having by far the highest sand to marl ratio in its upper half. Whilst on most other logs the ratio is about 1:1, at Fablo there is very little marl at all, giving a ratio of close to 5:1. Also of note is that the vast majority of beds fine upwards.

Moving west, the Fanlillo log (Vol.2, p.12 & p.71 – 75) is notable for a pronounced marine transgression in its upper half (from FA5 to FA1), and a few beds of matrix-supported conglomerates facies (section **3.2.13**) in the Lower Campodarbe Fm.

The next log to the west is the Yebra de Basa log (Vol.2, p.13 & p.76 – 82). This one contains the best examples of fan delta front conglomerates (FA9; section **3.3.9**) and alluvial fan conglomerates (FA10; section **3.3.10**) seen in the area, appearing in the Belsué-Atarés Fm. and Lower Campodarbe Fm. respectively. A detailed discussion of these important deposits is given in section **5.2.2**.

The westernmost log of the four was at San Julián de Basa (Vol.2, p.14 & p.83 – 89). This log is very different from the other three because it contains more than 500 m of frequently fining-upwards, rip-up clast rich sands of FA4, from the base of the Belsué-Atarés Fm. up to almost the base of the Lower Campodarbe Fm. This is in marked contrast to the other logs, which are made up of marl-dominated facies associations in their lower halves. Also, towards the top of the log, a relatively thin package (11.2 m) of fan delta front conglomerates (FA9) is present.

5.2.2 Fan delta and alluvial fan deposits of Yebra de Basa

The Yebra de Basa log (Vol.2, p.13) contains the best examples of fan delta front conglomerates (FA9; section **3.3.9**) and alluvial fan conglomerates (FA10; section **3.3.10**) seen in the Belsué-Atarés Fm. They are collectively referred to as the Santa Orosia fan delta and fan, respectively, after Hogan & Burbank (1996). These very proximal facies associations are only found in the Belsué-Atarés Fm. in this sector of the Jaca Basin. Their uniqueness, and the fact that they abut against the structurally defined basin margin suggest that these deposits represent an unusual and important input point for coarse, pebbly sediments to gain access to the Jaca Basin.

These facies associations have been described in detail already (sections **3.3.9** – **3.3.10**). It is however worth looking at them to see if this unusual sediment input point can be placed within a delta classification scheme (section **5.2.2.1**), to assess the size

alluvial fan beds (FA10) dip at an angle of 26° to the NE. In between, the fan delta front deposits dip at 18° to the NE. If the prodelta and bottomset units were deposited horizontally, then the delta front would have had a depositional dip angle of 16° to the SW (18° to NE minus 34° to NE), and the subaerial alluvial fan beds an angle of 8° to the SW (26° to NE minus 34° to NE). Although the post-depositional growth of an anticline to the NE of the fan delta (**Fig. 5.1**) probably means that the actual depositional angle of the delta front was somewhat less than 16°, it still seems probable that it was relatively steep – of the Gilbert type. A steep delta front angle would be likely to cause debris flows, which would tend to form the type of internally massive, clast-supported sheets of conglomerate that were observed in the fan facies – described in section **3.3.9** (Walker, 1978; Postma, 1984; Sohn & Son, 2004).

Thus, on the Postma (1990) scheme, the Santa Orosia fan delta would be classified as a Type A-fed, classic Gilbert-type delta.

5.2.2.2 Dimensions and significance of the Santa Orosia fan delta

The size and importance of the Santa Orosia fan delta is best considered by comparing it to other well-studied fan delta systems in similar settings. The Montserrat fan delta complex of the SE margin of the Ebro Basin (**Fig. 5.4**; Marzo & Anadón, 1988) is particularly appropriate for this because it formed at almost exactly the same time, in an adjacent basin, and also in a broadly compressive tectonic regime. It initially formed as an alluvial fan, sourced in the Catalan Coastal Ranges, but was converted to a fan delta by the Biarritzian marine transgression in the late Lutetian (41.5 Ma) – the same event that caused the drowning of the Guara Fm. carbonate platform in the Jaca Basin (section **2.4.3.2**).

The Montserrat fan delta complex is considered to be a fairly large and significant system, being 6 km long (into the basin), 8 km wide, and with a total accumulated thickness of more than 1300 m (including 'subaerial fan delta facies'). It is not completely straightforward to work out the dimensions of the Santa Orosia fan delta, due to post-depositional folding and erosion. However, the area over which conglomerates are known to occur in the Belsué-Atarés Fm. implies that the fan delta system was around 8 km wide, at least 4 km long (into the basin), and 130 m thick (426 m – 556 m on the Yebra de Basa log; Vol.2, p.80 – 81). In the Lower Campodarbe Fm., the conglomerates are spread over an even wider area (up to 14 km across), and are

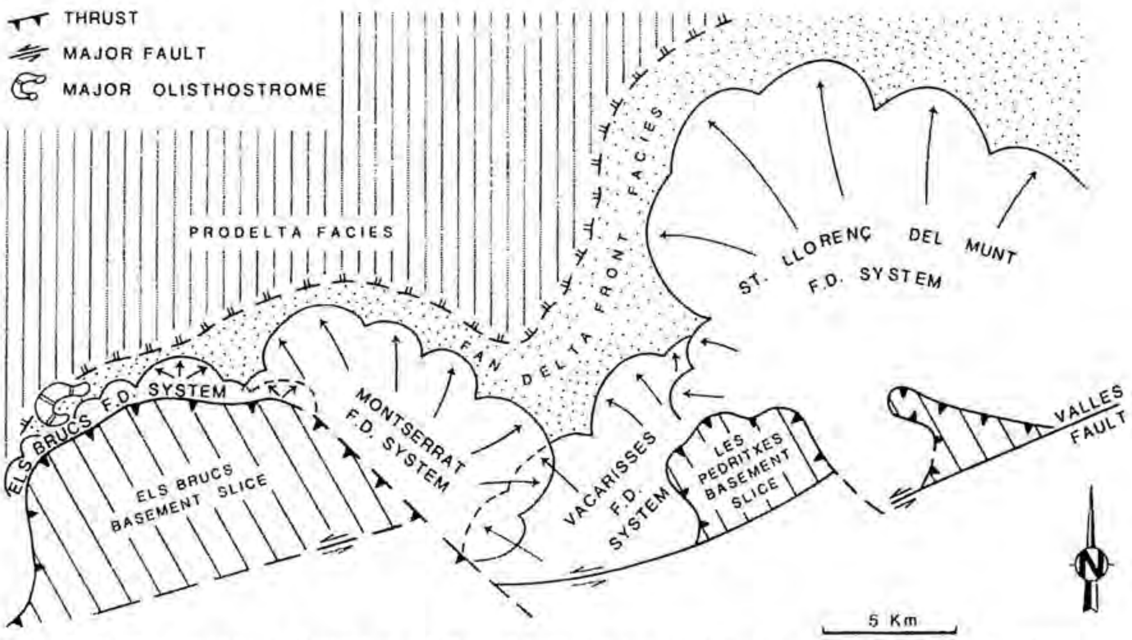


Fig. 5.4. The geological setting of the Montserrat and Sant Llorenç del Munt fan delta complexes. (From Marzo & Anadón, 1990.)

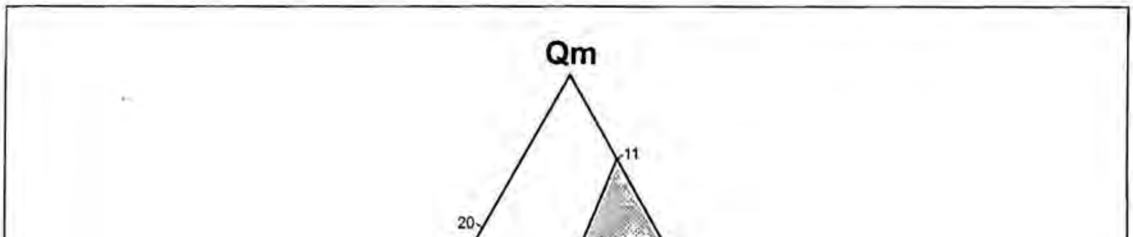


Fig. 5.7. Ternary diagram of sediment compositions at Yebra de Basa and San Julián de Basa. Classification of provenance after Dickinson (1985).

more than 1000 m thick, suggesting that the alluvial fan that superseded the fan delta was a large and long-lived depositional system.

Thus, although the Santa Orosia fan delta deposits were not as thick as those of the Montserrat system, the area of the basin over which they outcrop was very similar, so the Santa Orosia system can be thought of as a large and important system for the Jaca Basin just as the Montserrat system is for the Ebro Basin (Marzo & Anadón, 1988).

5.2.2.3 Controls on the Santa Orosia fan delta

Because the Santa Orosia fan delta was of significant size and thickness (section **5.2.2.2**), it was probably fed by a relatively large drainage basin (Collinson, 1996). The fact that the fan delta top (alluvial fan portion) was dominated by mass-flow processes (section **3.2.14**; section **5.2.2.1**) makes it likely that this drainage basin existed in an arid or semi-arid climate, where rainfall tended to be intense but episodic.

Marzo & Anadón (1988) interpreted the fact that the deposits of the Montserrat fan delta system were very thick (1300 m), relative to the area over which they outcrop, to imply rapid subsidence and fan aggradation at the basin margin. The fact that the deposits of the Santa Orosia system are much thinner (130 m thick), but outcrop over a similar area, could therefore mean that subsidence was relatively slow at the margin of the Jaca Basin. However, the fact that the fan delta was of the Gilbert type, with a steep front of 8 – 16° (section **5.2.2.1**), implies that it was not prograding into very shallow water (Postma, 1990). Sohn & Son (2004) found that in the Pohang Basin, SE Korea, the development of steep-fronted Gilbert-type fan deltas was limited to areas of the basin margin where high levels of fault activity had caused steepening of the margin and rapid subsidence in the adjacent basin.

The Santa Orosia fan delta is the only fan delta known to have formed during the infill of the Jaca Basin. Its existence and location are most probably related to the WNW–ESE-tending thrusts that outcrop about 4 km to the NNE of Yebra de Basa (**Fig. 5.1**). These same structures stretch for some 50 km along strike, defining a large part of the northern basin margin (**Fig. 1.3**). It is likely that a specific smaller-scale structure offering a weakness or topographic low through the northern basin margin existed a few kilometres to the NE of Yebra de Basa (such as a fault relay or a transfer fault), and was exploited by the alluvial fan feeder system. However, no such structure is visible in the outcrop of this area today, probably as a consequence of subsequent uplift and erosion.

5.2.3 Palaeocurrents

Nearly all palaeocurrent readings in this sector were taken from symmetrical ripples, indicating that wave reworking of sands (but not the conglomerates) was an important process in the Jaca Basin (**Fig. 5.5**). At Yebra de Basa, the trend of wave rippling is clearly defined as NNE–SSW. Further east at Fanlillo and Fablo, this swings around clockwise a little to NE–SW or ENE–WSW. As wave rippling is usually directed normal to the coastline, these trends suggest that the shoreline (i.e. the basin margin) was oriented roughly WNW–ESE in this sector. This happens to be parallel to the major thrusts that define the present-day northern basin margin – in this area and across the rest of the basin (**Fig. 5.5**; **Fig. 1.3**). Thus these palaeocurrent trends suggest that the northern basin was defined by the WNW–ESE-trending structures at the time that the Belsué-Atarés Fm. was being deposited.

Although very few unidirectional palaeocurrent indicators seem to have escaped the basinal wave reworking of sands, those that did (flute casts and cross-lamination from beds of medium, cross-laminated sandstones facies; section **3.2.7**) indicate flow towards the south. This flow direction is in agreement with the idea that there was south-directed flow across the northern basin margin into this part of the Jaca Basin.

To the south of the large anticline that separates Yebra de Basa from San Julián de Basa (**Fig. 5.5**), the wave-rippling trend is a little more erratic. Although the mean trend at San Julián de Basa is still roughly NNE–SSW, there is much more dispersion around this average. This may be because this section is further from the basin margin and so was affected by basinal currents of varying directions.

5.2.4 Sediment composition

During the logging, samples were collected from several fine–medium sandstone beds on each log. These were then thin-sectioned, and the sediment composition analysed by point-counting the different grain types under a microscope. **Fig. 5.6** shows the composition data from the Yebra de Basa and San Julián de Basa specimens. It was felt that these two sections – one close to the basin margin, the other about 4 km further into the basin, would be the most likely to exhibit compositional differences. The composition of specimens from Fablo and Fanlillo was also analysed, but is not included on **Fig. 5.6** for clarity and because the compositions were very similar to those

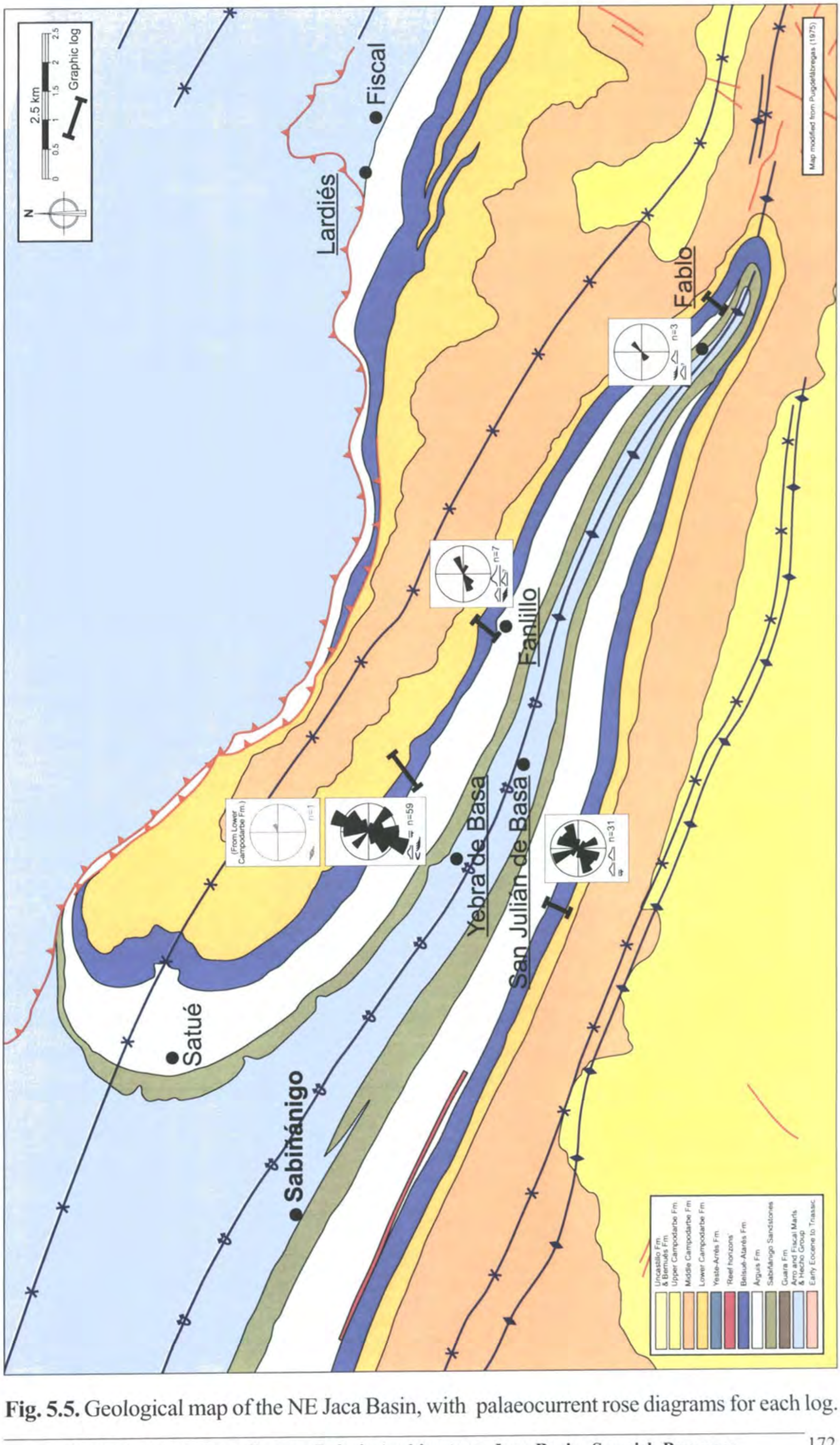


Fig. 5.5. Geological map of the NE Jaca Basin, with palaeocurrent rose diagrams for each log.

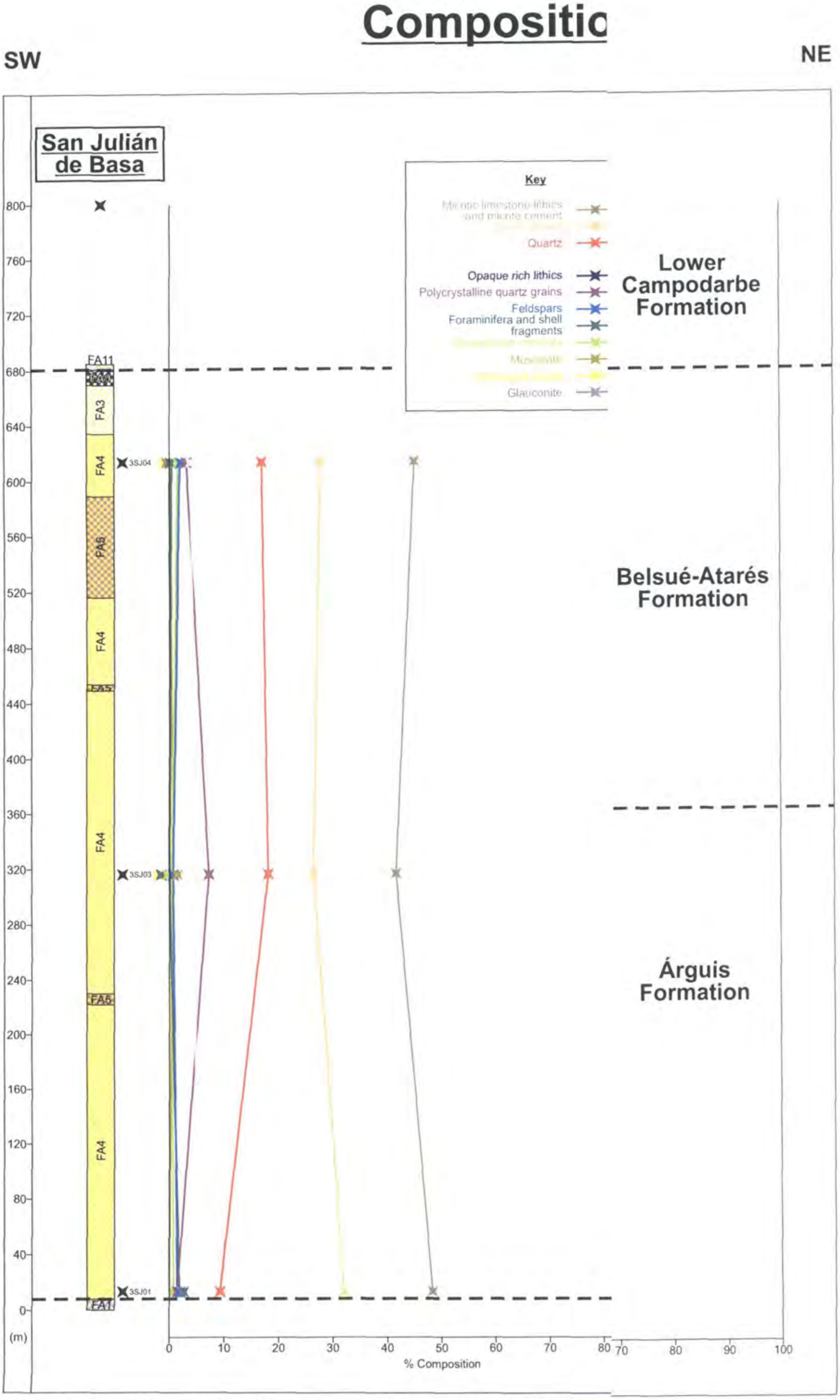


Fig. 5.6. Comparison of sediment compositions at San Julián de Ba

from the first two logs. It was also noted that each of the specimens had a very similar texture when viewed down the microscope – poorly sorted, angular grains.

The composition data from Yebra de Basa and San Julián de Basa was also plotted on a Qm–F–Lt ternary diagram (monocrystalline quartz – feldspars – total lithics including polycrystalline quartz; **Fig. 5.7**). Dickinson (1985) showed that sediments with similar types of provenance terrane plotted within certain defined fields on the Qm–F–Lt diagram. All specimens from Yebra de Basa and San Julián de Basa fall into the 'lithic recycled' sub-field of the 'recycled orogen' field on the Dickinson scheme. Because of the near lack of high-grade metamorphic and igneous rocks in the axial zone, this is what would be expected for sediments found in a foreland basin of the Pyrenees.

Fig. 5.6 and **Fig. 5.7** both indicate that there are no significant differences in composition between the sediments of the Yebra de Basa log and those from San Julián de Basa. This implies that the two localities were supplied with sediment from the same source area (i.e. drainage basin or basins). This finding does not however preclude that the sediments, although coming from the same place, may have reached the positions of the two sections via different sediment transport paths.

Fig. 5.6 and **Fig. 5.7** also show that sediment composition does not vary systematically (or even significantly) throughout the thickness of the two logs. There is however one exception to this, visible in the Yebra de Basa data at the Belsué-Atarés Fm. – Lower Campodarbe Fm. boundary on **Fig. 5.6**. Across this boundary, there is a 10% drop in the quantity of micritic limestone lithics, a corresponding 10% increase in calcite grains, and a number of smaller but significant variations in some other grain types. This fairly large and abrupt change in composition probably reflects different (or partly different) source areas for the marine Belsué-Atarés Fm. and the non-marine Lower Campodarbe Fm. From the clast-types present, Jolley (1987) determined that the Lower Campodarbe Fm. in this sector of the Jaca Basin was sourced in the Pyrenean axial zone directly to the north.

It was noted that each the samples from all of the sections contained a few percent of a number of different 'exotic' grains, such as polycrystalline quartz grains, feldspars, opaque iron minerals, muscovite and chloritised biotite. Grains such as these must have originally come from igneous or metamorphic rocks, which in northern Spain are only found in the Pyrenean axial zone (Jones, 1997). Thus, the Belsué-Atarés Fm. in this area was fed sediments that originated in the high Pyrenees.

5.3 Correlation, interpretation and discussion

Section **5.2** covered the fundamental aspects of the marine and early non-marine growth strata of the NE Jaca Basin sector. This section, section **5.3**, builds upon these fundamentals, aiming towards fully understanding the controlling mechanisms behind the rapid lateral and vertical changes in facies that characterise this area.

The first stage of this is the discussion of the level of correlation that exists between the four graphic logs (section **5.3.1**). This should allow the identification of any structural controls on sedimentation in the area, and the proposal of a palaeogeographical model (section **5.3.2**). Finally, a discussion of the evidence for changes in relative sea-level during the deposition of the Belsué-Atarés Fm., and the potential causes of this, will be given (section **5.5.3**).

5.3.1 Correlation between graphic logs

Fig. 5.8 and **Fig. 5.9** are two correlation panels for the four logs completed in the NE Jaca Basin sector. The first is orientated WNW–ESE, and the second is orientated almost perpendicularly at SW–NE. Correlation panel 1 (**Fig. 5.8**) has been drawn with the standard vertical exaggeration of ×10, as used on most correlation panels in this thesis. Correlation panel 2 (**Fig. 5.9**) has been drawn with a reduced vertical exaggeration of ×4 but with the standard vertical scale, allowing the two very closely spaced logs to be drawn further apart than normal. On both panels, all logs are 'hung' from the Belsué-Atarés Fm. – Lower Campodarbe Fm. boundary – a contact that is sharp and distinctive across the entire Jaca Basin (Hogan & Burbank, 1996).

These correlation panels are however constructed purely on the basis of facies similarities, because palaeomagnetic dates were only available for the Yebra de Basa log and rough terrain made 'walking out' of beds impossible. The Belsué-Atarés Fm.– Lower Campodarbe Fm. boundary has already been shown to be diachronous – in places – by its succession of progradations and retrogradations in the Far NE Jaca Basin sector (Chapter 4). This means that the base of the Lower Campodarbe Fm. in this sector may well also be diachronous to some degree. Therefore, these correlation panels should be considered to be wholly stylistic. Whilst the vertical scales may be sediment thickness, these have no direct relationship to time. All the formation boundaries and lines of correlation marked merely indicate areas of the same facies association (depositional environment) on adjacent logs, are most likely to be diachronous, and so are not necessarily key surfaces of any sort.

The palaeomagnetic dates calculated by Hogan & Burbank (1996) have been included at their appropriate heights alongside the Yebra de Basa log on both correlation panels.

5.3.1.1 Correlation panel 1: WNW–ESE

Correlation panel 1 (**Fig. 5.8**) shows that there is a good degree of correlation between the Yebra de Basa, Fanlillo, and Fablo logs. The Yebra de Basa and Fablo logs begin with the offshore marine marls (FA1; section **3.3.1**) of the Árguis Fm., which are though to be beneath the base of the Fanlillo log. The first package of lower shoreface sandstones (FA3; section **3.3.3**), seen at Yebra de Basa and Fablo, is taken to represent the base of the Belsué-Atarés Fm. Within the Belsué-Atarés Fm., at around 160 m on the vertical scale, there is a package of upper shoreface and delta front sandstones (FA4; section **3.3.4**) that seemingly occurs on both the Yebra de Basa and Fanlillo logs. Above this point, the sand content of the Belsué-Atarés Fm. generally increases gradually for several hundreds of metres.

However, at around 415 m on the vertical scale and 37.5 Ma (Hogan & Burbank, 1996), a sudden and profound change occurs in the Belsué-Atarés Fm. succession on all logs: the marl-rich lower shoreface sandstones (FA3) are suddenly replaced by upper shoreface and delta front sandstones (FA4) or proximal delta front channelised sandstones (FA5; section **3.3.5**). These proximal facies associations persist on all sections for the remaining 150 – 190 m up to the base of the Lower Campodarbe Fm. (37.0 Ma; Hogan & Burbank, 1996). The only exception to this is the final 30 m of Yebra de Basa log, where the distinctive fan delta front conglomerates (FA9; section **3.3.9**) are seen. The uniqueness of the Yebra de Basa section is maintained into the Lower Campodarbe Fm. with alluvial fan conglomerates (FA10; section **3.3.10**) – the other two sections finish with the largely conglomerate-free fluvial sandstones and floodplain fines (FA11; section **3.3.11**).

In summary, the three logs on this correlation panel describe very similar coarsening upwards trends throughout the Belsué-Atarés Fm., from offshore marine marls (FA1) up to proximal delta front channelised sandstones (FA5). This trend is mostly gradual, but a sudden and major progradation of depositional environments occurs at 37.5 Ma on all sections. The fan delta conglomerates (FA9) are restricted to the uppermost portions of the Yebra de Basa and San Julián de Basa logs.

5.3.1.2 Correlation panel 2: SW–NE

Correlation panel 2 (**Fig. 5.9**) indicates that there is no correlation between the San Julián de Basa log and the Yebra de Basa log for the majority of the succession. Although both logs being with the offshore marine marls of the Árguis Fm., almost the entire thickness of the San Julián de Basa log is made up of upper shoreface and delta front sandstones (FA4) and proximal delta front channelised sandstones (FA5). Just 3.4 km away to the NE, the corresponding part of the Yebra de Basa section is made of further offshore marine marls (FA1), gradually grading upwards into lower shoreface sandstones (FA3). The first signs of any correlation between the two logs occurs at just below 520 m on the vertical scale (37.5 Ma; Hogan & Burbank, 1996), with the sudden arrival of proximal delta front channelised sandstones on both sections. This rapid change in depositional environment was also evident across the logs of correlation panel 1 (section **5.3.1.1**). From this point on, the two sections appear to be very similar: 70 m of proximal delta front channelised sandstones (FA5) are followed by 50 m of upper shoreface and delta front sandstones (FA4). Both sections end with the fan delta front conglomerates (FA9) – 30 m thick at Yebra de Basa, and 11 m thick at San Julián de Basa.

In summary, the lower two-thirds of the San Julián de Basa is much more sand-rich than the Yebra de Basa section, which is surprising as the latter section is closer to the Santa Orosia fan delta sediment input point. At 37.5 Ma, proximal delta front channelised sandstones arrive on both sections, and good correlation exists between the two at least as far as the end of the logs in the lowermost Lower Campodarbe Fm.

5.3.2 Barrier effect of the Río Basa anticline

The Río Basa anticline is thought to be the reason for the profound differences between the Yebra de Basa and San Julián de Basa sections. The 'Río Basa anticline' is the name hereby proposed for the kilometre-scale thrust-related anticline, the axial trace of which runs along the Río Basa between the villages of Yebra de Basa and San Julián de Basa (and the logged sections of the same names). The axial trace of this structure, or the surface expression of the thrust that created it, runs for 65 km in a WNW–ESE trend

(**Fig. 1.3**). Most of this length is to the WNW of Yebra de Basa, where the fold / thrust is one of several similar, parallel structures that define the present-day northern basin margin. What is not clear, and has never been tackled by previous research, is whether these WNW–ESE-trending structures such as the Río Basa anticline existed during the deposition of the Belsué-Atarés Fm. Work on the previously unstudied outcrops of the Belsué-Atarés Fm. from the northern margin of the Jaca Basin, presented in this chapter and subsequent chapters, should help determine this.

The Río Basa anticline is represented schematically on correlation panel 2 (**Fig. 5.9**). The most likely explanation for great differences between the Yebra de Basa and San Julián de Basa sections (which are only 3.4 km apart) is the growth of this anticline during the deposition of the Belsué-Atarés Fm. The topographic relief created by the growing structure would have separated the depositional system that operated at Yebra de Basa from the one that operated at San Julián de Basa. The evidence that the Río Basa anticline actually grew during the deposition of the Belsué-Atarés Fm., rather than had already fully grown previously, is that a thinned Belsué-Atarés Fm. succession is present on the crest of the structure (visible 2 km ESE of the Fablo section; **Fig. 5.1**).

The obvious question raised by the idea of growing Río Basa anticline is: why is the Yebra de Basa section, which is on the fan delta side of the anticline, generally dominated by marls, whereas the San Julián de Basa section, to the basinal side of the structure, is much richer in sands? An answer to this is presented in **Fig. 5.10** and described below. The first deposition in the area recorded on the logs was a drape of marls of the Árguis Fm. (**Fig. 5.10A**). On top of these, the main Jaca Basin axial depositional system (a deltaic complex that generally prograded along the basin axis towards the WNW; Puigdefàbregas, 1975) deposited the upper shoreface and delta front sandstones (FA4) that make up the majority of the San Julián de Basa section (**Fig. 5.10B**). At the same time, the area to the north of the growing Río Basa anticline was sheltered from the Jaca Basin axial deltaic system, and sedimentation there was dominated marl-rich lower shoreface sandstones (FA3). This also implies that the Santa Orosia fan delta was yet to provide any significant quantities of coarser sediments.

At 37.5 Ma (Hogan & Burbank, 1996), a major progradation of depositional environments caused upper shoreface and delta front sandstones (FA4) and proximal delta front channelised sandstones (FA5) to suddenly arrive on all the logged sections (**Fig. 5.10C**). The probable cause of this was a drop in relative sea-level. At around the same time, the first clast-supported conglomerates facies (section **3.2.14**) from the Santa

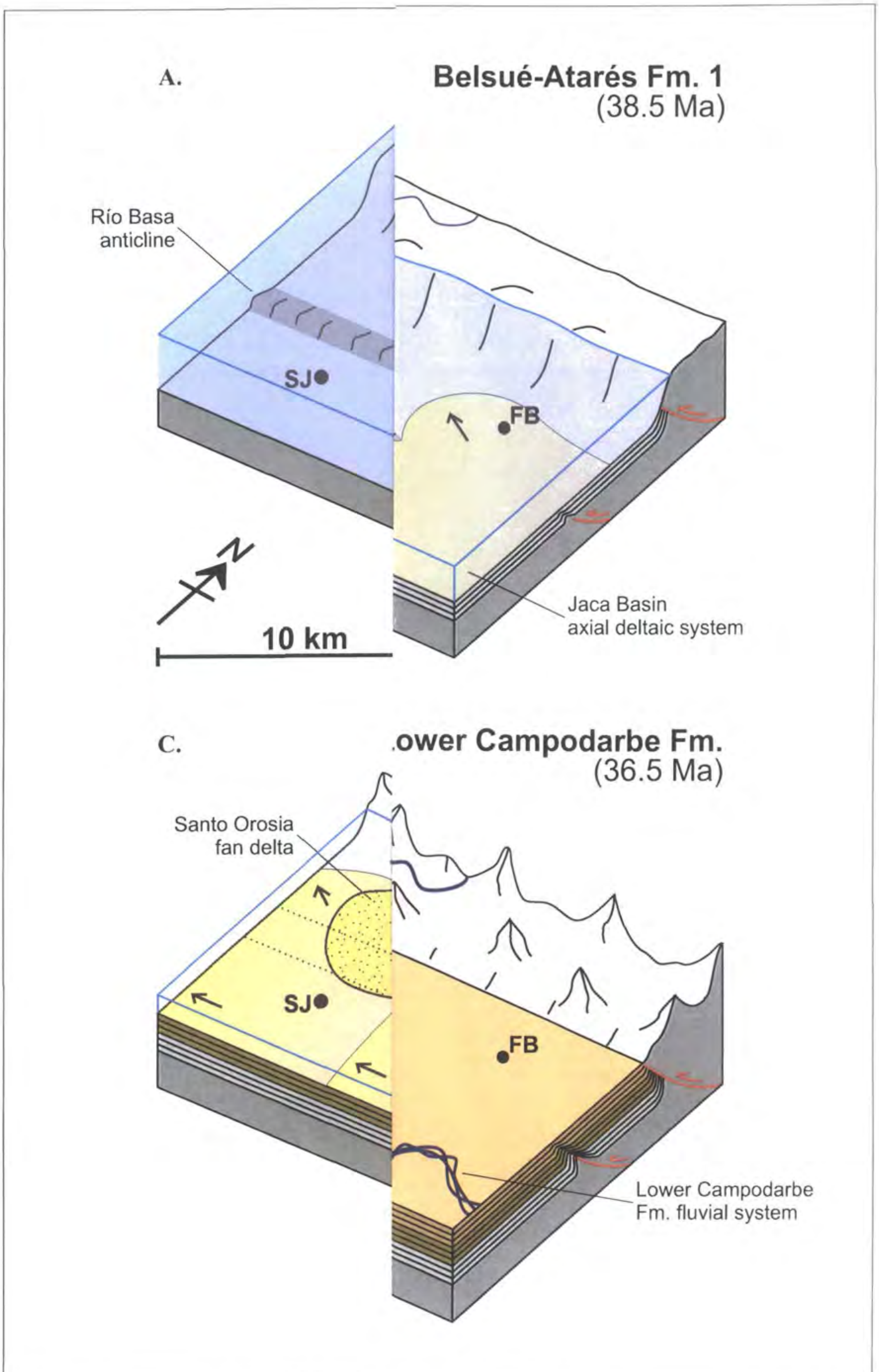


Fig. 5.10. Cartoon evolution of the pal‹ drape across entire area, including the blind thrust-related Río Basa anticline. **B**. M‹a. The Río Basa anticline becomes an important topographic high, preventing the main ‹s sediment accumulation rates to exceed the uplift rate of the crest of the Río Basa anti Basin-wide subaerial exposure converts the Santa Orosia fan delta into a southward

Orosia fan delta reached the Yebra de Basa section (428 m – 430 m; Vol.2, p.80). After this point in the evolution of the area, the Río Basa anticline no longer acted as a barrier between the axial (basinal) and transverse (fan delta) depositional systems. This may have been because the increased sedimentation rates associated with the more proximal depositional environments were able to exceed the uplift rate of the anticline crest, or it may simply be because the growth of the anticline slowed or ceased. At the very top of the Belsué-Atarés Fm., coarse, pebbly sediments came across the now buried Río Basa anticline and deposited a thickness of 11.2 m of the clast-supported conglomerates facies at San Julián de Basa.

The final stage of the sedimentation in this area recorded on the logs is the switch to non-marine conditions and the deposition of the Lower Campodarbe Fm. (**Fig. 5.10D**). The Santa Orosia fan delta was superseded by an alluvial fan, which deposited thick sheets of clast-supported conglomerates facies at both Yebra de Basa and San Julián de Basa, apparently unimpeded by the Río Basa anticline. Away from the alluvial fan, fluvial sandstones and floodplain fines (FA11) were dominant.

Although the composition of the sands at Yebra de Basa and San Julián de Basa is essentially the same (**Fig. 5.6** & **Fig. 5.7**; section **5.2.4**), this is not necessarily a problem for the idea of a growing Río Basa anticline acting as a barrier between the two sections. For instance, the axial (basinal) and transverse (fan delta) depositional systems may have been fed from the same drainage basin, but have entered the Jaca Basin via different routes. The palaeocurrent trends observed in the area do not lend much weight to the growing anticline model, although a slight change from tightly-defined NNE–SSW trends to a more dispersed pattern is notable across the structure (**Fig. 5.5**; section **5.2.3**).

5.3.3 Relative sea-level change

Two important trends in basin subsidence / relative sea-level, spanning multiple hundred of metres of sediment and several million years of time (Hogan & Burbank, 1996), may be inferred from the succession of facies in the Belsué-Atarés Fm. of this sector of the Jaca Basin. The presence of the 500-m-thick, almost continuous accumulation of upper shoreface and delta front sandstones (FA4) in the lower two-thirds of the San Julián de Basa log (**<u>Fig. 5.9</u>**) implies that the water depth in this part of the basin was maintained at around 10 m or less (above normal wave base; section **3.3.4**) for several million years. For this to have occurred, the basinal accommodation space must have been increasing (via basin subsidence or eustatic sea-level rise), but at the same time have been, on average, exactly balanced by the sediment accumulation rate. The net result of this would be no change in relative sea-level (water depth), so allowing the continuous build up of sediment in the same depositional environment (i.e. of the same facies association).

The second change in basin subsidence / relative sea-level is recorded at the base of the upper third of the San Julián de Basa succession, and at the same stratigraphic height on the other three logs. At this point, dated as 37.5 Ma, there was a sudden arrival of more proximal / shallower water facies associations on all sections. This most likely occurred because of a fall in relative sea-level, either due to a fall in eustatic sea-level or because of a reduction in the rate of subsidence of the basin.

The palaeomagnetic dates of Hogan & Burbank (1996) can be used to correlate the Belsué-Atarés Fm. with the eustatic sea-level curve of Haq *et al.* (1987; **Fig. 2.20**) Neither the general increase in accommodation space during the lower two-thirds of the Belsué-Atarés Fm., nor the sudden decrease in relative sea-level at the base of the upper third are reflected by changes on the eustatic sea-level curve. Thus, it seems likely that the general increase in accommodation space was due to basinal subsidence, whereas the sudden decrease in relative sea-level was caused by basinal uplift or a sudden increase in the sediment supply and accumulation rate.

As well as these large-scale trends in the facies succession, numerous smaller-scale variations were seen. In all of the logged successions there are several instances of 10 – 100-m-thick packages of one facies association being sharply overlain by similar thickness package of a more distal (deeper water) or more proximal (shallower water) facies association (**Fig. 5.8** & **Fig. 5.9**). Such trends imply a change in relative sea-level, and can, in certain circumstances, be understood using the principles of sequence stratigraphy.

5.3.3.1 Sequence stratigraphy in foreland basins

The ideas of sequence stratigraphy are usually invoked to explain the occurrence and character of sedimentary successions deposited during changes in relative sea-level. The basic sequence stratigraphic model involves a prograding clastic wedge being deposited in a passive margin setting (e.g. Posamentier & Vail, 1988). However, there are two reasons why this model cannot be immediately applied to the NE Jaca Basin sector. Firstly, sediment was supplied to this area from both the north (Santa Orosia fan delta) and the east (Jaca Basin axial deltaic system), meaning that a WNW–ESE orientated section (**Fig. 5.8**) cannot be considered to be a conventional parallel-to-depositional-dip section. The SW–NE section (**Fig. 5.9**) is of no help either due to the growth of the Río Basa anticline in the middle of it. Secondly, standard sequence stratigraphic models were not designed to work in areas affected by punctuated tectonic activity, such as foreland and thrust-top basins.

However, the recent work of Clevis *et al.* (2004) has shown that sequence stratigraphic principles can be applied to the infill of an idealised foreland basin. These authors constructed a three-dimensional, stratigraphic, forward numerical model of just such a basin, which was then infilled by both axial and transverse depositional systems. In agreement with previous work on this subject (Blair & Bildeau, 1988), Clevis *et al.* (2004) found from their model that during periods of tectonic activity, large-scale axial systems tended to maintain their operation, whereas smaller-scale transverse systems tended retreat. Once the axial system had filled in most of the basinal accommodation space, the transverse systems were able to rapidly prograde across the foreland. When phased tectonic activity and eustatic sea-level fluctuations were applied to the model, it produced parasequence-scale, 100-kyr-long, packages of prograding and shallowing-upward deltaic sediments, reminiscent of those from classic sequence stratigraphy (Van Wagoner *et al.*, 1988).

Sequence stratigraphic principles have also been successfully applied to the real-world examples of the Montserrat and Sant Llorenç del Munt fan delta complexes of the SE margin of the Ebro foreland basin (**Fig. 5.4**). These adjacent systems formed at a similar time and in a similar setting to the Santa Orosia fan delta (section **5.2.2.2**). At Montserrat, Marzo & Anadón (1988) identified eight distinct, vertically stacked regressive–transgressive cycles within the 1300-m-thick succession. These were interpreted as being caused by episodic subsidence in the basin due to pulsed tectonic activity in the adjacent mountain belt. At Sant Llorenç del Munt, López-Blanco (1993) observed eleven 'composite sequences' of 800-kyr duration and 70 – 180 m thickness. These were made up of lower-order (higher frequency) cycles that were 50 – 200 kyr long. Both orders of cycle were laterally extensive over kilometres, and so though to be controlled by allocyclic processes, e.g. variations in eustacy, climate or tectonics.

Thus, the examples cited above, and many other studies, have shown that classic sequence stratigraphic principles may be adapted and successfully applied to foreland basin settings.

5.3.3.2 Sequence stratigraphy and the NE Jaca Basin sector

Despite the fact that numerous previous workers have shown that it is possible to erect a sequence stratigraphic framework for the infill of foreland basins (examples above), this has not proven to be possible for the NE sector of the Jaca Basin. The principal problem is that aside from the major progradation in depositional environments at 37.5 Ma (**Fig. 5.8**), there are no obvious laterally extensive key surfaces or parasequences. Although there are parts of the succession where 10 – 100-m-thick packages of one facies association are sharply overlain by similar thickness package of a more distal (deeper water) or more proximal (shallower water) facies association, these patterns do not tend to be reflected at the same stratigraphic height on adjacent logs just a few kilometres away. The parasequences successfully identified in Sant Llorenç del Munt fan delta by López-Blanco (1993) were found to be laterally extensive over several kilometres.

There are a number of probable reasons why the marine infill of the NE Jaca Basin sector does not follow the conventional sequence stratigraphic patterns. Unlike the idealised foreland basin modelled by Clevis *et al.* (2004), or the foreland basin with one dominant, nearby sediment input point of Marzo & Anadón (1988) and López-Blanco (1993), the Jaca Basin was an actively deforming thrust-top basin. Each of the basin margins, which control sediment entry into the basin, were evolving during the deposition of the Belsué-Atarés Fm. Sediment was entering the basin from a least two different points (the Santa Orosia fan delta and the basinal system), which were orientated perpendicularly to one another. And perhaps most importantly, the transport and deposition of sediment within the basin was strongly controlled by a number of actively growing, kilometre-scale intrabasinal structures – such as the Río Basa anticline.

The theme of applying sequence stratigraphic concepts to the infill of the Jaca Basin will be the subject of further discussion in Chapter 9 on the Southern Jaca Basin sector – an area that previous workers have been able to fit into a sequence stratigraphic framework.

5.4 Conclusions

Sedimentation in this sector of the Jaca Basin was driven by both the large-scale, basinal (axial) system and the Santa Orosia fan delta (transverse) system. The growing

Río Basa anticline divided the two systems for much of the time, conveniently allowing the products of each to be analysed in isolation.

To the north of the Río Basa anticline, shielded from the basinal system, the lower half of the Belsué-Atarés Fm. was dominated by marl deposition. Then, at around 37.5 Ma, a unique structural low point or weakness developed in the WNW–ESE-trending, fold-and-thrust-defined northern basin margin. This allowed an alluvial system, sourced partly in the Pyrenean axial zone in a semi-arid climate, to bring very coarse, poorly sorted sands and clast-supported conglomeratic material into the Jaca Basin. The result was the progradation of steep-fronted (16°), Gilbert-type fan delta into the basin. The conglomerates it supplied spread over a fairly large area of at least 4 km by 8 km (perhaps due to slow subsidence rates), including crossing the crest of the Río Basa anticline. Ultimately, the fan delta was superseded by the Santa Orosia alluvial fan.

To the south of the growing Río Basa anticline, 500 m of upper shoreface and delta front sandstones (FA4) of the Jaca Basin axial system accumulated, indicating that the basin subsidence rate and sediment accumulation rate were almost exactly balanced for a several million years (eustatic sea-level did not rise during this time). At 37.5 Ma, a sudden switch to more proximal / shallower water facies associations on all sections indicates a rapid fall in relative sea-level across the area (again, not reflected on the eustatic sea-level curve). From this point onwards, higher sedimentation rates and/or a slower uplift rate meant that the Río Basa anticline no longer acted as a barrier between the axial and transverse depositional systems.

Although numerous sudden progradations / retrogradations in depositional environment were noted on each of the sections, placing these within a sequence stratigraphic framework did not prove to be possible because none of these features are laterally extensive between adjacent sections. The principal reasons for sequence stratigraphic concepts failing in this part of the Jaca thrust-top basin are that sediment was received from several input points, and that actively growing intrabasinal structures, rather that sea-level, were the principal control on the spatial distribution of facies and depositional environments.

5.5 Key Points

1. Sedimentary infill of the basin:

- The Santa Orosia fan delta was an important transverse depositional system, and was partly sourced in the Pyrenean axial zone.

- The Jaca Basin axial system consisted of a deltaic complex, and was also partly sourced from the Pyrenean axial zone.

2. Structural configuration of the basin:

- The northern margin of the Jaca Basin was structurally defined by WNW–ESE-trending folds and thrusts during the deposition of the Belsué-Atarés Fm.

3. Influence of intrabasinal growth structures:

- The actively growing Río Basa anticline acted as an effective barrier between the transverse and axial depositional systems for much of the Belsué-Atarés Fm.
- However, towards the end of Belsué-Atarés Fm. sedimentation, the barrier effect ceased to operate and the structure was overlapped.

4. Effect of sea-level changes:

- Basin subsidence and sediment accumulation rates were closely matched for much of the Belsué-Atarés Fm., giving zero net change in relative sea-level.
- A major fall in relative sea-level occurred at 37.5 Ma.
- Sequence stratigraphic concepts cannot be applied because of the lack of laterally extensive key surfaces (with the exception of the 37.5 Ma event).

The next chapter, Chapter 6, discusses the central portions of the northern margin of the Jaca Basin. Although the structurally-defined margin was not breached by a coarse-grained depositional system in this area, a second major growth structure did have a profound effect on sediment routing and facies distribution.

Chapter 6:
Northern Jaca Basin

6. Northern Jaca Basin

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6. Northern Jaca Basin

6.1 Introduction

The margins of a basin can exert a strong control on the character of the sedimentary infill of that basin. They may, for example, contain one or more input points, utilised by external depositional systems to enter a basin (e.g. Vincent & Elliott, 1996). They may also act as barriers, deflecting depositional systems (e.g. Jones, 2004), or even prevent their entry into the basin (e.g. Jolley, 1987). The margins of most basins are structurally controlled, and so in tectonically active regions, sediment entry points or barriers may evolve or disappear over time, precipitating dramatic changes in the type of sediments accumulating in a basin. Thus, in order to fully understand the sedimentary infill of a given basin, study of the basin margins and their evolution over time is of particular importance.

The nature of the northern margin of the Jaca Basin during the deposition of the Belsué-Atarés Fm. has, up until now, been somewhat enigmatic – largely due to the lack of pre-existing work on this area. Today, this basin margin is defined by a series of WNW–ESE-trending thrusts and related folds. The key questions are: to what extent did these structures exist during Belsué-Atarés Fm. times? And if they did, what controlling effect did they exert on the coeval sedimentation? Although evidence of the existence of the margin-defining structures was found in the Far NE Jaca Basin sector (Chapter 4), a fan delta belonging to the Belsué-Atarés Fm. was found to have entered the basin across the northern margin in the NE Jaca Basin sector (Chapter 5). Resolving the configuration and evolution of the northern basin margin, and how it affected the deposition of the Belsué-Atarés Fm., are the principal aims of this chapter.

These aims will be addressed with the analysis of basic sedimentological observations, such as facies and facies associations, palaeocurrents and sediment provenance (section **6.2**), and the construction and interpretation of correlation panels (section **6.3**).

6.2 Graphic logs of the Northern Jaca Basin sector

This sector of the field area covers the central portion of the northern margin of the Jaca Basin, lying around 3 km to the south of the town of Jaca (**Fig. 6.1**). Cutting

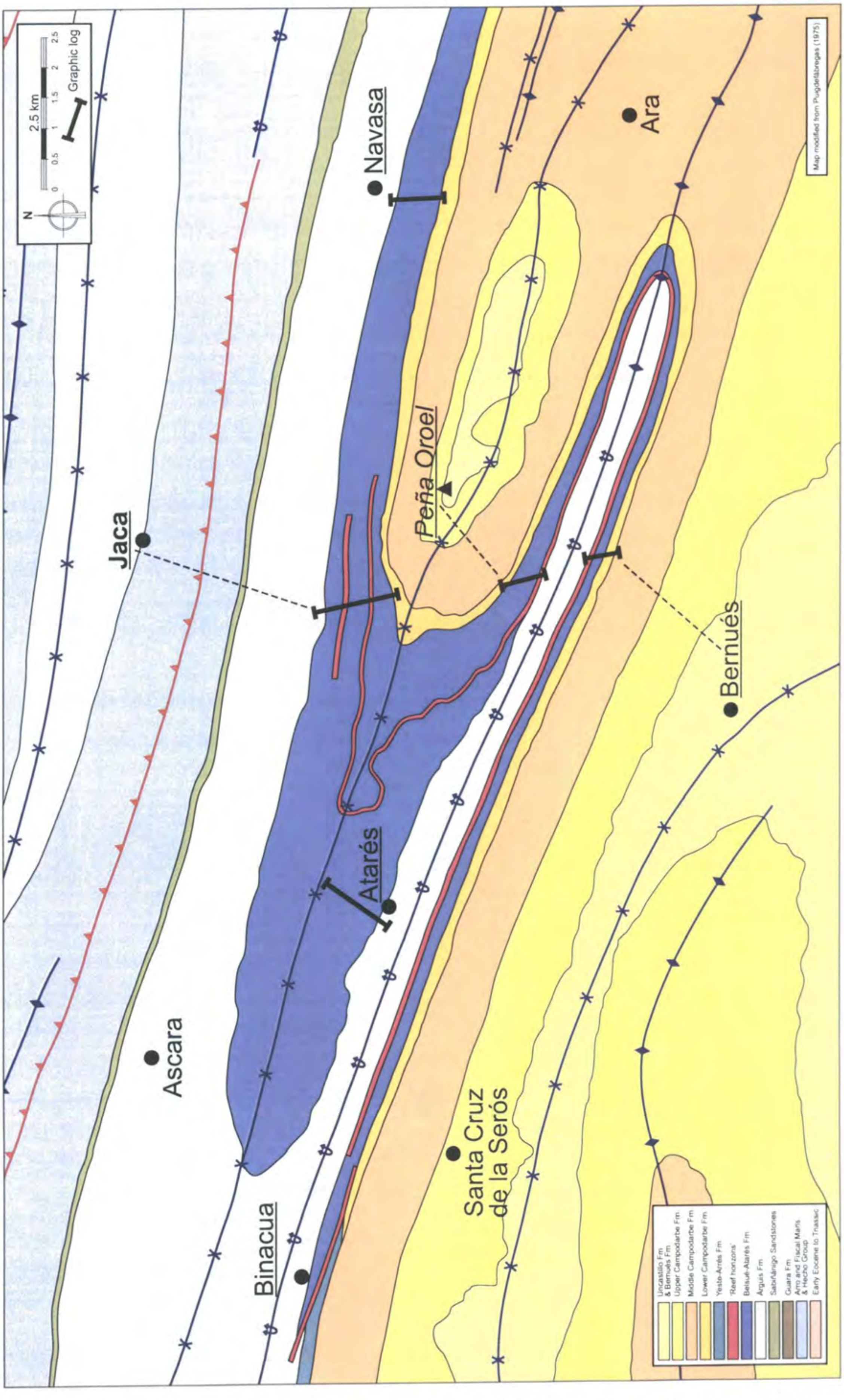

Fig. 6.1. Geological map of the Northern Jaca Basin, indicating the positions of the five graphic logs.

through the middle of this sector is a kilometre-scale, very tight to overturned anticline and associated syncline. This structure is one of the WNW–ESE-trending thrusts and associated folds that define the present-day northern basin margin (**Fig. 1.3**). This fold deforms many units from across the stratigraphic column (**Fig. 2.20**), from the Hecho Group (Early to Middle Eocene), the Belsué-Atarés Fm. (Middle Eocene), and up to and including the Bernués & Uncastillo Fm. (Late Oligocene to Early Miocene). The importance of this anticline, which has never been discussed in published literature, is the focus of this chapter. The name hereby proposed for this structure is the Binacua anticline, after the small village that lies just to the south of its crest (see the western side of **Fig. 6.1**).

Five graphic logs were completed in this sector – their locations are indicated on **Fig. 6.1**. Each log, in both summary and original full-scale version, is reproduced in the appendices in Vol.2.

Log name	Summary log	Original log
Navasa	Vol.2, p.15	Vol.2, p.90 – 96
Bernués	Vol.2, p.16	Vol.2, p.97 – 101
Peña Oroel	Vol.2, p.17	Vol.2, p.102 – 106
Jaca	Vol.2, p.18	Vol.2, p.107 – 115
Atarés	Vol.2, p.19	Vol.2, p.116 – 122

The basin-wide mapping of Puigdefàbregas (1975) found, interestingly, that the Belsué-Atarés Fm. is much thinner close to the crest of the Binacua anticline than in the syncline that flanks it to the north. This could be indicative of a syntectonic relationship – that the fold was growing whilst the Belsué-Atarés Fm. was being deposited. The evidence for such a relationship, and any consequent effects on the sedimentation of the Belsué-Atarés Fm., shall be discussed throughout the course of this chapter.

If the Binacua anticline grew whilst the Belsué-Atarés Fm. was being deposited, it will be of particular interest to this study because of its WNW–ESE orientation – parallel to general sediment transport direction along the axis of the Jaca Basin. With the exception of the Río Basa anticline (Chapter 5), all other growth anticlines in the basin are orientated N–S, perpendicular to the sediment transport trend. Although it is probable that the two sets of differently-orientated growth structures had different effects on the deposition of the Belsué-Atarés Fm., it is not obvious precisely what these effects would be, and how they might differ.

The following sections are based on data gathered during the course of this work. In this section, section **6.2**, sedimentological data from the Belsué-Atarés Fm., covering facies and facies associations, palaeocurrents, and sediment composition, will be described and interpreted. This interpretation will then be applied, in section **6.3**, to assess the evidence for the growth of the Binacua anticline during the deposition of the Belsué-Atarés Fm., and to determine the configuration of the northern basin margin.

6.2.1 Facies, facies associations and facies architecture

The facies and facies associations recorded on the five logs of this sector are diverse. The most easterly log, located at Navasa (Vol.2, p.15 & p.90 – 96), is however the most simple of the five. The 580-m-thick Belsué-Atarés Fm. is composed largely of lower shoreface sandstones (FA3; section **3.3.3**), with a few intervening 10-m-thick packages of upper shoreface and delta front sandstones (FA4; section **3.3.4**). It should be noted however, that because of the dense vegetation on this section, the recessive-weathering fines between the sandstones were almost never exposed.

Moving 6.5 km to the west, the Jaca log (Vol.2, p.18 & p.107 – 115) begins with 110 m of offshore marine marls (FA1; section **3.3.1**) of the Árguis Fm, followed by 710 m of the Belsué-Atarés Fm. The basal 160 m of this is sand dominated, with a high proportion of upper shoreface and delta front sandstones (FA4), some lower shoreface sandstones (FA3), and a lesser amount of offshore marine marls (FA1). At 174 m – 181 m (Vol.2, p.108), an unusual and laterally extensive bed of coral limestone facies (section **3.2.11**) was noted. The final 170 m of this section begins with a thick package of FA4, comprising sandstones rich in marl rip-up clasts up to cobble size (Vol.2, p.113 – 114). Above these is a thick package of marginal marine clays and sandstones (FA6; section **3.3.6**), dominated by grey and yellow clays and silts facies (section **3.2.15**). Either side of the Lower Campodarbe Fm. boundary is fines dominated (Vol.2, p.115).

Lying 5 km to the west of the Jaca log is the Atarés log (Vol.2, p.19 & p.116 – 112). The basal portion of this section is made up of 180 m of well-exposed pure marls facies (section **3.2.1**) and silty and sandy marls facies (section **3.2.2**), representing offshore marine marls (FA1) of the Árguis Fm. The Belsué-Atarés Fm. on this log is made up of a succession of seventeen, seemingly randomly ordered, 10 – 70-m-thick packages of different facies associations: offshore marine marls (FA1), lower shoreface sandstones (FA3), upper shoreface and delta front sandstones (FA4), marginal marine clays and sandstones (FA6), and carbonate ramp limestones (FA7; section **3.2.7**). Some of the latter are coral bearing. Unfortunately, a sudden end to the exposure and the synclinal nature of the outcrop meant that this section terminated considerably before the Lower Campodarbe Fm. could be reached.

Moving back east, 3 km due south of the Jaca log lies the Peña Oroel log (Vol.2, p.17 & p.102 – 106). The first 170 m of the 421-m-thick Belsué-Atarés Fm. is largely composed of offshore marine marls (FA1), containing some thin limestone beds (Vol.2, p.102 – 103), and three 10-m-thick packages of lower shoreface sandstones (FA3). Above is a very distinctive, laterally extensive, 22-m-thick bed of coral limestones facies (Vol.2, p.103 – 104). Just less than 70 m above this is 12 m of medium and coarse-grained sandstones of the proximal delta front channelised sandstones facies association (FA5; section **3.3.5**). The uppermost Belsué-Atarés Fm. comprises 29 m of marginal marine clays and sandstones (FA6), separated into two packages by a further 11 m of proximal delta front channelised sandstones (FA5; Vol.2, p.105 – 106). Either side of the Lower Campodarbe Fm. boundary is fines dominated (Vol.2, p.106).

The fifth and final log was situated 1 km to the south of the Peña Oroel log at Bernués (Vol.2, p.16 & p.97 – 101). The 238-m-thick Belsué-Atarés Fm. is largely composed of offshore marine marls (FA1) and lower shoreface sandstones (FA3), but with three intervening packages of interest. The first package, at the very base, is 10 m of upper shoreface and delta front sandstones (FA4). Around the middle of the Belsué-Atarés Fm. is a laterally extensive package of carbonate ramp limestones (FA7), rich in a diverse range of corals (Vol.2, p.97 – 98). The third package of interest is 34 m of proximal delta front channelised sandstones (FA5), featuring abundant marl rip-up clasts (Vol.2, p.003), situated close to the top of the Belsué-Atarés Fm. Either side of the Lower Campodarbe Fm. boundary is again fines dominated (Vol.2, p.99). The log extended up through nearly 220 m of the Lower Campodarbe Fm. This too was very much fines dominated, with the vast majority being made up of grey and yellow clays and silts facies, of the fluvial sandstones and floodplain fines facies association (FA11; section **3.3.11**).

The environments of deposition of the Belsué-Atarés Fm. of the Northern Jaca Basin sector are: offshore marine (represented by FA1), offshore–transition zone (FA2), lower shoreface (FA3), upper shoreface and delta front (FA4), proximal delta front (FA5), marginal marine (FA6), and carbonate ramp (FA7). Together these represent a complete spectrum of deltaic infill of a marine sedimentary basin, with each individual environment reflecting different water depths and/or levels of clastic sediment input.

6.2.2 Palaeocurrents

The sandstone-rich sections in this part of the basin offered abundant opportunities to take palaeocurrent measurements from a range of sedimentary structures. Most readings came from symmetrical ripples, but the orientations of asymmetrical ripples, grooves on bed bases and tabular cross-bedding were also measured. The trends in the palaeocurrent data are bi-directional, and fall between N–S- and NE–SW-directed, with the average being NNE–SSW (**Fig. 6.2**).

As described in greater detail in section **4.2.2**, wave rippling in shallow marine environments is often variably directed, but is more likely to be directed normal to the local shoreline than parallel to it (Reading & Collinson, 1996). The NNE–SSW bi-directional palaeocurrents in this sector would therefore indicate a shoreline that was orientated WNW–ESE. This closely ties in with the thrusts and related folds of the same orientation, which define the present-day northern basin margin (**Fig. 1.3**). Thus, it seems that the northern margin thrusts and folds had formed, or at least partly formed, before the deposition of Belsué-Atarés Fm., creating a shoreline that the basinal waves tended to be directed against.

6.2.3 Sediment composition

During the logging process, samples were collected from several fine–medium sandstone beds for compositional analysis. The aim was to see if there were any major compositional differences between or within the sections. **Fig. 6.3** shows the results of this process for the Atarés, Bernués and Navasa sections. The compositions of samples from the other two sections were analysed but found to be similar to those from the first three, so were omitted from the plot for clarity. Further to the samples taken from sandstone beds, some limestone beds were also analysed. Although the data from these is shown on the composition plot, the trend lines are only drawn between the sandstone data points.

The compositions of each of the samples are fairly similar – there are no major lateral discontinuities or vertical trends. In fact, the compositions are more similar to one another in this area than from any other parts of the basin. However, there are a few exceptions. For example, the samples from Navasa are lacking in opaque rich lithics and polycrystalline quartz grains, although this may not be particularly significant as these grain types were always fairly rare (0.4 – 5% typically). All samples did however

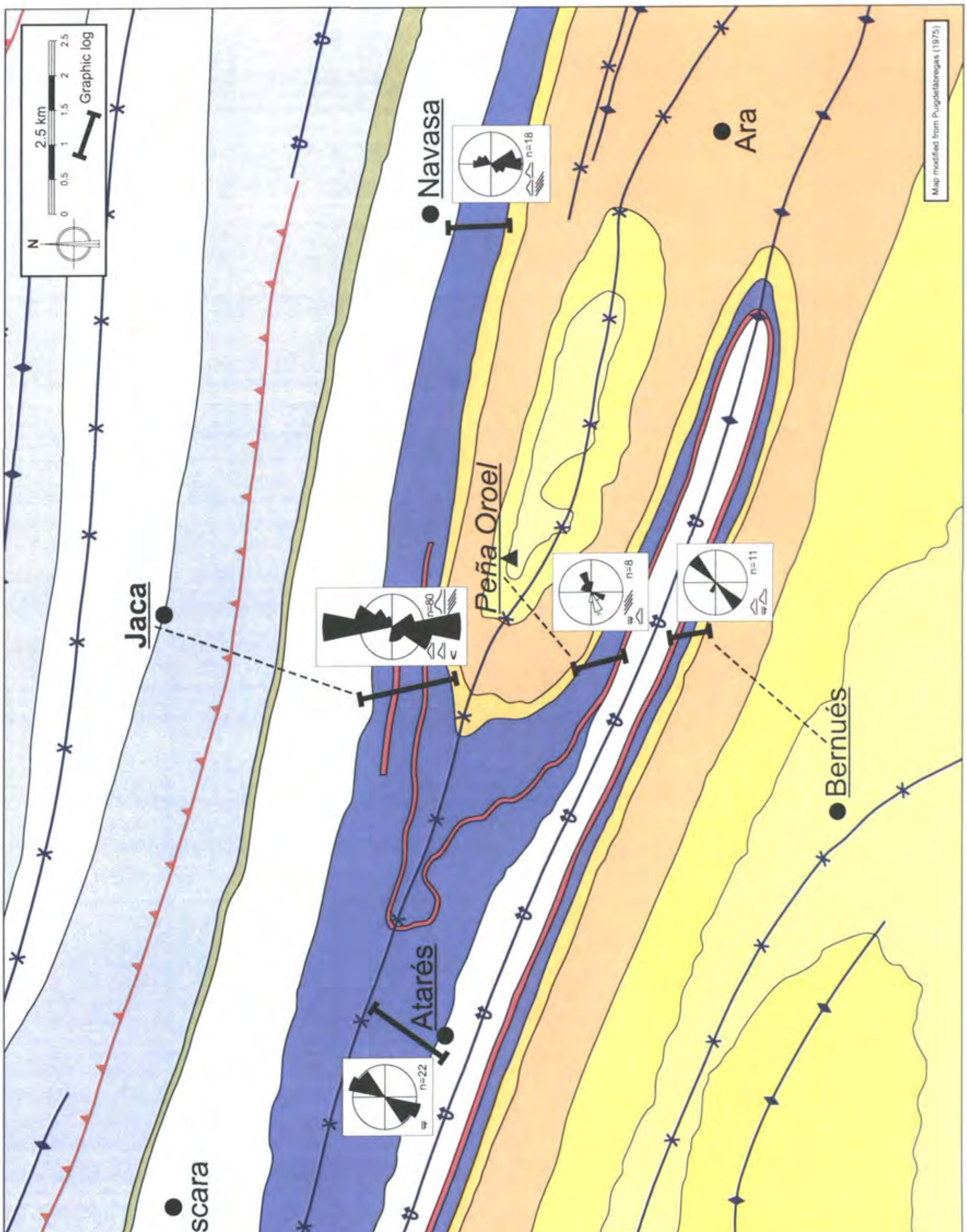

Fig. 6.2. Geological map of the Northern Jaca Basin, with palaeocurrent rose diagrams for each log.

contain a few percent of a number of different 'exotic' grains, indicating a source area that was at least partly located in the Pyrenean axial zone (Jones, 1997).

The compositional similarities across this sector suggest that the sediments came from the same source area or areas, which also continued to yield more-or-less the same grain types throughout the deposition of the Belsué-Atarés Fm. However, this is not necessarily a problem for the idea that the Binacua anticline was an actively growing barrier between the Atarés and Navasa sections to the north, and the Bernués section in the south. For instance, although the sands may have come from the same source area, they may have reached their points of deposition via different sediment transport paths.

6.3 Correlation, interpretation and discussion

Section **6.2** covered the fundamental aspects of the marine growth strata of the Northern Jaca Basin sector. This section, section **6.3**, takes these fundamentals and builds upon them, with the aim of fully understanding the structural controls on the Belsué-Atarés Fm. sedimentation in this sector of the Jaca Basin.

The first stage of this is the discussion of the level of correlation that exists between the five graphic logs (section **6.3.1**). The influence of Binacua anticline on the syntectonic sediments can be determined from a south–north-orientated correlation panel across the structure and its associated syncline (section **6.3.2**). The evolution of this structure, as recorded by the growth strata and sedimentological observations from across the rest of the area, should give an insight into the state of development of the northern basin margin during the deposition of the Belsué-Atarés Fm. (section **6.3.3**).

6.3.1 Correlation between graphic logs

Fig. 6.4 and **Fig. 6.5** are W–E- and S–N-orientated correlation panels, respectively, covering all five graphic logs completed in this sector. Correlation panel 1 (**Fig. 6.4**) has been drawn with the standard vertical exaggeration of ×10; correlation panel 2 (**Fig. 6.5**) has a reduced vertical exaggeration of ×4 but a standard vertical scale, allowing the three closely-spaced logs to be positioned further apart than normal.

No palaeomagnetic or biostratigraphic dating has been undertaken in this area, so the correlation had to be constructed purely on the basis of facies. The Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary was used to determine the relative vertical positions of the logs. This usually sharp and distinctive boundary, which is often marked by a profound colour change in the clay- and silt-grade sediments (Chapter 3), has been shown by Hogan & Burbank (1996) to have formed more or less synchronously across some parts of the Jaca Basin. However, in other parts of the basin, this contact has been interpreted as being diachronous (Chapter 4). The implication of this is that the correlation panels should be considered to be wholly stylistic. While the vertical scales may be sediment thickness, these may have no direct relationship to time. The formation boundaries and other lines of correlation noted merely indicate areas of the same facies association (depositional environment) on adjacent logs – they are most likely to be diachronous, and so are not necessarily key surfaces of any sort.

For correlation panel 1 (**Fig. 6.4**), the base of the Lower Campodarbe Fm. was simply drawn horizontally, and the Navasa and Jaca logs 'hung' from it. The vertical positioning of the Atarés log, which did not reach the Lower Campodarbe Fm., was determined using the top of the Árguis Fm. This contact is defined by the first appearance of a facies association that is at least as proximal as lower shoreface sandstones (FA3). The problems with this are that this contact is often gradational, and that the thickness of the Belsué-Atarés Fm. is variable, meaning the stratigraphic 'height' of the top of the Árguis Fm. is also variable.

The correct vertical positioning of the three logs on correlation panel 2 (**Fig. 6.5**) was also difficult to determine, because most of the stratigraphic column is folded by Binacua anticline and associated syncline. Furthermore, the Belsué-Atarés Fm. and perhaps other units change thickness markedly across the structure (**Fig. 6.1**). In the end, the convention adopted was that used on all other correlation panels – that the base of the Lower Campodarbe Fm. should occur at the same stratigraphic height on all logs i.e. its position on each log should lie on a horizontal line across the page. The top of the Árguis Fm. was then defined using the convention described above, allowing the folded formation boundaries to be sketched in. A useful coral limestone marker bed, referred to by Puigdefàbregas (1975; see **Fig. 6.1**) as one of several 'reef horizons', was present in the lower portions of all three logs and so helped further validate the correlation.

6.3.1.1 Correlation panel 1: W–E

The degree of correlation between the three logs on the first correlation panel is poor – the logs do not look a great deal like one another (**Fig. 6.4**). Having said that though, all three do at least begin with 50 – 190 m of offshore marine marls (FA1) of the Árguis Fm., and the Navasa and Jaca logs both end with fluvial sandstones and floodplain fines (FA11) of the Lower Campodarbe Fm. In between however, the Belsué-Atarés Fm. is variable both vertically within each log, and between logs – yet the variations do not obviously correlate from log to log. On the Navasa section in the east, the Belsué-Atarés Fm. is sand-rich throughout. Around 11 km to the west, the Atarés log has multiple tens-of-metres-thick sand-free packages, an unusually thick 90 m of marginal marine clays and sandstones (FA6), and four 10-m-thick packages of carbonate ramp limestones (FA7). In between these two, the Jaca log has similarities to both adjacent logs, with both sand rich and marl rich packages, a thick accumulation of FA6, and a package of carbonate ramp limestones (FA7).

It is inferred that different depositional processes, and perhaps different depositional systems, were responsible for forming the sections of Belsué-Atarés Fm. at Navasa and Atarés. In between these two localities, at Jaca, there was a degree of interfingering, creating a hybrid section with parts in common with the other two.

6.3.1.2 Correlation panel 2: S–N

This second correlation panel crosses the Binacua anticline, and its associated syncline, at an angle that is perpendicular to the trend of the fold axis. The degree of correlation between the three logs on this panel is better than on the first (**Fig. 6.5**), perhaps because the sections were set only a few kilometres apart.

All three logs begin with offshore marine marls (FA1) or offshore–transition zone marls and sandstones (FA2) of the Árguis Fm. Lying above these, 60 – 160 m up into the Belsué-Atarés Fm., is a package of coral-rich carbonate ramp limestones (FA7) that correlates well between all logs ('reef horizons' of Puigdefàbregas, 1975). This package varies from 7.2 m thick in the syncline at Jaca, to 22.0 and 32.8 m thick on the flanks of the anticline at Peña Oroel and Bernués, respectively. Above this, on all logs, the Belsué-Atarés Fm. consists of alternating packages of FA1 and lower shoreface sandstones (FA3), which vary in thickness and number, and do not correlate between logs. On all three logs, the Belsué-Atarés Fm. ends with a sand dominated package – 100 m of upper shoreface and delta front sandstones (FA4) at Jaca, and 11 m and 35 m of proximal delta front channelised sandstones (FA5) at Peña Oroel and Bernués respectively. Occurring alongside these are clay rich packages – marginal marine clays and sandstones (FA6) at Jaca and Peña Oroel, and pure marls facies at Bernués.

The most important interpretation from this correlation panel is that the Belsué-Atarés Fm. thins markedly onto the crest of the Binacua anticline – from 710 m thick at

Jaca, through 421 m at Peña Oroel, to 238 m south of the anticline crest at Bernués. This is strong evidence of a syntectonic relationship between the Belsué-Atarés Fm. and the fold. The affect that the growth of the fold had on the lateral distribution of facies is discussed in the following section.

6.3.2 Influence of the Binacua anticline

The Binacua anticline is a WNW–ESE-trending kilometre-scale fold that lies between the Peña Oroel and Bernués logs (**Fig. 6.1**). As noted above, the Belsué-Atarés Fm. thins to around one-third of its usual thickness on the flanks of the structure, and perhaps more so on its crest. From this, a syntectonic deposition has been inferred. The growth of this structure, and probably the other nearby parallel structures (**Fig. 1.3**), created an area of shallow water and perhaps a shoreline, onto which NNE–SSW-directed basinal wave rippling tended to be directed.

The growth of the structure not only affected the sediment thickness, but also the facies developed around it. The most pronounced example of this is the package of coral-rich carbonate ramp limestones (FA7) that was much more thickly developed on the flanks of the anticline (22.0 m and 32.8 m) than in the adjacent syncline (7.2 m; **Fig. 6.5**). This is thought to have occurred because uplifted areas of the sea floor, with better sunlight and fewer clastic sediments present, tend to favour carbonate production. A second example is the Lower Campodarbe Fm. at Bernués (Vol.2, p.99 – 101), which is strongly dominated by clays and silts. Very unusually, in the 220 m studied it does not contain any beds of medium, cross-bedded coloured sandstones facies (section **3.2.20**). Because this lithofacies is thought to represent fluvial channel sands, its absence from this section suggests that rivers tended to be deflected away from the crest of the growing Binacua anticline during Lower Campodarbe Fm. times.

From the sedimentological data collected during this work, and the interpretation of a growing Binacua anticline, inferences about the nature of the wider northern basin margin during Belsué-Atarés Fm. times can also be made.

6.3.3 Northern basin margin configuration

The northern margin of the Jaca Basin is, at the present-day, defined by a series of WNW–ESE-trending thrusts and associated folds. At least one of these structures, the Binacua anticline, is thought to have been growing during the deposition of the Belsué-

Atarés Fm. The crest of this particular structure did not however achieve subaerial exposure during Belsué-Atarés Fm. times, as this formation is known to have been deposited on the very crest of the fold (**Fig. 6.1**; Puigdefàbregas, 1975). In spite of this, the generally fines-dominated nature of the sediments in this part of the Jaca Basin suggests that the northern basin margin acted as an effective barrier, preventing coarse-grained sediments from the Pyrenean axial zone to the north from directly entering the basin. This is in contrast to the NE Jaca Basin sector to the east, where the Santo Orosia fan delta brought conglomerates into the basin across its northern margin (Chapter 5).

It therefore seems likely that not only did the Binacua anticline grow during the deposition of the Belsué-Atarés Fm., but also that the other nearby, parallel structures (**Fig. 1.3**) did as well. The topography created by these WNW–ESE-orientated thrusts and thrust-related folds not only protected this part of the basin from coarse sediments being eroded from the Pyrenean axial zone, but also created a shoreline onto which basinal waves were directed. The active growth of numerous, kilometre-scale structures in this area could also explain the poor degree of W–E-directed correlation between the Atarés, Jaca and Navasa logged sections (section **6.3.1.1**).

It is interesting to note that the growth of the northern margin structures during Belsué-Atarés Fm. times represents a phase of out-of-sequence thrusting in the south Pyrenean foreland. This is because the thrust that underlies the Jaca Basin was also known to be active and forming growth anticlines on the southern basin margin during the deposition of the Belsué-Atarés Fm. (Chapter 8 and Chapter 9).

6.4 Conclusions

Belsué-Atarés Fm. sedimentation in this part of the Jaca Basin was strongly controlled by the out-of-sequence growth of the WNW–ESE-trending thrusts and related folds that define the northern basin margin. The resulting uplift created a barrier that prevented coarse-grained sediments from the Pyrenean axial zone directly entering the basin, and formed a shoreline onto which basinal waves tended to be directed.

The most southerly of the northern margin structures, here named the Binacua anticline, began to grow during the deposition of the Belsué-Atarés Fm. (or possibly earlier), and continued at least until the Late Oligocene. Although its crest did not achieve subaerial exposure before the rest of the area, its growth did strongly affect the facies deposited across it. On the flanks of the structure, the uplift caused the Belsué-Atarés Fm. to thin down to less than one-third of its usual thickness, and allowed a 30-

m-thick package of coral limestones facies to accumulate. The growth of the structure also deflected river channels in the overlying Lower Campodarbe Fm.

6.5 Key Points

1. Sedimentary infill of the basin:

- Sedimentation in this sector of the basin was dominated by marls and clays, although there were also sands (which had Pyrenean axial zone signatures).

2. Structural configuration of the basin:

- The northern margin of the Jaca Basin was structurally defined by actively uplifting, WNW–ESE-trending thrusts and related folds during Belsué-Atarés Fm. times.
- Some, if not all, of these structures were active for at least 10 Myr (beginning during Belsué-Atarés Fm. deposition, or earlier), and represented a phase of out-of-sequence thrusting.

3. Influence of intrabasinal growth structures:

- The actively growing Binacua anticline strongly affected the thickness and facies of the syntectonic Belsué-Atarés Fm., for example by promoting the deposition of coral limestones facies on its flanks.
- The uplift of the structure also deflected fluvial channels of the Lower Campodarbe Fm.

4. Effect of sea-level changes:

- In this part of the basin, there is no clear evidence for cyclical changes in sea-level in the Belsué-Atarés Fm.

The next chapter, Chapter 7, discusses the western portions of the Jaca Basin. This area offers further insights into the northern basin margin, including evidence of a second important sediment entry point. The western end of the southern basin margin is also studied, and appears to have been distant from any significant siliciclastic supply.

Chapter 7:
Western Jaca Basin

7. Western Jaca Basin

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7. Western Jaca Basin

7.1 Introduction

As explained in Chapter 6, the margins of a sedimentary basin may exert a very strong control on the nature of the deposition that occurs in that basin. The principal reason for this is that basin margins tend to be structurally defined – depending on the orientations and types of structures present, the margins may act barriers, keeping external sediments out of a basin, or provide input points, through which external depositional systems may enter and then prograde across a basin (Jolley, 1987; Vincent & Elliott, 1996; Gupta, 1999; Jones, 2004). Therefore, in order to fully understand the sedimentary infill of a basin, it is first necessary to understand the nature and evolution of the basin margins. The lack of pre-existing work on the northern margin of the Jaca Basin is an obvious gap in the general understanding of this basin.

This chapter focuses on the Belsué-Atarés Fm. outcrops of the western end of the Jaca Basin – which rim both the northern and southern basin margins (**Fig. 1.1**). The central, eastern and far eastern portions of the northern basin margin were studied in chapters 4 – 6. It was found that the northern margin structures were growing during the deposition of the Belsué-Atarés Fm., causing rapid lateral changes in thickness and facies, and in one place, allowing a coarse-grained depositional system to enter the basin (Chapter 5). One of the aims of this chapter is to complete the study of the northern margin, documenting any further affects on the sedimentation caused by uplift of the margin-defining structures. This work will also continue the search for the input points through which the sediments Belsué-Atarés Fm. gained entry into the Jaca Basin.

The second aim of this chapter is to address the same issues for the western end of southern basin margin. This margin is also defined by a series of WNW–ESE-trending thrusts and related folds. Although the central and eastern portions of this margin are known to have been actively uplifting and deforming whilst the Belsué-Atarés Fm. was being deposited (Millán *et al.* 1994; Castelltort *et al.*, 2003), the western end has never been studied in detail in the published literature. The aims of this chapter will be addressed with the analysis of basic sedimentological observations, such as those of facies and facies associations, palaeocurrents and sediment composition (section **7.2**), and the construction of correlation panels and models of sedimentation (section **7.3**).

7.2 Graphic logs of the Western Jaca Basin sector

This sector of the field area covers the western end of the Jaca Basin, in which the Belsué-Atarés Fm. outcrops rim both the northern and southern basin margins (**Fig. 7.1**). Although both these basin margins are presently defined by a series of WNW–ESE-trending thrusts and associated folds, there are no know similar structures to define a western basin margin (Puigdefàbregas, 1975). It is possible that the Jaca Basin was simply open in this direction towards the Bay of Biscay, although Remacha *et al.* (1998) found evidence in the Hecho Group of a structural high that may have prevented this.

Eight graphic logs were completed in this sector – five along the northern margin, and three along the southern margin. The locations of the logs are indicated on **Fig. 7.1**, and each is also reproduced, in both summary and original full-scale version, in the appendices in Vol.2.

Log name	Summary log	Original log
Binacua	Vol.2, p.20	Vol.2, p.123 – 126
Alastuey	Vol.2, p.21	Vol.2, p.127 – 128
Puente La Reina	Vol.2, p.22	Vol.2, p.129 – 130
Arrés	Vol.2, p.23	Vol.2, p.131 – 133
Martes	Vol.2, p.24	Vol.2, p.134 – 135
Triste	Vol.2, p.25	Vol.2, p.136 – 138
Salinas de Jaca	Vol.2, p.26	Vol.2, p.139 – 140
Villalangua	Vol.2, p.27	Vol.2, p.141 – 143

The Belsué-Atarés Fm. in this area is relatively thin (35 – 100 m thick), variable, and has never been the subject of detailed published work beyond the basin-wide mapping of Puigdefàbregas (1975). However, the WNW–ESE-trending structures that define the southern basin margin in this area (**Fig. 1.3**) have previously been studied in detail (Nichols, 1989; Turner, 1990; Turner, 1992; Lloyd *et al.*, 1998; Nichols & Hirst, 1998). The main focus of this interest has been into the effects that the growth of the structures had on the terrestrial depositional systems that superseded the deltaic Belsué-Atarés Fm. in the Jaca Basin.

The southern margin of the Jaca Basin represents the southern limit of deformation in the south Pyrenean foreland, i.e. the south Pyrenean thrust front, and is today represented by the External Sierras range of hills. The key geological structure

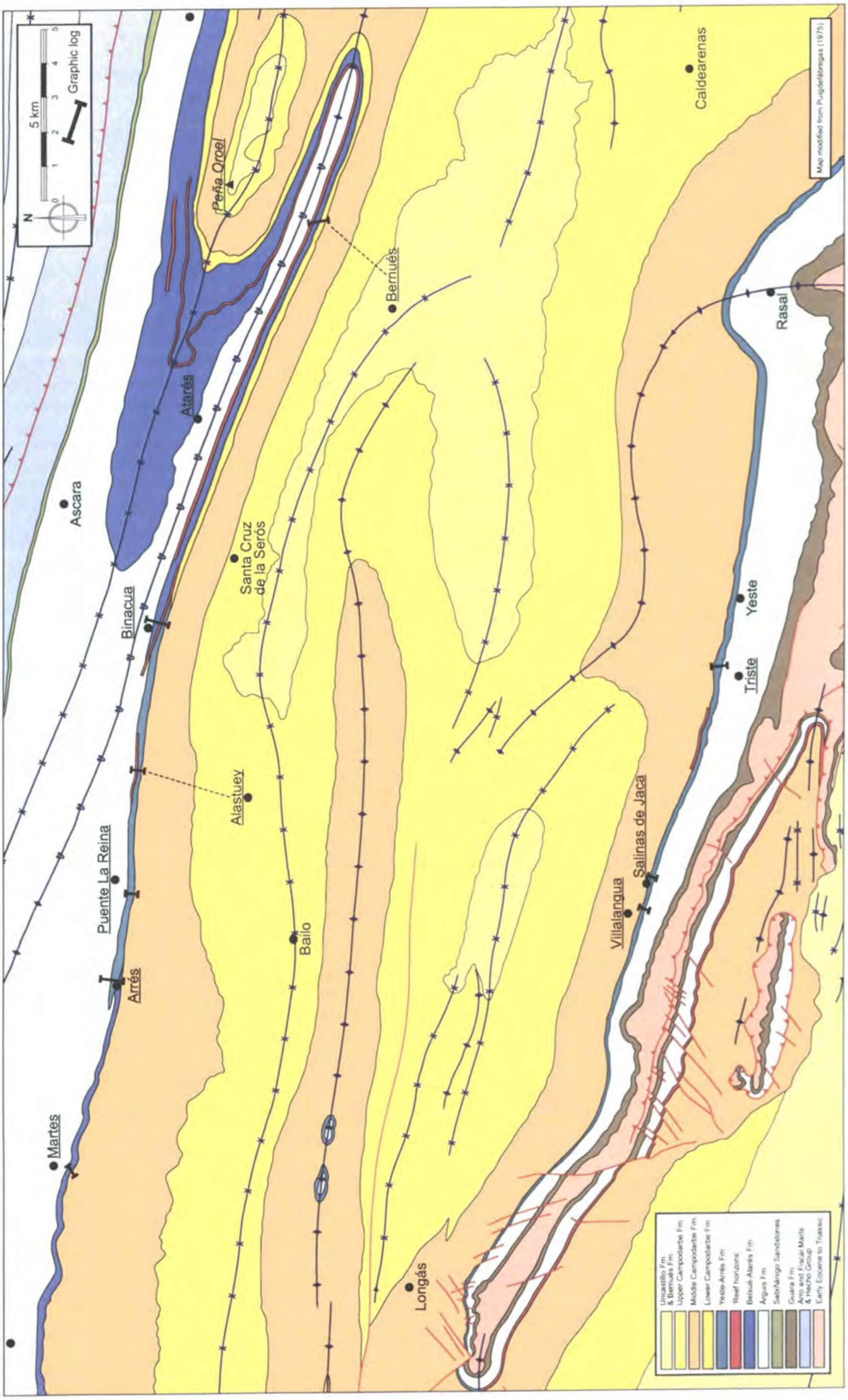


Fig. 7.1. Geological map of the Western Jaca Basin, indicating the positions of the eight graphic logs.

at the western end of the External Sierras is the multiple-kilometre-scale Santo Domingo anticline, visible in the SW portion of **Fig. 7.1** (labelled on **Fig. 1.3**). This structure consists of a large detachment fold and associated south-directed thrust system, and formed during the Late Oligocene and Early Miocene (Garrido *et al.*, 1995). It grew because the focus of the thrust sheet rotation that affected the central External Sierras during Belsué-Atarés Fm. times (discussed in detail in section **9.2.1.1**) shifted westwards to the western end of the External Sierras (Pueyo *et al.*, 2000).

Turner (1992) studied the effect that the growth of Santo Domingo anticline and the emergence of the western External Sierras had on the terrestrial depositional systems of the time. The conclusion reached was that the growth of the various structures caused the variations in the alluvial stratigraphy that are observed across the area. These variations are interpreted as representing changes in fluvial style, and have been used to distinguish the Upper Campodarbe Fm., the Bernués Fm. and the Uncastillo Fm. from one another. Tectonic deformation along the southern margin of the Jaca Basin continued throughout the Oligocene and Miocene. As a result, a series of eleven alluvial fans were shed from the thrust front into the Ebro foreland basin (Nichols & Hirst, 1998). Evidence of the ongoing tectonic deformation is spectacularly recorded in the abundant growth structures that pervade the alluvial fan conglomerate bodies (Lloyd *et al.*, 1998).

Thus, although it is well documented that the margin-defining structures in this part of the Jaca Basin were actively growing during its terrestrial infill phase, the existence and role of these structures during the preceding marine phase has never been properly investigated. To-date, the only published contribution towards filling this significant knowledge gap has come from Turner (1990). In this work it was suggested that the earliest structure to form at the western end of the Jaca Basin was one of the northern-margin-defining thrusts, during the latest Eocene, and that the sequence of thrust development proceeded southwards from there.

The study of the sedimentological characteristics of the Belsué-Atarés Fm. in this area should help constrain when the growth of the basin-bounding structures was initiated. However, because all the Belsué-Atarés Fm. outcrops in this sector are aligned parallel to the WNW–ESE-trending structures, obvious stratal-thinning-type growth relationships are expected to be absent. Instead, evidence of a structural definition to the northern and southern basin margins here will have to be sought amongst the facies distributions, palaeocurrent directions and progradational trends of the regional depositional systems.

As well as the structures and their effects on sedimentation, the sedimentological characteristics of the Belsué-Atarés Fm. in this sector are somewhat unusual and merit in-depth study in themselves. The mapping of Puigdefàbregas (1975) indicates that at the western end of the northern and southern basin margins, the Belsué-Atarés Fm. passes into a laterally equivalent formation known as the Yeste-Arrés Fm. (**Fig. 7.1**). Puigdefàbregas (1975) mapped this formation as being around 100 m thick, and distinguished it from the largely deltaic Belsué-Atarés Fm. because it is composed of "sandstones and marls of littoral [inter-tidal zone] facies". The existence and positioning of such a considerable thickness of a highly distinctive facies association could reveal much about the dynamics of the Jaca Basin during Belsué-Atarés Fm. times.

The following sections of this chapter are based on data collected during the course of this work. This section, section **7.2**, focuses on description and interpretation of the facies, palaeocurrent and sediment composition data collected from the Belsué-Atarés Fm. and Yeste-Arrés Fm. The interpretation of these will then be applied, in section **7.3**, to provide an explanation of the significance of the unusual Yeste-Arrés Fm. and to determine the configuration of the northern and southern margins of the Jaca Basin during its marine infill phase.

7.2.1 Facies, facies associations and facies architecture

The facies and facies associations recorded on the eight logs undertaken in this area are very diverse. The Binacua log (Vol.2, p.20 & p.123 – 126) is the easternmost undertaken on the northern basin margin in this sector. It begins with more than 200 m of the Árguis Fm., which is mainly composed of offshore marine marls (FA1; section **3.3.1**). There are, however, significant quantities of silt, sandstone and limestone beds amongst the marls, which together represent the offshore–transition zone marls and sandstones facies association (FA2; section **3.3.2**). The Árguis Fm. on this section also features a relatively thin 8 m of lower shoreface sandstones (FA3; section **3.3.3**), and 19 m of carbonate ramp limestones (FA7; section **3.3.7**). Overlying the Árguis Fm., and consisting of more proximal facies associations, is the 81.6-m-thick Belsué-Atarés Fm. An unusually high proportion of this, around three-quarters, is composed of grey and yellow clays and silts facies (section **3.2.15**) of the marginal marine clays and sandstones facies association (FA6; section **3.3.6**). Most of the rest of the Belsué-Atarés Fm. is split evenly between two packages of carbonate ramp limestones (FA7). As is the case on all logs in this sector, the marine Belsué-Atarés Fm. is capped with fluvial sandstones and red soils (FA12; section **3.3.12**) of the Middle Campodarbe Fm.

The Alastuey log (Vol.2, p.21 & p.127 – 128) lies 4.5 km to the west of the Binacua log. The mapping of Puigdefàbregas (1975) indicates that this is the easternmost section to pass through the full thickness of the Yeste-Arrés Fm. On this section, the Yeste-Arrés Fm. is 56.4 m thick, and composed entirely of tidal flat sandstones (FA8; section **3.3.8**). This facies association largely comprises parallel-laminated sandstones facies (section **3.2.12**), with a few medium, cross-laminated sandstones facies (section **3.2.7**) interbeds.

A further 3.5 km to the west lies the Puente La Reina log (Vol.2, p.22 & p.129 – 130). This passes through 96.0 m of the Yeste-Arrés Fm., which is again composed almost entirely of parallel-laminated sandstones facies of the tidal flat sandstones (FA8) facies association. However, at 44.8 – 57.6 m (Vol.2, p.129), there is a uniquely thick and coarse package of medium, cross-laminated sandstones facies and coarse, cross-bedded sandstones facies (section **3.2.8**). Marl or clay rip-up clasts are abundant throughout the sandstones in this package, and some channelisation is evident.

Moving 2.6 km to the west, the Arrés log is the next encountered (Vol.2, p.23 & p.131 – 133). In this section the Yeste-Arrés Fm. is only 34.2 m thick, but is otherwise very similar to that on the preceding two logs. Unusually, 100 – 170 m beneath the base of the Yeste-Arrés Fm. in the Árguis Fm. are four, 1.2 – 3.2-m-thick beds of parallel laminated sandstones facies (Vol.2, p.131).

The most westerly log on the northern Jaca Basin margin, lying 5.6 km west of Arrés, is the Martes log (Vol.2, p.24 & p.134 – 135). Puigdefàbregas (1975) indicates that this section passes through the Belsué-Atarés Fm. once more, and the lithologies logged were strikingly different to those of the Yeste-Arrés Fm. sections further east. The section begins with sand-free offshore marine marls (FA1) of the Árguis Fm. Abruptly overlying these is the 66.0-m-thick Belsué-Atarés Fm. This is almost entirely composed of sandstones, about three-quarters of which are medium, cross-bedded sandstones facies of the upper shoreface and delta front facies association (FA4; section **3.3.4**). In many beds plant debris is unusually abundant, and a few also contain apparently un-reworked *Nummulites* and other marine fossils.

About 16 km to the south of the northern basin margin lies the southern basin margin. Puigdefàbregas (1975) indicated that it is the Yeste-Arrés Fm. that rims the whole of the southern margin in this sector, and not its lateral equivalent the Belsué-Atarés Fm. (which outcrops further to the east). The boundary between the Yeste-Arrés

Fm. and underlying Árguis Fm. is either undefined or gradational in the exposures visited, and so no attempt to arbitrarily separate the two formations has been made. A similar problem with defining the base of the Belsué-Atarés Fm. was encountered further east along the southern margin (Chapter 8 & Chapter 9). In general though, the Árguis Fm. is dominated by offshore marine marls (FA1), whilst the Yeste-Arrés Fm. from the southern margin is primarily composed of offshore–transition zone marls and sandstones (FA2). This also makes the Yeste-Arrés Fm. from the southern margin very different to that from the northern margin, which a dominated by tidal flat sandstones (FA8). It is not at all obvious why the two areas of outcrop were placed within the same formation by Puigdefàbregas (1975).

The easternmost log from the southern margin in this sector was situated at Triste (Vol.2, p.25 & p.136 – 138). It covers the uppermost 217 m of the Yeste-Arrés Fm. & Árguis Fm., up to the base of the Middle Campodarbe Fm. Over 90% of this thickness comprises the offshore–transition zone marls and sandstones facies association (FA2; section **3.3.2**). About one-quarter of the FA2 beds are rich in marine fossils, and some beds are extremely so. Fossil types include: *Nummulites*, bivalves, bryozoans, foraminifera, oysters, echinoids and gastropods; many were fragmented although some were whole. Standing out towards the top of this otherwise marl dominated succession are a 4.8-m-thick package of upper shoreface and delta front sandstones (FA4), a 3.6-m-thick package of proximal delta front channelised sandstones (FA5; section **3.3.5**), and 10 m of marginal marine clays and sandstones (FA6; section **3.3.6**). As is the case on all logs in this sector, the marine deposits are capped with fluvial sandstones and red soils (FA12) of the Middle Campodarbe Fm.

The Salinas de Jaca log (Vol.2, p.26 & p.139 – 140) lies 4.9 km to the west. The 109 m of Yeste-Arrés Fm. & Árguis Fm. covered by this log is similar to that at Triste, being marly and rather fossiliferous. It is however composed of near-continuous marly silts and sandstones facies (section **3.2.3**), rather than being divided up into metre-scale-thick beds of alternating sand or marl dominance. Towards the very top of the sequence, a 0.8-m-thick bed of bioclastic limestones facies (section **3.2.9**) and a 1.6-m-thick bed of grey and yellow clays and silts facies (Vol.2, p.140) are the only two distinctive units in the whole succession.

The westernmost log on the southern margin is at Villalangua (Vol.2, p.27 & p.141 – 143), 1.4 km to the west of Salinas de Jaca. The 173-m-thick portion of the Yeste-Arrés Fm. & Árguis Fm. studied here is very similar to that further east. Around two-thirds of the studied thickness is composed of fossiliferous marly silts and sandstones facies of the offshore–transition zone marls and sandstones (FA2) facies association. This section does however contain a few more limestone beds in its lower half than the Salinas de Jaca section, including a 4.8-m-thick one (Vol.2, p.141). Also of note is a 6.4-m-thick bed of medium, cross-bedded sandstone facies, bearing marine fossils and abundant marl rip-up clasts, just beneath the base of the Middle Campodarbe Fm. (Vol.2, p.141).

Unlike most other parts of the Jaca Basin, the Árguis Fm., Belsué-Atarés Fm. and Yeste-Arrés Fm. of this sector represent only a limited spectrum of marine depositional environments. Most of the sections record long-lived offshore (represented by FA1) and offshore–transition zone (FA2) conditions, typified by marl-rich lithologies. Sand-rich, more proximal facies associations are unusually rare. Lower shoreface deposits (represented by FA3) are only seen as thin accumulations (8 – 26-m-thick) on three of the eight logs, whilst upper shoreface and delta front (FA4) and proximal delta front (FA5) deposits are essentially absent, except at Martes where the former dominates. Marginal marine (FA6) and carbonate ramp (FA7) depositional environments are represented on a few logs. The Yeste-Arrés Fm. from the northern basin margin is completely unlike that from the southern margin, and was entirely formed on a tidal flat (FA8).

In summary, this sector of the Jaca Basin was dominated by a succession of deep marine, distal marine and marginal marine depositional environments, with little significant sand-grade siliciclastic input (except at Martes).

7.2.2 Palaeocurrents

Palaeocurrent readings were collected from a range of sedimentary structures found within the marine formations of this sector (**Fig. 7.2**). Most readings came from symmetrical ripples, giving bi-directional trends, but asymmetrical ripples and tabular cross-lamination were also measured. In addition, some readings were taken from cross-lamination and cross-bedding in the non-marine Middle Campodarbe Fm. Well-established palaeocurrent directions in the Yeste-Arrés Fm. of the northern basin margin include NNE–SSW, NW–SE, W–E, and N–S, with many other readings falling in between. At Martes, there was evidence of south-directed flow in the Belsué-Atarés Fm., which continued up into the overlying Middle Campodarbe Fm. Along the southern basin margin there were fewer opportunities to measure palaeocurrents in the marl dominated lithologies, but a WNW–ESE trend seemed to be evident.

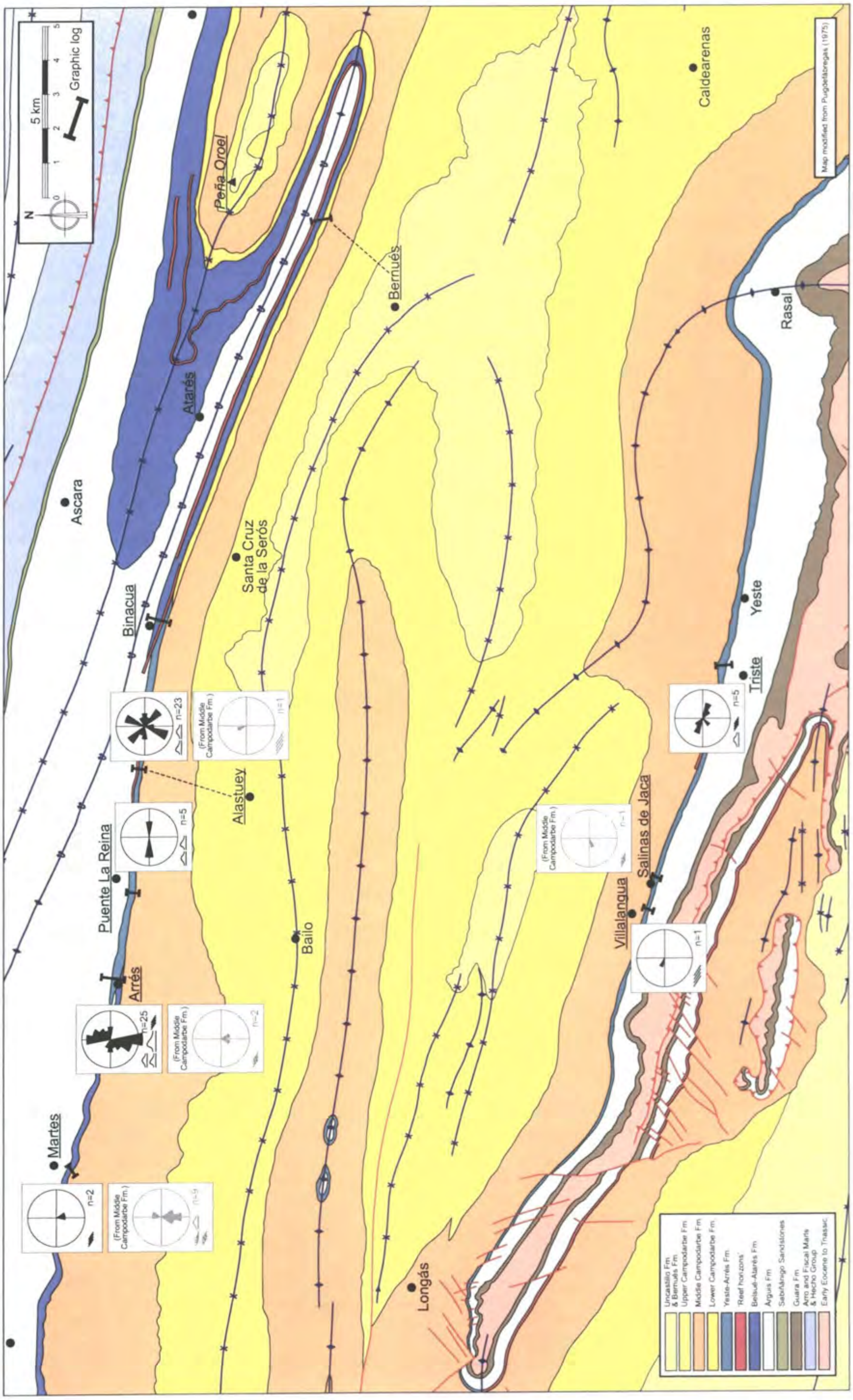


Fig. 7.2. Geological map of the Western Jaca Basin, with palaeocurrent rose diagrams for each log.

Along the northern basin margin to the east of this sector, the palaeocurrent patterns tend to be NNE–SSW-directed (chapters 4 – 6), which was been interpreted to represent basinal waves flowing normal to a shoreline defined by the WNW–ESE-trending structures. In this part of the northern basin margin, there is again some NNE–SSW-directed potentially shoreline-normal flow (at Arrés and Alastuey), but also some directions that could be shoreline-parallel (Puente La Reina) and shoreline-oblique (Alastuey again). The southerly-directed flow in the Belsué-Atarés Fm. and Middle Campodarbe Fm. at Martes suggests that sediment entered the Jaca Basin across the northern margin at this point.

Along the southern basin margin, the WNW–ESE palaeocurrent trend in the Yeste-Arrés Fm. & Árguis Fm. is parallel to the structures that define the present-day margin. These palaeocurrent readings suggest that at the time of their formation, the southern margin was a topographic high, forming a shoreline that flow was directed parallel to. If this was the case, then it is most likely that the southern margin structures were actively uplifting during Yeste-Arrés Fm. & Árguis Fm. times, or else they would have been swamped by the on-going sedimentation.

7.2.3 Sediment composition

Samples were collected from several fine–medium sandstone beds on each log, and their composition analysed to see if there were any major differences between or within the sections. **Fig. 7.3** and **Fig. 7.4** show the results of this process for the northern basin margin (at Martes, Puente La Reina and Jaca) and the southern basin margin (at Villalangua, Salinas de Jaca and Triste), respectively. The compositions of the samples from the other two sections on the northern margin were analysed but found to be similar to those from the first three, so were omitted from the plot for clarity.

On the northern basin margin (**Fig. 7.3**), the samples gathered at Binacua were from the Belsué-Atarés Fm., whereas those from Puente La Reina were from the Yeste-Arrés Fm. Despite this, the compositions of both were remarkably similar. However, the samples gathered at Martes, although also from the Belsué-Atarés Fm., were somewhat different. For example, in the Martes samples, the fraction of quartz is significantly higher (22.4 – 36.0% vs. 16.0 – 25.2%), and fraction of micritic limestone lithics and micrite cement is much lower (32.0 – 48.8% vs. 50.8 – 67.2%). Furthermore, the proportions of opaque rich lithics, polycrystalline quartz grains and opaque iron minerals were also significantly greater at Martes. Furthermore, the Martes samples

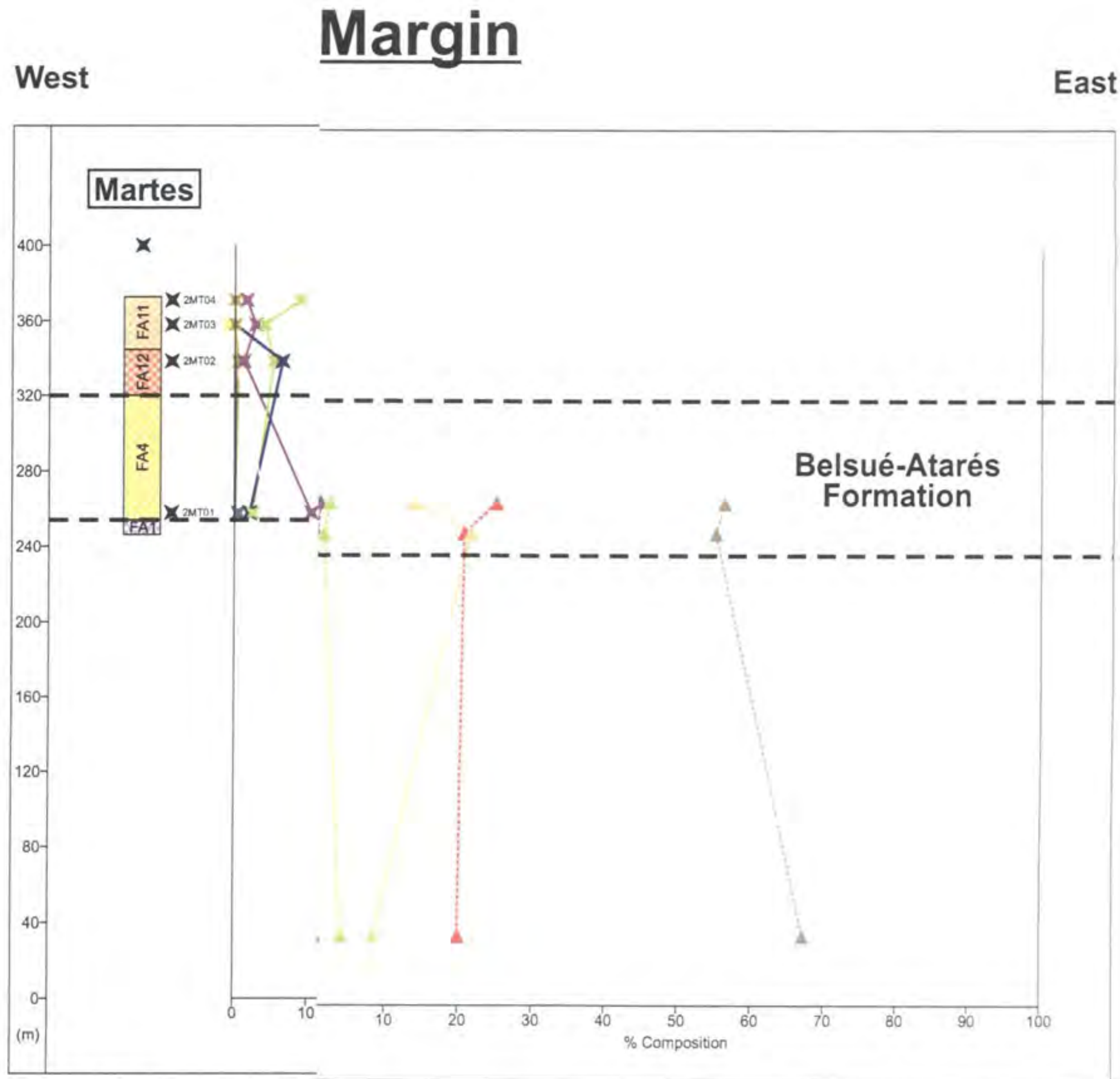


Fig. 7.3. Comparison of

Margin

West

East

contained a grain type that was not seen at all at the other two localities (sandy micritic limestones lithics). It therefore seems most probable that the sediment source area and regional depositional system that supplied Martes was distinct from those that supplied Puente La Reina and Binacua to the east.

On the southern basin margin (**Fig. 7.4**), all samples came from the Yeste-Arrés Fm. & Árguis Fm. However, because the only sandstones to be found in these sections were in the last few metres beneath the base of the Middle Campodarbe Fm., only one sample per log was taken. Furthermore, the complete lack of sandstones on the Salinas de Jaca section meant that a siltstone bed had to be analysed. This almost certainly explains why this sample contained an anomalously large proportion of micrite and an anomalously small proportion of quartz. The compositions of the samples from Villalangua and Triste were very similar, and it is therefore likely that they were deposited by the same regional depositional system.

The sandstones from the southern margin contain a relatively high proportion of quartz (about 35%), a relatively low proportion of micritic limestones lithics and micrite cement (again, about 35%), and significant proportions of opaque rich lithics, polycrystalline quartz grains and opaque iron minerals. This makes them very similar to the samples from Martes on the northern margin, but quite dissimilar to those from Puente La Reina or Binacua. Thus it is possible, though not necessarily the case, that the Belsué-Atarés Fm. at Martes and the Yeste-Arrés Fm. & Árguis Fm. from the western end of the southern basin margin came from the same source area, and were deposited by the same regional depositional system. This depositional system would be distinct from the one that was responsible for the Yeste-Arrés Fm. at Puente La Reina and the Belsué-Atarés Fm. at Binacua. However, the fact that all samples contained a few percent of a number of different 'exotic' grains, derived from igneous and metamorphic rocks, suggests that both depositional systems were at least partly sourced in the Pyrenean axial zone (Jones, 1997).

7.3 Correlation, interpretation and discussion

Section **7.2** covered the fundamental aspects of the marine growth strata of the Western Jaca Basin sector. This section, section **7.3**, takes these fundamentals and builds upon them, aiming towards fully understanding the complex record of marine sedimentation, and detecting any structural controls that may have operated.

The first stage of this is the discussion of the level of correlation that exists between the eight graphic logs from opposing margins of the basin (section **7.3.1**). From this, and the sedimentological data, a model of the depositional systems that operated in the western portion of the Jaca Basin during Belsué-Atarés Fm. times shall be determined (section **7.3.2**). A good understanding of the sedimentation should allow any structural controls to be detected, thus helping to constrain the configuration of the northern and southern basin margins at this time (section **7.3.3**).

7.3.1 Correlation between graphic logs

Fig. 7.5 and **Fig. 7.6** are two parallel, W–E-orientated correlation panels. The former covers the five graphic logs from the northern basin margin, whilst the latter covers the three logs from the southern margin. The northern margin panel (**Fig. 7.5**) also features the Bernués log, which lies nearly 12 km to the east of the Binacua log in the Northern Jaca Basin sector (Chapter 6), to aid correlation between the two areas. The next log to the east along the southern basin margin, the Bentué de Rasal log of the Southern Jaca Basin sector (Chapter 9), was not included on the southern panel (**Fig. 7.6**) because it was around 20 km away and across the crest of a kilometre-scale growth anticline (the Rasal anticline).

No palaeomagnetic or biostratigraphic dating has been undertaken in this area, so the correlations had to be constructed purely on the basis of facies. The vertical positions of each of the logs on the correlation panels were determined by simply 'hanging' them from a horizontally drawn base of the Lower / Middle Campodarbe Fm., which tends to be a sharp and distinctive boundary. The base of the Lower / Middle Campodarbe Fm. has been shown by Hogan & Burbank (1996) to have formed more or less synchronously along a 23-km-long section of the southern basin margin, between the Villalangua log in this sector and the Árguis log in the Southern Jaca Basin sector (Chapter 9). Some of the palaeomagnetic dates of Hogan & Burbank (1996) are included next to the Villalangua log on the southern margin panel (**Fig. 7.6**).

However, it is worth remembering that despite the findings of Hogan & Burbank (1996), the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary has already been shown to be diachronous – in places – by its succession of progradations and retrogradations in the Far NE Jaca Basin sector (Chapter 4). This means that the base of the Lower / Middle Campodarbe Fm. in this sector could also be diachronous. Therefore, these correlation panels should be considered to be wholly stylistic. Whilst the vertical scales may be sediment thickness, these have no direct relationship to time. Each of the formation boundaries marked merely indicate areas of the same facies association (depositional environment) on adjacent logs, are most likely to be diachronous, and so are not necessarily key surfaces of any sort.

7.3.1.1 Correlation panel 1: northern margin

The degree of correlation between adjacent logs along the western end of the northern basin margin is quite variable (**Fig. 7.5**) – some sections look very similar to their immediate neighbours, whilst between others there are few common features. However, all logs at least begin in the offshore marine marls (FA1) and offshore–transition zone marls and sandstones (FA2) of the Árguis Fm., and end in the fluvial sandstones and red soils (FA12) of the Middle Campodarbe Fm. It is within the interval between these two bounding formations that most of the inter-log variations lie, and also on which this study is principally focussed.

At the eastern end of the first correlation panel is the Bernués log from the Northern Jaca Basin sector (Chapter 6). The 238.4-m-thick Belsué-Atarés Fm. at Bernués is quite dissimilar to the 81.6-m-thick Belsué-Atarés Fm. at Binacua, the easternmost log in this sector. The section at the former locality is characterised by a 34-m-thick package of proximal delta front channelised sandstones (FA5) in an otherwise predominantly marly succession, whereas the latter section is largely composed of marginal marine clays and sandstones (FA6), with a couple of intervening carbonate ramp limestones (FA7). The considerable differences between these sections can at least partly be explained by the fact that they are separated by nearly 12 km.

Somewhere between the Binacua log and the Alastuey log, which lies 4.5 km to the west, the Belsué-Atarés Fm. grades into its lateral equivalent the Yeste-Arrés Fm. (Puigdefàbregas, 1975). These two formations consist of fundamentally different and highly distinctive facies and facies architectures. The Alastuey, Puente La Reina and Arrés logs all pass through the Yeste-Arrés Fm., and together cover a stretch of the northern basin margin that is just over 6 km long. In each the Yeste-Arrés Fm. is entirely represented by tidal flat sandstones (FA8) of near identical appearance. The only variations are in the thickness of the FA8 package – it is 56.4 m thick in the east at Alastuey, 96.0 m thick at Puente La Reina, and only 34.2 m thick in the west at Arrés.

Somewhere between the Arrés log and the Martes log, which lies 5.6 km to the west, the Yeste-Arrés Fm. grades back into the laterally equivalent Belsué-Atarés Fm.

This is again represented by a fundamental change in facies and facies architecture. The 66-m-thick Belsué-Atarés Fm. at Martes is entirely composed of upper shoreface and delta front sandstones (FA4), some of which contain *Nummulites*.

Thus it seems likely that the Belsué-Atarés Fm. in the Martes area and the Yeste-Arrés Fm. in the Arrés–Puente La Reina–Alastuey area were deposited by very different depositional processes, perhaps driven by different regional-scale depositional systems. The relationship eastwards between the Yeste-Arrés Fm. at Alastuey and the Belsué-Atarés Fm. at Binacua and at Bernués is less clear-cut. It seems most likely that the marginal marine (FA6) dominated Binacua log may occupy a transitional zone between the offshore marine (FA1) to deltaics (FA5) of Bernués and the tidal flats (FA8) of the Yeste-Arrés Fm. at Alastuey.

7.3.1.2 Correlation panel 2: southern margin

The degree of correlation between adjacent logs along the western end of the southern basin margin is very strong (**Fig. 7.6**) – all three sections appear to be very similar to one another. Each log passes through the uppermost 200 m or so of the undifferentiated Yeste-Arrés Fm. & Árguis Fm. This is almost entirely composed of very fossiliferous offshore–transition zone marls and sandstones (FA2). The precise architecture of this facies association does, however, vary from log to log. At Triste it is made up of ten-metre-scale oscillations between silty and sandy marls facies and marly silts and sandstones facies. At Salinas de Jaca, the marly silts and sandstones facies is near continuous and almost un-bedded. The facies architecture at Villalangua lies somewhere in between these two extremes.

Other slight variations are evident in the uppermost few tens of metres of Yeste-Arrés Fm. & Árguis Fm. At Triste, the log ends with a 4.8-m-thick package of upper shoreface and delta front sandstones (FA4), a 3.6-m-thick package of proximal delta front channelised sandstones (FA5), and 10 m of marginal marine clays and sandstones. None of these packages are seen 5 km to the west at Salinas de Jaca, where the FA2 deposits remain right up to the top of the Yeste-Arrés Fm. & Árguis Fm. Moving 1.4 km westwards to the Villalangua section, the top of the Yeste-Arrés Fm. & Árguis Fm. is made up of an 8-m-thick package of upper shoreface and delta front sandstones (FA4). However, all sections end with the same fluvial sandstones and red soils (FA12) of the Middle Campodarbe Fm.

Thus, the Yeste-Arrés Fm. & Árguis Fm. of the western end of the southern basin margin was deposited by one depositional system, in a regionally extensive offshore–transition zone depositional environment (FA2). Towards the very end of marine sedimentation, laterally inextensive and less than 10-m-thick lobes of deltaic sandstones (FA4 and FA5) were deposited in some areas.

The uppermost portions of the Yeste-Arrés Fm. & Árguis Fm. of the southern basin margin are completely different to any of the sections through the Yeste-Arrés Fm. of the northern margin, 16 km to the north. Therefore, it seems likely that each area was part of different regional-scale depositional system.

7.3.2 Depositional systems of the western Jaca Basin

Integration of the facies (section **7.2.1**), palaeocurrent (section **7.2.2**), composition (section **7.2.3**), and correlation data (section **7.3.1**) allows the recognition of a number of regional-scale depositional systems that contributed to the deposition of the Belsué-Atarés Fm. and Yeste-Arrés Fm. in the Western Jaca Basin sector.

One such depositional system was responsible for the tidal flats (FA8) of the Yeste-Arrés Fm. in the Arrés–Puente La Reina–Alastuey area of the northern basin margin. It seems that this system was the same one that deposited the Belsué-Atarés Fm. at Binacua and in areas further to the east. The primary evidence for this is the eastward gradation between the tidal flats (FA8) at Alastuey, the marginal marine sediments (FA6) of Binacua, and the offshore marine (FA1) to proximal delta front (FA5) deposits of Bernués and areas further east (**Fig. 7.5**). Further evidence of one depositional system for the Yeste-Arrés Fm. and the Belsué-Atarés Fm. on the northern margin comes from the composition data – the sediments at Puente La Reina, Binacua (**Fig. 7.3**), and Bernués (**Fig. 6.3**), all have very similar make-ups.

The deposits of the Yeste-Arrés Fm. tidal flats (FA8) are only 34.2 – 96.0 m thick. This is very much thinner than the Belsué-Atarés Fm. offshore marine (FA1) to proximal delta front (FA5) sequence that is seen further east, which is 238 m thick at Bernués and reaches 710 m at Jaca (Chapter 6). This rapid westward-directed stratal thinning, when considered in conjunction with the long-lived inter-tidal zone (FA8) depositional environment of the Yeste-Arrés Fm., implies that the rate of creation of accommodation space during the deposition of the Belsué-Atarés Fm. / Yeste-Arrés Fm. was far slower in the west than the east. In the Belsué-Atarés Fm. area in the east, relatively rapid accommodation space creation, due to rapid basinal subsidence, allowed the thick offshore marine (FA1) to proximal delta front (FA5) sequence to accumulate. In the west, sedimentation was able to keep up with the slower subsidence rate, maintaining a marine water depth of close to 0 m and allowing the long-lived Yeste-Arrés Fm. tidal flats (FA8) to form.

The Belsué-Atarés Fm. at Martes was unique. The complete dominance of upper shoreface and delta front sandstones (FA4) is in abrupt contrast to the Yeste-Arrés Fm. tidal flats (FA8) just 5.6 km to the east (**Fig. 7.5**). The Martes sandstones were also of distinctive and unusual composition – rich in quartz and various 'exotic' grains, poor in micritic limestone lithics (**Fig. 7.3**). Palaeocurrent information recorded a southerly-directed flow in the Belsué-Atarés Fm. and in the overlying fluvial Middle Campodarbe Fm. (**Fig. 7.2**). The relatively thin 66-m-thickness of the Belsué-Atarés Fm., and the more-or-less complete lack of fines preservation (Vol.2, p.134), suggests that it too, like the Yeste-Arrés Fm. further east, was deposited during times of slow subsidence. Importantly, the upper shoreface and delta front sandstones (FA4) at Martes are isolated from all other similar proximal siliciclastic deposits in the Jaca Basin. Therefore it is likely that they were fed by their own unique sediment input point, supplying sediments of a distinctive composition southwards into the basin.

The Yeste-Arrés Fm. & Árguis Fm. of the western end of the southern basin margin seems to have been deposited by a single depositional system, bearing sediments of a fairly constant composition (**Fig. 7.4**). The depositional environment was a long-lived offshore–transition zone area (represented by FA2). Marl sedimentation dominated over siliciclastics until almost the very end of marine conditions, when a number of short-lived (less than 10 m thick), sand dominated, laterally inextensive delta lobes fed into the area. The dominant palaeocurrent of this system was WNW–ESE-directed wave rippling. This is though to represent shoreline-parallel currents, flowing parallel to a topographic high created by active uplift on the structures that define the southern basin margin.

Comparing the composition of Yeste-Arrés Fm. on the southern and northern basin margins, the sediments from the south tended to be much more quartz rich (34.4 – 35.2% vs. 16.0 – 25.2%) and micritic limestones lithics poor (32.8 – 37.2% vs. 50.8 – 67.2%) than those further north (**Fig. 7.3** and **Fig. 7.4**). This could mean that the Yeste-Arrés Fm. deposits from the two margins were sourced from different areas, or that the southern margin sediments had simply been transported further, causing the more resilient quartz grains to form an increasingly dominant fraction. In fact, the sediments from the southern margin have compositions that are really quite similar to those from

Martes (**Fig. 7.3** and **Fig. 7.4**). It is therefore possible that the offshore–transition zone marls and sandstones (FA2) of the Yeste-Arrés Fm. & Árguis Fm. from the southern basin margin are the distal equivalents of upper shoreface and delta front sandstones (FA4) of the Belsué-Atarés Fm. from Martes on the northern margin.

7.3.3 Structural controls on sedimentation in the Western Jaca Basin

Sedimentation in the Western Jaca Basin sector was driven by three separate regional-scale depositional systems (**Fig. 7.7**). The first system (numbered '1.' on **Fig. 7.7**) was responsible for the tidal flats of the Yeste-Arrés Fm. on the northern basin margin. The second ('2.' on **Fig. 7.7**) fed southwards into the Jaca Basin via an isolated entry point at Martes. The third system ('3.' on **Fig. 7.7**) deposited the offshore–transition zone marls and sandstones at the western end of the southern basin margin. Each of these depositional systems shows evidence of some degree of tectonic control.

Tectonics controlled the formation of the northern margin Yeste-Arrés Fm. tidal flats because a subsidence rate that was relatively slow but continuous, and very similar to the sediment accumulation rate, would be necessary to maintain inter-tidal zone conditions for long enough to allow nearly 100 m of sediment to accumulate. The thickness of the Yeste-Arrés Fm. also varies significantly along the 6 km length of its outcrop that was studied (**Fig. 7.5**): from 56.4 m in the east, up to 96.0 m in the middle, and then down to 34.2 m in the west. This probably reflects local variations in subsidence, related to an evolving northern basin margin.

The isolated nature, significant thickness (66 m) and southerly-directed palaeocurrents of the sand-dominated Belsué-Atarés Fm. at Martes suggests that it was deposited by an isolated depositional system that came across the northern basin margin. The northern margin is defined by a series of WNW–ESE-trending thrusts and related folds that, in other areas of the basin, acted as a barrier, preventing the entry of depositional systems coming from the north. Thus it seems likely that the Martes system crossed the northern basin margin at a structurally-controlled low point. Unfortunately, no evidence of such a point is preserved amongst the structures that outcrop to the north of Martes at the present-day.

A degree of structural control was also evident along the western end of the southern basin margin, where palaeocurrents in the Yeste-Arrés Fm. & Árguis Fm. seem to suggest flow parallel to a shoreline defined by the uplifting, WNW–ESE-trending southern margin structures.

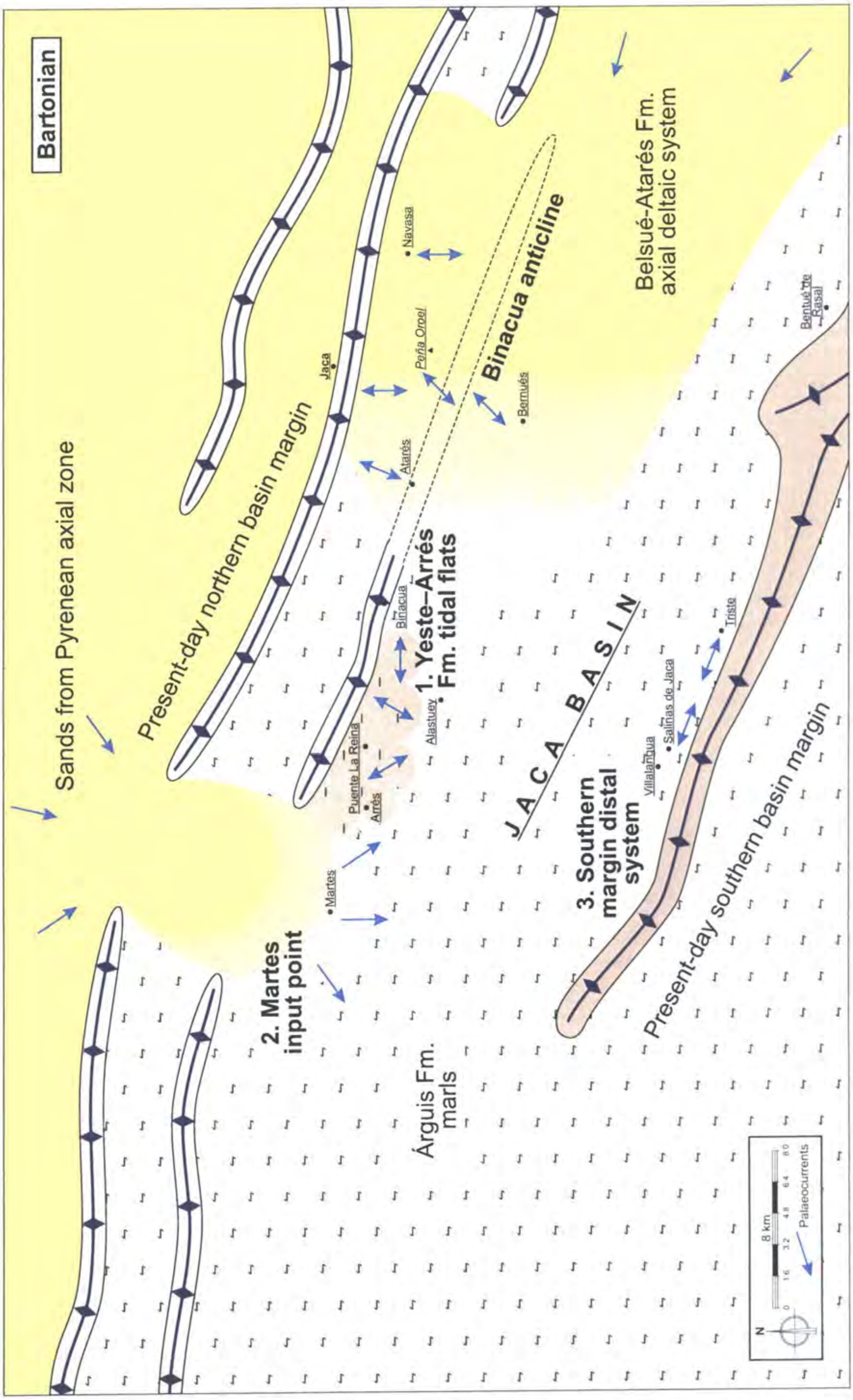


Fig. 7.7. Palaeogeography of the Western Jaca Basin sector during the Bartonian.

Thus, basin-scale tectonics and local-scale tectonic structures associated with the basin margins exerted a considerable controlling effect on the marine depositional systems of the Western Jaca Basin sector.

7.4 Conclusions

Sedimentation in the Western Jaca Basin sector was driven by three separate regional-scale depositional systems (**Fig. 7.7**). The first system was actually the distal portions of the Jaca Basin axial deltaic system, and supplied the sediments to the Yeste-Arrés Fm. tidal flats. The inter-tidal zone conditions persisted in this area long enough to deposit almost 100 m of sediment because of a close balance between the subsidence rate and the sediment accumulation rate.

The second system was positioned to the west of the tidal flats, at Martes. Here, the Martes deltaic system supplied sediments, from the Pyrenean axial zone, into the Jaca Basin via a structural low-point through the northern basin margin. This system represents an important sediment input for the western Jaca Basin.

The third system deposited the offshore–transition zone marls and sandstones of the Yeste-Arrés Fm. & Árguis Fm. of the western end of the southern basin margin. In this area, palaeocurrents were parallel to the uplifting WNW–ESE-trending structures that define the southern margin. Compositional similarities with the sands at Martes suggest that these deposits could be the distal equivalents of the Martes deltaic system.

7.5 Key Points

1. Sedimentary infill of the basin:

- Moving westwards, the Belsué-Atarés Fm. becomes increasingly dominated by more distal / marginal facies and facies associations.
- The Belsué-Atarés Fm. is much thinner in the west (< 100 m) than the east (> 700 m), implying that marine accommodation space was less in this area when the Belsué-Atarés Fm. was being deposited.
- The Yeste-Arrés Fm. tidal flats represent the later stages of sedimentation by the most distal portions of the Jaca Basin axial deltaic system.
- The Martes deltaic system supplied sands from the Pyrenean axial zone into the western portions of the Jaca Basin.

- The Yeste-Arrés Fm. of the southern basin margin represents an offshore–transition zone environment (FA2), and is very different to that of the northern margin.

2. Structural configuration of the basin:

- The western end of the northern basin margin was probably structurally defined by actively uplifting, WNW–ESE-trending thrusts and related folds during Belsué-Atarés Fm. / Yeste-Arrés Fm. times.
- The western end of the southern basin margin was probably structurally defined by actively uplifting, WNW–ESE-trending thrusts and related folds during Yeste-Arrés Fm. & Árguis Fm. times.
- There is no evidence for a structurally defined western margin to the Jaca Basin.

3. Influence of intrabasinal growth structures:

- Intrabasinal growth structures were not present in this sector of the basin.

4. Effect of sea-level changes:

- In this part of the basin, there is no clear evidence for cyclical changes in sea-level in the Belsué-Atarés Fm. / Yeste-Arrés Fm.

The next chapter, Chapter 8, discusses the eastern portions of the southern margin of the Jaca Basin, and the linkages with the Aínsa Basin. In this area, the Belsué-Atarés Fm. utilised two important sediment input points through the southern margin. Once in the basin, the deposition of the Belsué-Atarés Fm. sediments was strongly affected by a number of cycles in relative sea-level.

Chapter 8:

SE Jaca Basin

8. SE Jaca Basin

Contents

8. SE Jaca Basin

8.1 Introduction

Along-strike variations in structural style and sediment deposition are extremely common features of foreland basins (Hirst & Nichols, 1986; Puigdefàbregas & Souquet, 1986; Bentham *et al.*, 1992; Burbank *et al.*, 1992; Vincent & Elliott, 1996; Nijman, 1998), yet are not always incorporated into basinal models. Such variations become particularly important when, as is often the case, a major drainage system runs parallel to the strike of the mountain belt. In this instance, sedimentary and tectonic events at the 'upstream' end of the foreland basin system will be strongly reflected in the stratigraphy 'downstream'. Without a complete knowledge of the along-strike variations in the mountain belt, a study that focused on the stratigraphy at the far end of the system would not be able to arrive at a correct interpretation.

Understanding such variations requires study of the foreland structure and stratigraphy, not only from the hinterland to the foreland, but along the entire length of the mountain chain as well. This is only achievable if the complete stratigraphic column and the tectonic structures are exposed across most of the area. Yet more detailed work is required in the study of thrust-top basins, where typically abundant growth structures exert a controlling effect on sediment dispersal systems, tending to further exaggerate along-strike variations in stratigraphy (Ramos *et al.*, 2002).

Clearly, this breadth and depth of study would be an enormous task in any orogenic belt, and so an understanding of the along-strike variations is best achieved by the integration of the work from many groups of authors. Palaeomagnetic and biostratigraphic information should greatly assist in this.

The south Pyrenean foreland basin system presents an almost ideal location in which to study the importance of lateral variations along an orogenic system. Across the south Pyrenean foreland, the general trend was for tectonic and sedimentary events to occur first in the east, and then propagate westwards (Puigdefàbregas, 1975). The regional trend of east-to-west orogen-parallel drainage is a product of this. The south Pyrenean foreland basin is compartmentalised into the Tremp–Graus, Aínsa and Jaca thrust-top basins, and the Ebro foreland basin. Each of the thrust-top basins contain growth structures, usually N–S-orientated anticlines, which are known to have exerted a strong controlling effect on the sedimentation (e.g. De Boer *et al.*, 1991; Millán *et al.*, 1994; Castelltort *et al.*, 2003).

Many different groups of authors have worked in the different Pyrenean sub-basins (see Castelltort *et al.*, 2003, and references therein for Jaca Basin, Dreyer *et al.*, 1999, and references therein for Aínsa Basin, and Clevis *et al.*, 2004, and references therein for Tremp–Graus Basin), although the integration of results between areas has not always been attempted. This chapter aims to establish the linkages between the eastern and more proximal Aínsa Basin, and the more distal Jaca Basin to the west. This is achieved by the integration of previous work from the two basins (section **8.2**) and on the controlling effects of intrabasinal growth structures (section **8.3**), with an interpretation the newly collected data presented here (section **8.4** and section **8.5**). The results of this process are an understanding of the palaeogeography of the Jaca Basin during the Middle to Late Eocene, and an appreciation of how and why along-strike variations in structures and sediments were undoubtedly one of the most important characteristics of the south Pyrenean foreland basin system.

8.2 Aínsa Basin

If the stratigraphy and sedimentary history of a depositional basin that is situated in an along-strike varying foreland basin system is to be studied, it is clearly important to understand and take account of areas which were 'upstream' in the regional sediment transport system. In the case of the Jaca Basin, the Aínsa Basin was in the more proximal position. The structure and stratigraphy of the Aínsa Basin are already well documented in the literature – a brief review is given here. A more general discussion of the history and infilling of this basin is given in section **2.5** and, along with the stratigraphy, is summarised on **Fig. 2.20**.

8.2.1 Geological history

The Aínsa Basin lies immediately to the east of the Jaca Basin, across the Boltaña anticline (**Fig. 8.1**), and forms the middle compartment of the south Pyrenean thrust-top basin system. To the east of the Aínsa Basin, over the Mediano anticline, lies the Tremp–Graus Basin. Before the emplacement of the south Pyrenean frontal thrusts, these basins were part of the greater south Pyrenean foreland basin – which also included the Ebro Basin to the south. Emplacement of the frontal thrusts occurred first

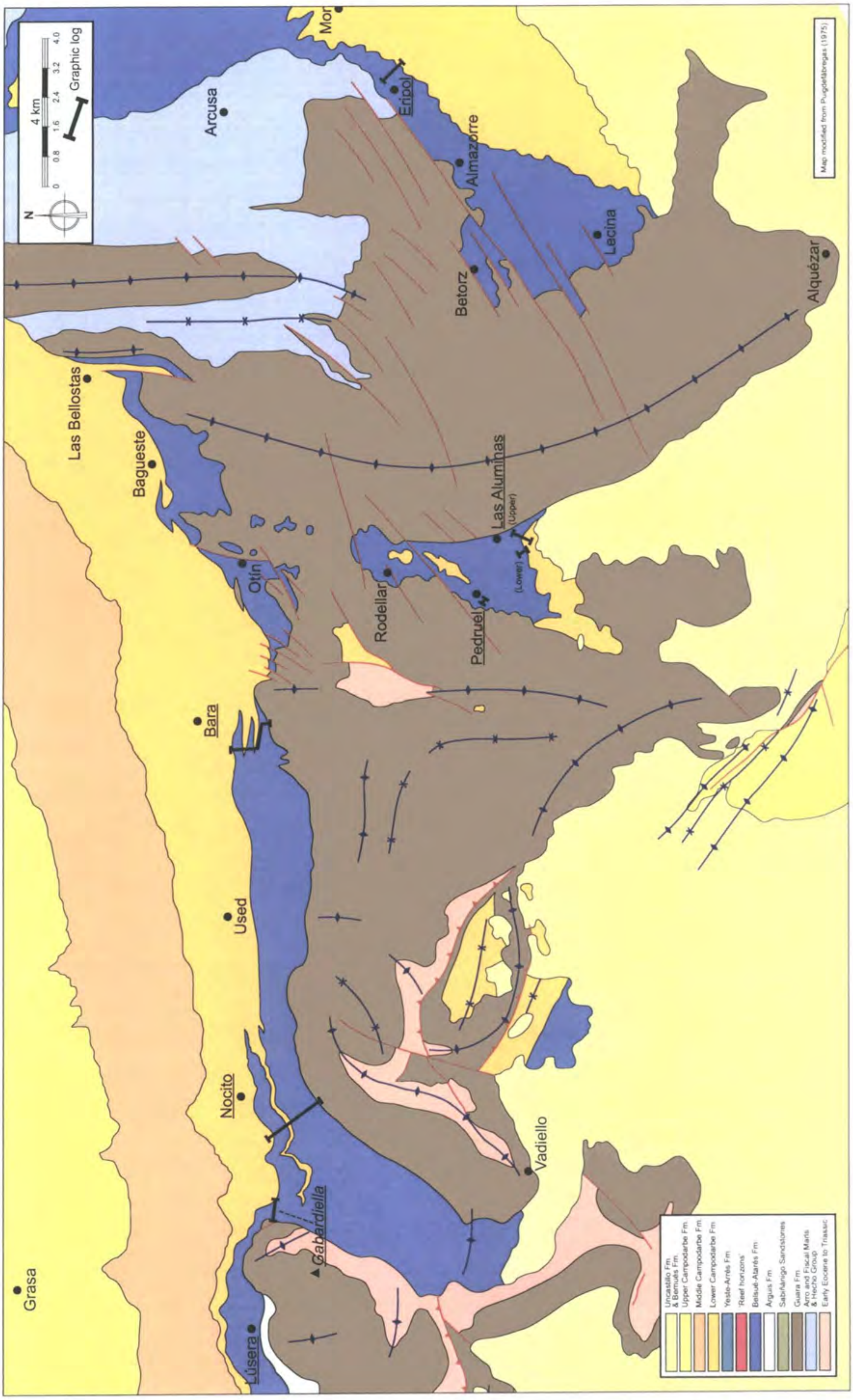


Fig. 8.1. Geological map of the SE Jaca Basin, indicating the positions of the seven graphic logs.

at the eastern end of the south Pyrenean area, and then progressed westwards. Thus the consequent tectonic uplift and the formation and progradation of coarse-grained clastic sedimentary systems also began in the east, in the Tremp–Graus Basin, and progressed westwards, through the Aínsa Basin and into the Jaca Basin.

The N–S trending synclinal Aínsa Basin began to form at the Ypresian–Lutetian transition (48.6 Ma) because of activity on the adjacent South Pyrenean central unit (SPCU) thrust sheet (Dreyer *et al.*, 1999). By the early Lutetian, the subsiding Aínsa Basin was being supplied with large quantities of sediment from the delta top and alluvial plain environments of the Tremp–Graus Basin to the east (**Fig. 8.2A**), forming the deep marine slope deposits of the San Vicente Fm. (Muñoz *et al.* 1998; **Fig. 8.3**). At the same time, to the south and west of the Aínsa Basin, the extensive Guara Fm. carbonate platform grew.

Thrusting continued its westward propagation from the middle Lutetian to the Bartonian, initiating the growth of the N–S growth anticlines of the External Sierras (marked '2'–'4' on **Fig. 8.2B**) along the southern margin of the Jaca Basin. Between around 44.4 Ma and 41.3 Ma, the deltaic Sobrarbe Fm., sourced from the alluvial-plain-dominated Tremp–Graus Basin to the east, entered the Aínsa Basin across its structurally lower southern end, and prograded along its axis towards the NNW (Jones, 1997; Dreyer *et al.*, 1999). To the south of the Aínsa Basin, low relief continental conditions were said to have existed. Importantly for this work, Dreyer *et al.* (1999) believed that in a similar manner, other deltaic systems, also fed from the same easterly source, flowed further west and into the synclines between anticlines of the External Sierras. The deltaic systems were then able to prograde northwards along these N–S conduits, and into the Jaca Basin.

On **Fig. 8.2B** from Dreyer *et al.* (1999), two such entry points into the Jaca Basin are indicated – these are presumably the synclines between the Balces and Alcanadre anticlines at Rodellar, and the probable similar structure between the Nocito and Gabardiella anticlines near Nocito (**Fig. 8.1**). However, Dreyer *et al.* (1999) did not present any evidence for the utilisation of these conduits by depositional systems in this way, and only referred to an old review of the regional geology (Soler & Puigdefàbregas, 1970). Thus, it seems reasonable to say that at the time, what was presented on **Fig. 8.2B** by Dreyer *et al.* (1999) was more of a theory than an established fact. Puigdefàbregas (1972) has also outlined a similar theory, but again did not present any evidence or particular reasoning for it.

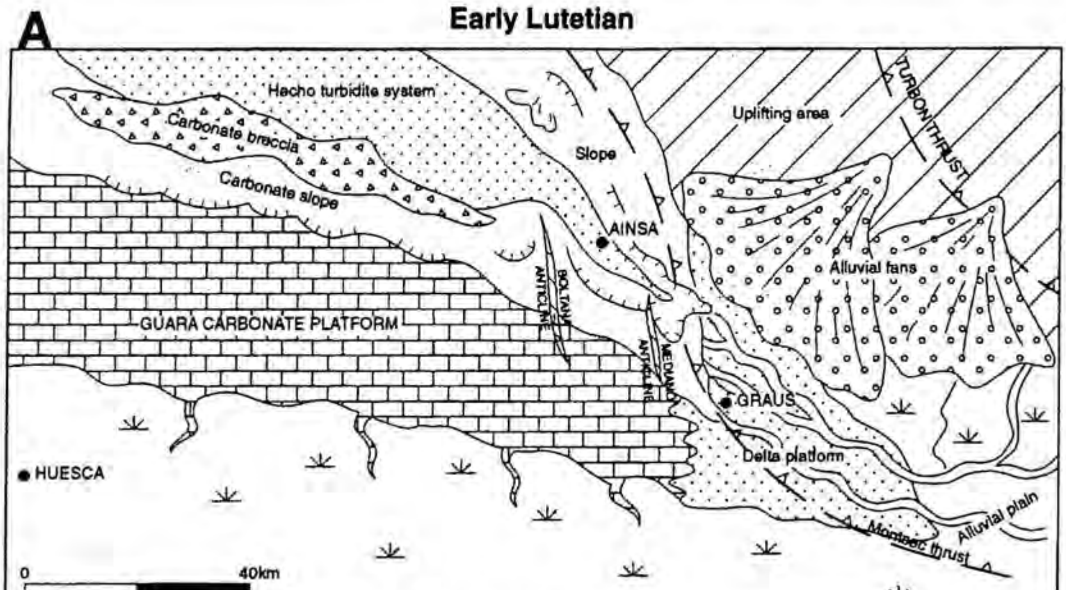


Fig. 8.2. Palaeogeography of the Jaca Basin–Aínsa Basin–Tremp–Graus Basin area, as suggested by Dreyer *et al.* (1999). **A**. During the early Lutetian. **B**. During the late Lutetian.

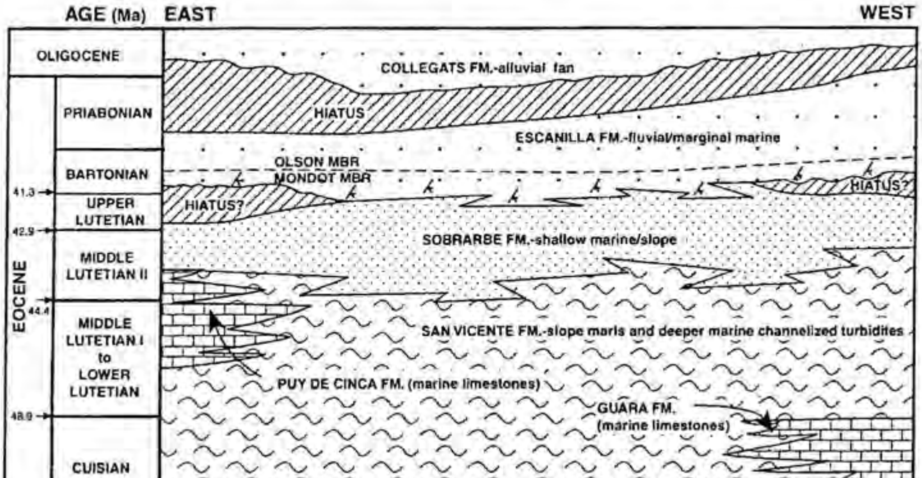


Fig. 8.3. Stratigraphy of the Aínsa Basin. (From Dreyer *et al.*, 1999.)

By the Bartonian, the Sobrarbe Fm. had been superseded by the NW-flowing fluvial system of the Escanilla Fm. Bentham *et al.* (1992) undertook a detailed study of the sedimentology of the Escanilla Fm., and also dated it by establishing five palaeomagnetic sections through it in the Aínsa Basin and the Tremp–Graus Basin. These authors found that the Escanilla Fm. formed between 42.7 and 36.5 Ma. At the very base of the formation, palaeocurrents were in the same direction as those of the preceding Sobrarbe Fm. – towards the NW. However, after a brief marine transgression at 42.5 Ma, a sudden switch towards SSW-directed flow occurred (Jones, 1997). Bentham *et al.* (1992) suggested that tectonics, for example out-of-sequence thrust reactivation to the north, would be the most likely explanation for this. In general, the Escanilla Fm. was noted by to have an odd character, with the internal geometries of the sandstones suggesting braided stream deposition, yet with the preservation of large quantities of overbank fines. The authors felt that this reflected rapid subsidence of the axis of the Aínsa Basin.

8.2.2 Correlation with the Jaca Basin

Bentham *et al.* (1992) used their palaeomagnetic dating to compare tectonic and sedimentary events between the Aínsa Basin and the Jaca Basin. For example, the drowning of the Guara Fm. carbonate platform and the consequent onset of the deposition of the Árguis Fm. in the Jaca Basin occurred, they said, at 42.6 Ma (Hogan, 1993). This was not only at almost exactly the same time as the marine transgression near the base of the Escanilla Fm. in the Aínsa Basin, but also as a short-term eustatic sea-level rise described by Haq *et al.* (1987). It should be noted however that this correlation could be called into question by the 41.5 Ma date for the base of the Árguis Fm. at Árguis derived by Pueyo *et al.* (2002). It is a matter of whether the top of the Guara Fm. at Árguis represents a hiatus or not. During the course of this work, the top of the Guara Fm. was usually found to be sharply defined, but rarely noted as being gradational (at Bara and Nocito; section **8.4.1**), and on one occasion was marked by an angular unconformity (at Gabardiella; section **8.4.1**). Thus, further work is required before it can be said whether the top of the Guara Fm. represents a depositional hiatus across the whole basin, or indeed whether the top of the Guara Fm. even formed synchronously across the area.

The way that Bentham *et al.* (1992) believed the N–S anticlines of the External Sierras controlled the marine infill of the Jaca Basin was somewhat different to the idea presented by Dreyer *et al.* (1999). The latter authors believed that several of the synclines between the anticlines provided entry points for sedimentary systems to breach the External Sierras and deposit northward-prograding deltas in the Jaca Basin. Bentham *et al.* (1992) believed that the marine infill of the Jaca Basin prograded from east to west. As it encountered each subsiding syncline and growing anticline, its progradation was held back until sedimentation rates could exceed the differential subsidence rates. This, they said, led to vertically persistent facies boundaries, similar to those described by De Boer *et al.* (1991; section **8.3**). However, it is quite possible that both sets of authors could be more-or-less correct i.e. deltaic systems could have prograded from both the south and from the east.

Bentham *et al.* (1992) explained that the barrier effect of the anticlines would cause facies boundaries to be strongly diachronous across the Jaca Basin, and be most likely to migrate in a step-wise fashion, from anticline to anticline. Following the same lines of thinking, the multiple-kilometre-scale Boltaña anticline would have been able to act as a very powerful and persistent barrier, thus explaining why the deltaic Belsué-Atarés Fm. of the Jaca Basin is around 5 Myr younger than the deltaic Sobrarbe Fm. of the Aínsa Basin (Hogan, 1993). Jolley (1987) also believed that the Boltaña anticline was an effective barrier, as it prevented the direct passage of the westward-prograding eastern fluvial system of the Lower Campodarbe Fm. into the Jaca Basin (**Fig. 8.4**).

Bentham *et al.* (1992) proposed a palaeogeographical reconstruction of the south Pyrenean thrust-top basin area (**Fig. 8.5**). The key points made were that the feeder system for the Belsué-Atarés Fm. delta apparently prograded over the Boltaña anticline during the Bartonian and Priabonian, although during the latter, a second contribution coming from the ESE was also indicated. During the Lower Oligocene the area was said to be dominated by alluvial fans, some of which fed the westward-flowing fluvial system of the Lower Campodarbe Fm.

8.2.3 Palaeovalleys through the thrust front?

Dreyer *et al.* (1999) implied that most of the sediments of Belsué-Atarés Fm. deltaics were input into the Jaca Basin via two synclinal entry points at the eastern end of the External Sierras (**Fig. 8.2B**). Although the details were not explained, it seems likely that one of these synclinal entry points, or palaeovalleys, is now the present-day Rodellar valley.

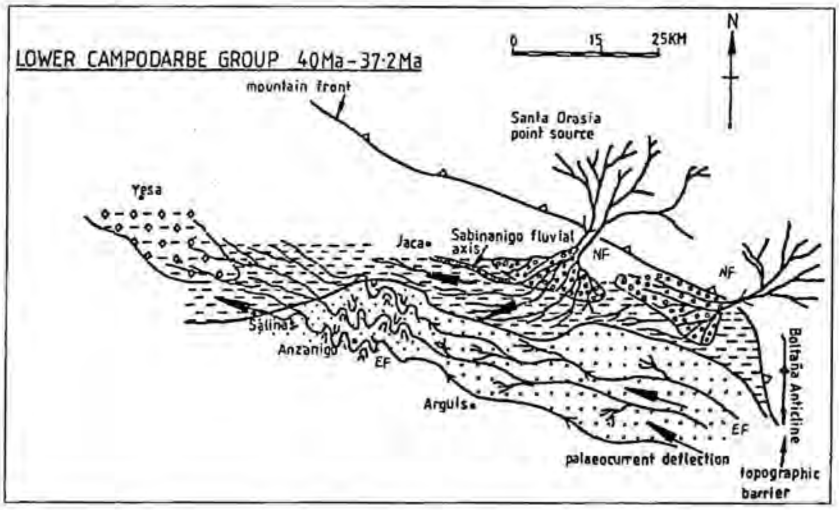


Fig. 8.4. Palaeogeography of the Jaca Basin during the deposition of the Lower Campodarbe Fm., as suggested by Jolley (1987). Note the status of the Boltaña anticline as a topographic barrier.

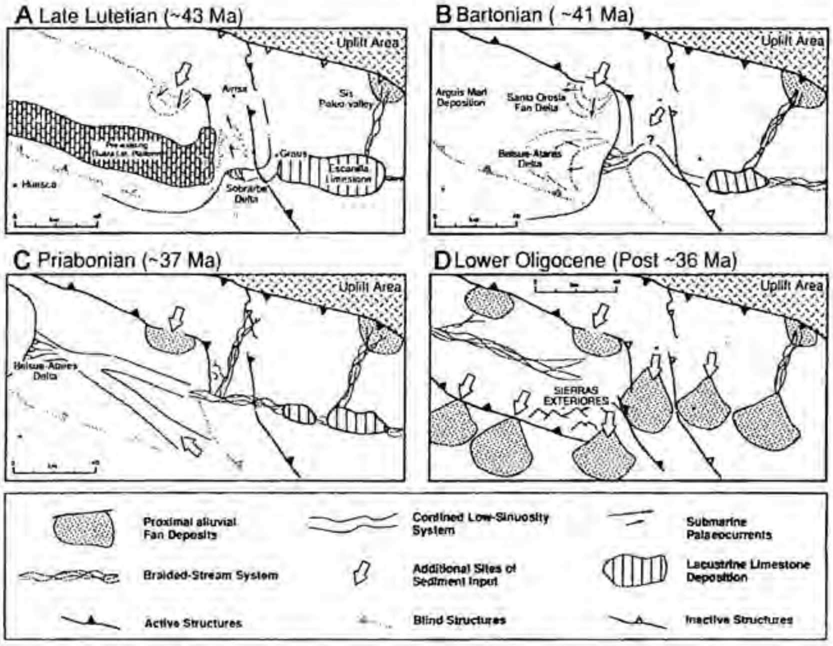


Fig. 8.5. Palaeogeography of the Jaca Basin–Aínsa Basin–Tremp–Graus Basin area, from the late Lutetian to the lower Oligocene, as suggested by Bentham *et al.* (1992).

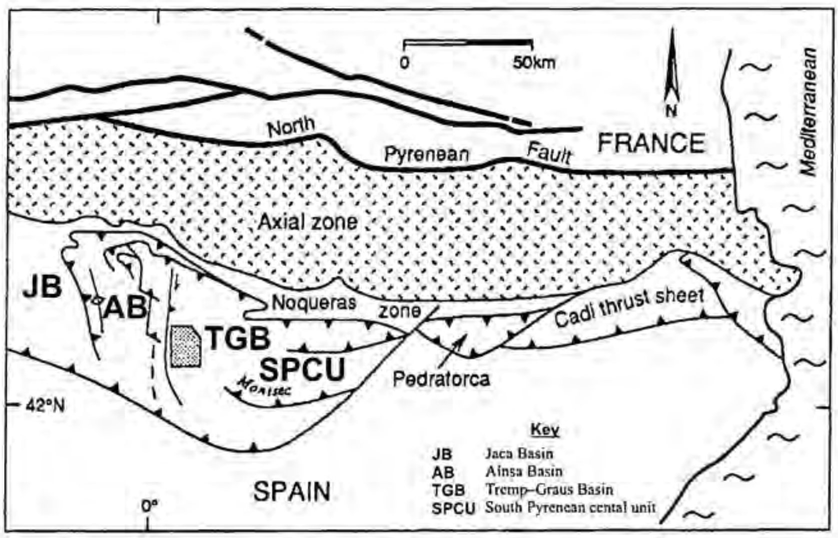


Fig. 8.6. Structural configuration of the South Pyrenean central unit (SPCU) thrust sheet, on which the Tremp–Graus basin sits, and surrounding area. Shaded area is the study area of De Boer *et al.* (1991). (Modified from De Boer *et al.*, 1991.)

It is known that the deltaic Sobrarbe Fm. entered the synclinal Aínsa Basin from the south and prograded north (section **8.2.1**; Jones, 1997; Dreyer *et al.*, 1999). It therefore does not seem too unreasonable to think that a similar process may have occurred involving the Rodellar palaeovalley and the Jaca Basin. This idea occurred to Jones (1997), who undertook a detailed sedimentological study of the Belsué-Atarés Fm. in the Rodellar valley.

Jones (1997) found 120 m of exposed Belsué-Atarés Fm., and noted that it could be divided in two. The lower portion consisted of fine to medium sandstones with abundant flaser bedding, asymmetrical and symmetrical ripples, and herringbone cross bedding, passing upwards into channels with coarse, scoured, pebbly bases. Fossils included *Nummulites* and oysters, and bioturbation included *Ophiomorpha*. A tidal flat depositional environment was interpreted. The upper portion consisted of coarse-grained sandstones, some of multi-storey character, commonly featuring planar and trough cross-bedding and erosive bases with shelly and small-pebble lags. The interpreted depositional environment was deltaic distributary channels and mouth bars.

The palaeocurrent indicators were of critical importance for the determining whether the Rodellar valley acted as a palaeovalley during the deposition of the Belsué-Atarés Fm. In the lower half of the formation, although most of the indicators were of the unidirectional type, the overall trend was bimodal: towards the NNE and the SSW. In the upper half, bi-directional readings from wave-ripples gave NNW–SSE directions, with some unidirectional readings towards the NW. Jones (1997) concluded that, viewed together, the palaeocurrent readings "indicate a NNW–SSE bimodal current direction".

Jones (1997) went on to study the 40 m of Lower Campodarbe Fm. that conformably overlies the Lower Campodarbe Fm. in the Rodellar valley. The depositional environment was interpreted as meandering fluvial channels with some crevasse splays onto an adjoining floodplain. Palaeocurrents were variable – as is typical of a meandering system – but all were broadly towards the south (directions 142 to 221). Thus, at least during the deposition of the Lower Campodarbe Fm., the Rodellar palaeovalley provided an important conduit through the south Pyrenean thrust front, allowing material from the axial zone to pass southwards into the foreland Ebro Basin. However, ambiguous palaeocurrent information from the Belsué-Atarés Fm. means that the role of the Rodellar palaeovalley during the marine phase of basin infilling has, until this time, not been clearly determined.

8.3 Vertically persistent facies boundaries

Considerable work by sedimentologists and structural geologists in tectonically active basins over the past 30 years or so has shown that growing structures may affect the deposition of syntectonic sediments in many ways. However, it was De Boer *et al.* (1991) who provided the first published account of one particular phenomenon – vertically persistent facies boundaries occurring above the crests of growth anticlines. This feature was described from the syntectonic strata of the Tremp–Graus Basin.

The Tremp–Graus Basin is the eastern compartment of a greater South Pyrenean thrust-top basin (**Fig. 8.6**). The boundary between the Tremp–Graus Basin and Aínsa Basin is an inferred lateral ramp of the thrust sheets of the South Pyrenean central unit (SPCU), and is reflected at the surface by the N–S-orientated Mediano growth anticline (Holl & Anastasio, 1993; Poblet *et al.*, 1998). In the westernmost parts of the Tremp–Graus Basin there are a series of weak anticlines and synclines, across which the angle of dip changes by only a few degrees. The folds are orientated NW–SE, and are about 2 km apart. They originate from deformation of the cover rocks because of thrusting over a basal detachment of Triassic evaporites (Puigdefàbregas, 1975).

De Boer *et al.* (1991) found that facies boundaries in both marine and non-marine syntectonic sediments of the Tremp–Graus Basin often occurred above the crests of the weak anticlines, and persisted in the same crestal position for up to 70 m vertically. One particularly clear example involved the boundary between conglomeratic fluvial channel bodies, with palaeosols, and well-sorted marine sandstones and marls, rich in *Nummulites*. This boundary, which represents the ancient coastline, was vertically persistent for around 60 m above the crest of an anticline that had only a 2–3° dip difference across its axis. From sedimentation rates, the authors estimated that the coastline was fixed in position for the order of 100 kyr.

It was known that the whole of the Tremp–Graus Basin was undergoing subsidence whilst the folds were forming and the syntectonic sediments being deposited. In the northern portions of the basin, close to the alluvial fan feeder systems that brought material from the north, sediment supply rates were large in relation to the (differential) uplift rates of the crests of the anticlines, so the folds had no obvious effect on the facies development. It was only further towards the south and southwest, where the intensity of clastic supply was less, that the vertically persistent facies boundaries were observed. The authors explained that a fold could only cause a facies boundary to be vertically persistent if the sediment supply rate and the (differential) fold crest uplift rate were similar, and if the entire area was experiencing net subsidence, allowing sedimentation rather than bypass to occur on the fold crests.

The mapping of Puigdefàbregas (1975) was the first to identify possible vertically persistent facies boundaries in the Jaca Basin – an example will be discussed in section **8.5.3.1**.

8.4 Graphic logs of the Southern Jaca Basin sector

This sector of the field area covers a large region, from the village of Nocito in the west, past the Rodellar valley, and over towards the village of Eripol. This represents an area of the south Pyrenean thrust front that is about 30 km long, and situated around 30 km north of the town of Barbastro. Seven graphic logs were completed – their locations are indicated on **Fig. 8.1**. The easternmost (Eripol) was through the Sobrarbe Fm. of the Aínsa Basin. To the west of this, three short logs were taken through the limited exposures of the Belsué-Atarés Fm. in the Rodellar valley (Las Almunias (Upper), Las Almunias (Lower) and Pedruel). Finally, the westernmost logs were through the full thickness of the Belsué-Atarés Fm. and interfingering Lower Campodarbe Fm. at the western end of this area (Bara, Nocito and Gabardiella). Each log, in both summary and original full-scale version, is reproduced in the appendices in Vol.2.

Log name	Summary log	Original log
Eripol	Vol.2, p.28	Vol.2, p.144 – 146
Las Almunias (Upper)	Vol.2, p.29	Vol.2, p.147 – 148
Las Almunias (Lower)	Vol.2, p.30	Vol.2, p.149
Pedruel	Vol.2, p.31	Vol.2, p.150
Bara	Vol.2, p.32	Vol.2, p.151 – 157
Nocito	Vol.2, p.33 – 34	Vol.2, p.158 – 169
Gabardiella	Vol.2, p.35	Vol.2, p.170 – 173

The SE corner of the Jaca Basin contains at least three, kilometre-scale, N–S orientated growth anticlines, and the 26-km-long, 4-km-across basin-bounding Boltaña anticline. Whilst these anticlines were growing, syntectonic marine sediments were prograding in directions both parallel and perpendicular to the trend of the folds (Puigdefàbregas, 1975; Bentham *et al.*, 1992; Millán *et al.*, 1994; Hogan & Burbank, 1996; Pueyo *et al.*, 2002; Castelltort *et al.*, 2003). The relationships between the structures and their syntectonic sediments are spectacularly and almost completely exposed, making this area a relatively popular place for workers in the fields of syntectonic sedimentation and basin dynamics to visit.

However, previous work has raised as many questions as it has answered (section **8.2**). The key unanswered problems at the moment are: What can the 'upstream' Sobrarbe Fm. of the Aínsa Basin tell us about the 'downstream' Belsué-Atarés Fm.? Did the Belsué-Atarés Fm. deltaic systems enter the Jaca Basin via synclinal palaeovalleys through the External Sierras (the thrust front)? Did any depositional systems pass over the crest of the Boltaña anticline and into the Jaca Basin? How did the kilometre-scale Alcanadre and Gabardiella anticlines affect the general westward progradation of the Belsué-Atarés Fm. along the synclinal axis of the Jaca Basin? Each of the sections logged was carefully selected to help answer these questions.

From this point onwards, the data collected during the course of this work is presented. In this section, section **8.4**, basic sedimentological data such as facies and facies associations, palaeocurrents, and sediment composition are described and interpreted. The understanding of these fundamentals will then be applied in section **8.5** to arrive at the answers to the key questions posed above.

8.4.1 Facies, facies associations and facies architecture

The sedimentary successions depicted on each of the logs in this sector are highly variable. The likely reasons for this are the considerable distance of the south Pyrenean thrust front along which the logs are spread (30 km), and the presence of a number of intervening kilometre-scale growth structures.

The most easterly log, and the only one undertaken in the Aínsa Basin, was completed near Eripol (Vol.2, p.28 & p.144 – 146). This log spanned from around the top of the San Vicente Fm., through the Sobrarbe Fm., and into the Escanilla Fm. It was immediately obvious that the facies and facies associations present were very similar to those noted in the Jaca Basin. It is therefore inferred that the depositional processes and environments found in each of the basins were also very similar (S. Jones, pers. comm., 2001), although they did not necessarily occur / exist at the same time. The section on the log is very much dominated by marl for the first 60 m or so, representing an offshore marine depositional environment (FA1; section **3.3.1**). Above this is a few tens of metres of lower shoreface sandstones (FA3; section **3.3.3**). Between 106 m – 110 m, an unusually fossiliferous bed was noted (Vol.2, p.145). Dip-slope exposure allowed this bed to be traced laterally for a few hundred metres in all directions. Within the bed is a great abundance of large and unique bivalves, not seen elsewhere on the sections or indeed anywhere in the Jaca Basin. It was felt that this bed would be of importance in any future sequence stratigraphic interpretation of the succession. Above this is an usually thick 82 m of marginal marine clays and sandstones (FA6; section **3.3.6**). The section ends with the arrival of the yellow and red beds of the brightly coloured clays and silts facies (section **3.2.16**), belonging to fluvial sandstones and red soils facies association (FA12; section **3.3.12**) of the Escanilla Fm.

Moving westwards and into the Jaca Basin, a group of three short logs were completed in the Rodellar valley. All three feature abrupt variations in facies, sometimes with the finest and coarsest sediments being found immediately on top of one another. The Las Almunias (Upper) log (Vol.2, p.29 & p.147 – 148) and Las Almunias (Lower) log (Vol.2, p.30 & p.149) both begin with largely fine, well bioturbated sandstones facies (section **3.2.5**), overlain by 30 m of fine, marl dominated lithologies. Both logs end with fluvial sandstones and red soils (FA12) of the Lower Campodarbe Fm. The Pedruel log (Vol.2, p.31 & p.150), situated very close to the western edge of the Rodellar valley, is sand-dominated, but contains an unusually high proportion of fossils throughout, including *Nummulites*, bivalves and gastropods.

Moving westwards, the next log encountered is the Bara log (Vol.2, p.32 & p.151 – 157). Unlike most logs in the Jaca Basin, which begin with marl-dominated facies associations (FA1 or FA2; section **3.3.1** and section **3.3.2**) of the Árguis Fm., these are notably absent in this log. This is in agreement with the mapping of Puigdefàbregas (1975; **Fig. 8.1**). Instead, this log begins with a few tens of metres of *Nummulites*-bearing bioclastic and sandy bioclastic limestones facies (section **3.2.9** and section **3.2.10**; Vol.2, p.151). These were distinguished from the universally almost-white coloured uppermost Guara Fm., which they immediately overlie, because of their dark-grey colour and sand content. However, when within metres to a few tens of metres of the contact, the colours seem to merge into a light grey, suggesting a somewhat gradational boundary. In all the other logs in the Jaca Basin that cross the top of the Guara Fm., except the adjacent logs at Nocito and Gabardiella, the contact is marked by a sharp change in lithology from limestones to either marls or sandstones. After the first 45 m of transitional carbonate facies, the remainder of the Belsué-Atarés Fm. in this log is dominated by approximately 20 – 50-m-thick, equal-thickness oscillations in facies association. Upper shoreface and delta front sandstones (FA4, section **3.3.4**) or proximal delta front channelised sandstones (FA5, section **3.3.5**) alternate with poorly exposed and probably marl dominated packages, thought to be offshore–transition zone marls and sandstones (FA2, section **3.3.2**) or lower shoreface sandstones (FA3, section **3.3.3**). After the initial 160 m of the Belsué-Atarés Fm., a 170-m-thick package of Lower Campodarbe Fm. is present. Above this, a further 270 m of Belsué-Atarés Fm. was observed, before the final arrival of the Lower Campodarbe Fm. Although the change in facies at the formation boundaries is sharp and distinctive, small-scale oscillations were noted, giving interfingering packages of marine and terrestrial sediments just a few metres thick (Vol.2, p.152 & p.157). The Lower Campodarbe Fm. is principally composed of fluvial sandstones and red soils (FA12), with a slightly lesser amount of fluvial sandstones and floodplain fines (FA11; section **3.3.11**).

The Nocito log (Vol.2, p.33 – 34 & p.158 – 169) lies 10 km west of the Bara log, and there are many similarities between the two. The Nocito section also has a 40-m-thick package of sandy bioclastic limestone facies at its base, again demonstrating an apparent gradational contact with the underlying Guara Fm. Once more, nothing that could represent the usually marly Árguis Fm. was found to be present. Also similar to the Bara log, the Belsué-Atarés Fm. consists of alternating upper shoreface and delta front sandstones (FA4) or proximal delta front channelised sandstones (FA5), and poorly exposed offshore–transition zone marls and sandstones (FA2) or lower shoreface sandstones (FA3). After the initial 780 m of Belsué-Atarés Fm., a 110-m-thick package of fluvial sandstones and red soils (FA12) of the Lower Campodarbe Fm. is present (Vol.2, p.165 – 166). Above this, a further 270 m of Belsué-Atarés Fm. sediments were found, before the final arrival of the Lower Campodarbe Fm.

The westernmost log was situated about 2 km west of the Nocito log at Gabardiella (Vol.2, p.35 & 170 – 173), just to the east of the crest of the Gabardiella anticline. Because of this, the thickness of Belsué-Atarés Fm. here is only around one-third of that at Nocito. The basal contact between the Belsué-Atarés Fm. and the Guara Fm. is very unusual for the Jaca Basin (Vol.2, p.170). Above the usual Guara Fm. bioclastic limestones facies are 14 m of alternating pure marls facies and fine, well bioturbated sandstones facies, all of which dip at a steep 72° towards the ESE. Above this is an 8 m gap in exposure, and then further alternations of pure marls facies and fine, well bioturbated sandstones facies – but these beds dip at only 36° towards the ESE. This angular unconformity is not a small-scale feature as it can be observed at all other exposures in the vicinity. It is also the only angular unconformity ever noted within the Árguis Fm., Belsué-Atarés Fm. or Lower Campodarbe Fm. during this work across the Jaca Basin. Because of the period of time of non-deposition and/or erosion that the unconformity surface must represent, it was chosen as the Guara Fm.–Belsué-Atarés Fm. boundary for this log. Above this point, the first 160 m or so are dominated by marly lithofacies, with two 15-m-thick packages of proximal delta front channelised sandstones (FA5). After this basal portion the nature of the section fundamentally changes, with the remaining 140 m being composed entirely of proximal delta front channelised sandstones, with few marly interbeds. The Lower Campodarbe Fm. is once again represented by fluvial sandstones and red soils (FA12).

8.4.2 Palaeocurrents

It was hoped that the palaeocurrent readings collected from across this sector would help answer the important question of how the Belsué-Atarés Fm. deltaic system entered the Jaca basin. Unfortunately however, the directions calculated were somewhat variable (**Fig. 8.7**). At Eripol in the Aínsa Basin, no particular trend was evident. In the Rodellar valley, the Las Almunias (Lower) and Pedruel logs record a bimodal N–S trend, from a variety of unidirectional and bi-directional indicators. The palaeocurrent data from the Las Almunias (Upper) log came from the extremely rare symmetrically rippled, coloured sandstones facies of the Lower Campodarbe Fm., interpreted to represent terrestrial lakes (section **3.2.18**). As such, its W–E trend, although interesting, does not help constrain the Belsué-Atarés Fm. At Bara, the palaeocurrents recorded radiated in all directions. At Nocito, a NW–SE bi-directional trend was strongly defined by symmetrical wave ripples. At Gabardiella, a similarly strongly defined wave rippling trend was orientated W–E.

The N–S bi-modal currents in the Belsué-Atarés Fm. of the Rodellar valley were also found by Jones (1997; section **8.2.3**). This trend almost certainly signifies that the Belsué-Atarés Fm. was being confined by the two N–S-orientated anticlines that flank the Rodellar valley (the Balces and Alcanadre anticlines; **Fig. 1.3**; **Fig. 8.7**). However, the issue of whether Belsué-Atarés Fm. system entered the Jaca Basin by flowing northwards through the Rodellar palaeovalley remains unresolved. Nevertheless, as Jones (1997) found clear evidence of confined south-directed flow in the overlying Lower Campodarbe Fm., it can be said that the syncline between the Balces and Alcanadre anticlines provided an important and long-lived basinal entry / exit point, through the south Pyrenean thrust front.

The palaeocurrent patterns further west at Nocito and Gabardiella, trending NW–SE and W–E respectively, are quite difficult to explain. In both cases, virtually all the

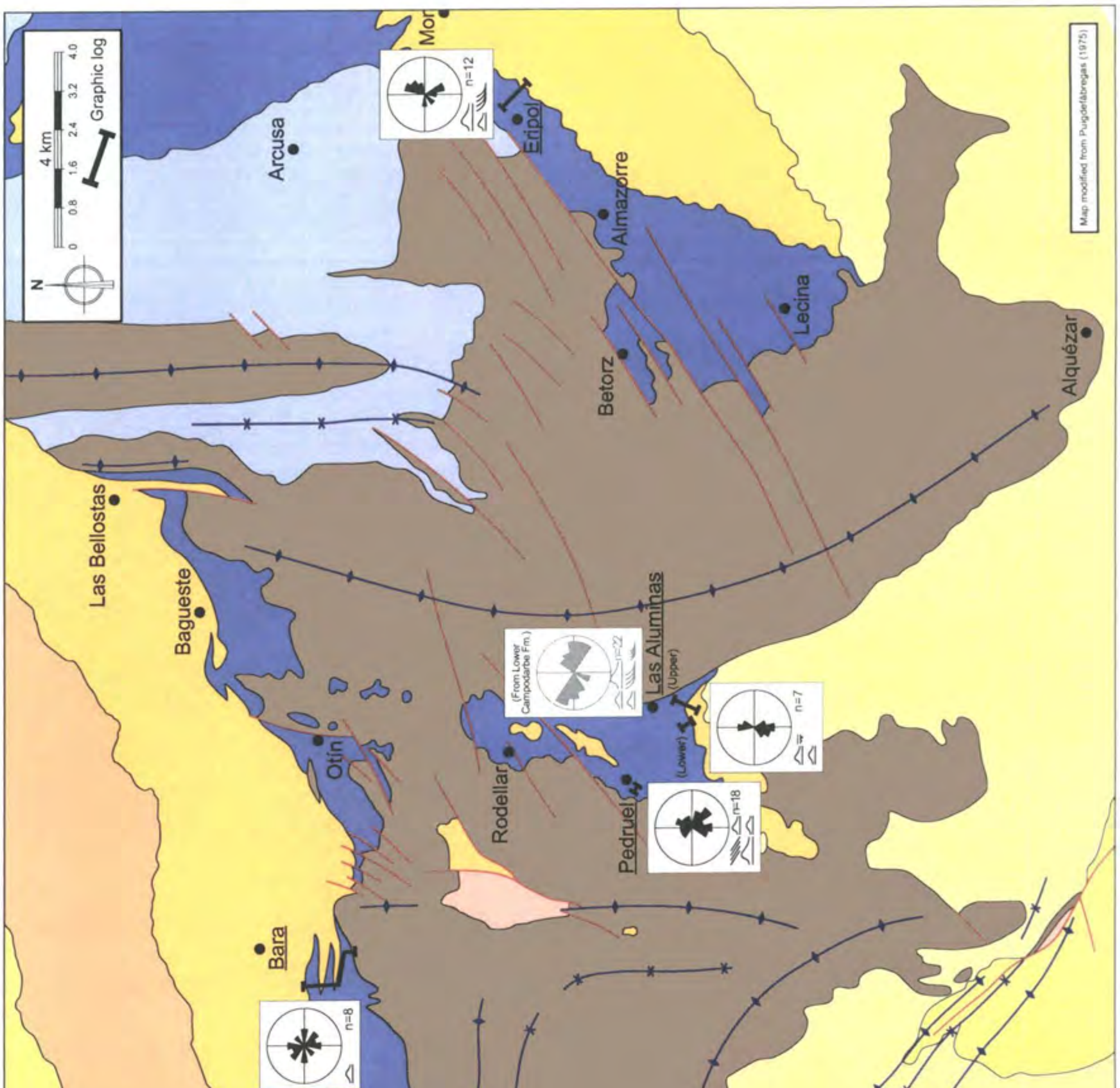


Fig. 8.7. Geological map of the SE Jaca Basin, with palaeocurrent rose diagrams for each log.

readings come from symmetrical ripples. These were formed by the wave reworking of sands of the coarse, cross-bedded sandstones facies, which forms part of the proximal delta front channelised sandstones facies association (FA5). It could be that the W–E trend at Gabardiella reflects a general palaeocurrent trend in the Jaca Basin – parallel to the W–E basin axis. The NW–SE trend at Nocito could be due to some kind of interaction between a Jaca Basin axial trend and a postulated NNE–SSW trend along the synclinal axis of the potential Nocito palaeovalley. As it stands though, and much like at Rodellar, the ambiguous palaeocurrents do not provide clear evidence for the Nocito syncline acting as an entry point into the Jaca Basin for the Belsué-Atarés Fm. system.

8.4.3 Sediment composition

During the logging process, samples were collected from several fine–medium sandstone beds on each log, thin-sectioned, and their compositions analysed. **Fig. 8.8** shows the composition data from Eripol, Bara and Gabardiella. It was hoped that comparing the compositions of the deltaics in the Aínsa Basin with those in the Jaca Basin might help determine whether these two systems were of the same provenance. The make-up of samples from the other four logs were also briefly analysed, but were not included on **Fig. 8.8** for clarity and because they were little different to those from the first three. It was also noted that all samples had a very similar texture when viewed under a microscope – poorly sorted, angular grains.

The most obvious trend is that the sediments from Eripol in the Aínsa Basin have a remarkably similar composition to samples from Gabardiella and Bara in the Jaca Basin. Between the two areas, the proportions of the three main constituent grains – micritic limestones lithics (27.6 – 48.8% vs. 31.6 – 50.4%), calcite grains (21.6 – 50.4% vs. 23.2 – 34.8%), and quartz (11.6 – 21.6% vs. 14.4 – 20.8%) – we quite similar. The amounts of the less commonly occurring grains, such as opaque-rich lithics, polycrystalline quartz grains, feldspars, opaque iron minerals, muscovite and chloritised biotite, were also very similar. The implications of this are that it is highly likely that the Belsué-Atarés Fm. and Sobrarbe Fm. shared the same provenance area, and were probably formed by the same regional-scale depositional system. Furthermore, the presence of the few percent of 'exotic' minerals and grains from igneous and metamorphic rocks implies that this depositional system was at least partly fed from the Pyrenean axial zone (Jones, 1997).

Beyond the similarities between the compositions of the samples from each of the logs, no further temporal or spatial trends in the thin-section data were apparent.

8.5 Correlation, interpretation and discussion

In section **8.4**, an interpretation of the sedimentological characteristics of the marine growth strata of the SE Jaca Basin sector was presented. Section **8.5** builds on these interpretations, via the construction of correlation panels and depositional models. The aim is to answer the key questions raised by previous work regarding how the sediments of the Belsué-Atarés Fm. entered the Jaca Basin, and to what extent the numerous growth anticlines exerted a controlling effect.

This section begins by discussing what can be learnt from the study of the Aínsa Basin, which was positioned towards the more proximal end of the general south Pyrenean sediment dispersal system, for application to the Jaca Basin (section **8.5.1**). The Pyrenean sediment dispersal system had to find a way into the structurally enclosed Jaca Basin – two entry points through the southern margin of the basin may have existed along the synclinal Rodellar and Nocito palaeovalleys (section **8.5.2**). Once the sediments had entered the Jaca Basin, other N–S orientated growth anticlines potentially affected their transport and final deposition (section **8.5.3**).

8.5.1 Comparing the Aínsa Basin to the Jaca Basin

Although the data collected during the course of this work in the Aínsa Basin was limited to a single graphic log (at Eripol), and some palaeocurrent and sediment composition analysis, this was sufficient to allow a first hand comparison to be made between the deltaic Sobrarbe Fm. and its younger counterpart, the deltaic Belsué-Atarés Fm. of the Jaca Basin (Bentham *et al.*, 1992). The detailed work of other authors on the Sobrarbe Fm., particularly Dreyer *et al.* (1999), was also taken into consideration.

All lithofacies observed on the 231-m-long log at Eripol were immediately recognised as having counterparts across in the Jaca Basin (section **8.4.1**; Vol.2, p.144 – 146), and so could be placed in the scheme of Jaca Basin facies associations (Vol.2, p.28; **Fig. 3.2**). The implications of this are that the depositional processes operating and depositional environments present during the deposition of the Sobrarbe Fm. would – at least in the case of this one log – also operate / be present in the Jaca Basin some time later. Furthermore, the composition of the Sobrarbe Fm. at Eripol was very similar to samples from the Bara and Gabardiella logs in the Jaca Basin (section **8.4.2**; **Fig. 8.8**). Although this is hardly proof, it does seem highly like that the Sobrarbe Fm. and the Belsué-Atarés Fm. were fed by the same large-scale depositional system.

The importance of this is that the geometry and infill of the Aínsa Basin could be analogous to, and provide a model for, the palaeovalleys along the southern margin of the Jaca Basin acting as sediment entry / exit points. The Aínsa Basin is defined by a syncline (the Buil syncline) between two N–S orientated anticlines (the Mediano and Boltaña anticlines). The deltaic Sobrarbe Fm. entered the basin across its structurally lower southern end, and prograded northwards (section **8.2.1**; Jones, 1997; Dreyer *et al.*, 1999). The Sobrarbe Fm. was superseded by the fluvial Escanilla Fm., which was also confined by the flanking anticlines, but flowed towards the south (section **8.2.1**; Bentham *et al.*, 1992; Jones, 1997). The Rodellar and Nocito palaeovalleys are also defined by synclines between two N–S orientated anticlines, and filled with deltaic sediments. These too were superseded by a fluvial system (the Lower Campodarbe Fm.) that was confined by the anticlines and flowed towards the south (section **8.2.3**; Jones, 1997).

Thus is seems most likely that the sedimentary system that entered the southern end of the Aínsa Basin, depositing the Sobrarbe Fm., also went on to enter the Jaca Basin via the Rodellar and Nocito palaeovalleys, which provided the only structural lows through the southern basin margin (the south Pyrenean thrust front). Establishing the absolute timings of the entries of deltaic systems into the Aínsa Basin and Jaca Basin is not easy. The problem is that the closest palaeomagnetic dates in the Jaca Basin are from nearly 40 km to the west of the Boltaña anticline at Árguis (Pueyo *et al.*, 2002). These are not of immediate use because there is good reason to believe that the formation boundaries in the syntectonic sediments of the Jaca Basin are strongly diachronous (Bentham *et al.*, 1992).

However, a deduction of the timings is possible, and goes as follows. The drowning of the Guara Fm. carbonate platform is thought to have resulted from a eustatic sea-level rise (Bentham *et al.*, 1992), visible on the sea-level curves of Haq *et al.* (1987), and thus should have occurred near synchronously across the basin. If there was no hiatus in sedimentation after the drowning of the Guara Fm. platform, then the age of sediments that immediately overlie it would be the same as the age of the uppermost Guara Fm. If these two statements are true, then the age of the basal Árguis Fm. at Árguis, 41.5 Ma (Pueyo *et al.*, 2002), can be projected west or east to give the age of the sediments that immediately overlie the Guara Fm. in any part of the Jaca

Basin. The upshot of this is that the basal Belsué-Atarés Fm. in the Rodellar and Nocito areas could have formed at 41.5 Ma. The Sobrarbe Fm. began to form at 44.4 Ma (**Fig. 8.3**), and continued up until just before the marine transgression (Bentham *et al.*, 1992), which would be at 41.5 Ma (Pueyo *et al.*, 2002). Thus it seems that around the time that the Sobrarbe Fm. deltaic sedimentation was coming to an end in the Aínsa Basin, the large-scale depositional system that had supplied the sediment had expanded its influence 15 – 30 km westwards into the Rodellar and Nocito palaeovalleys, initiating deltaic sedimentation in the Jaca Basin.

8.5.2 Importance of the Rodellar and Nocito palaeovalleys

Although the sections above explain why it is highly likely that the sediments of the Belsué-Atarés Fm. at least partly entered the Jaca Basin via the Rodellar and Nocito palaeovalleys, further arguments for this can be made. In the SE Jaca Basin sector, the Belsué-Atarés Fm. is at its thickest (up to 1000 m), coarsest (around half the sediments present are medium-grained sands or coarser), and has its highest proportion of the most proximal facies association (up to half of the sections are made up of proximal delta front channelised sandstones; FA5). In all other areas of the Jaca Basin, the Belsué-Atarés Fm. tends to be thinner, finer, more marly and dominated by more distal facies associations (most commonly, lower shoreface sandstones; FA3). This is often increasingly evident as the distance from the SE Jaca Basin sector increases. The most likely explanation for this basin-wide facies trend is that a large volume of the sands that are now part of the Belsué-Atarés Fm. entered the Jaca Basin in the vicinity of the SE Jaca Basin sector.

The Nocito log contains the thickest accumulation of medium-grained or coarser sandstones seen in the entire Jaca Basin. If the Nocito palaeovalley was a mere embayment with no sediment input point at its southern end, it is very hard to imagine why such a volume of sands would have been deposited. In the case of the Rodellar valley, it is unfortunate that the patchy exposure, flat topography and only gently dipping strata do not allow the full thickness of the Belsué-Atarés Fm. in that syncline to be studied. Although the palaeocurrent readings from Rodellar and Nocito are not diagnostic (N–S to NW–SE bimodal and bi-directional; section **8.4.2**), this is not necessarily a problem as many were taken from small-scale structures that were the product of re-working by intrabasinal processes such as waves. Furthermore, the directions recorded and their degree of consistency do a least indicate that deltaic sedimentation in these synclines was strongly confined by the flanking anticlines.

It has already been established that sediment was being supplied from the east via the same system that supplied the Aínsa Basin (section **8.4.3**), and that the Rodellar and Nocito palaeovalleys would have formed extremely convenient entry points through the barrier-like south Pyrenean thrust front. However, Bentham *et al.* (1992) suggested that the Belsué-Atarés Fm. sediments passed over the Boltaña anticline and so into the Jaca Basin (**Fig. 8.5**). In the light of recent work (and some of their own), this does not seem to be very likely: Immediately prior to the formation of the Belsué-Atarés Fm., the Boltaña anticline confined the Sobrarbe Fm., allowing only north-directed flow (Jones, 1997; Dreyer *et al.*, 1999). During Belsué-Atarés Fm. times, the Escanilla Fm. was also confined by the Boltaña anticline, this time allowing only south-directed flow (Bentham *et al.*, 1992; Jones, 1997). Finally, after the deposition of the Belsué-Atarés Fm., the Boltaña anticline acted as a barrier to the direct passage of the westward-prograding eastern fluvial system of the Lower Campodarbe Fm. into the Jaca Basin (Jolley, 1987).

Thus, the Boltaña anticline seems to have acted as an effective barrier to sedimentary systems before, during, and after the time of deposition of the Belsué-Atarés Fm. Therefore, in the absence of suggestions of other input points in the SE Jaca Basin sector, it seems only reasonable to conclude that the Rodellar and Nocito palaeovalleys were the principal, and perhaps only, sediment input points for the Belsué-Atarés Fm. in this part of the basin (**Fig. 8.9**). At the time when the Belsué-Atarés Fm. system was flowing northwards through the palaeovalleys, to the south lay the emergent Iberian margin, dominated by low-relief continental conditions (Dreyer *et al.*, 1999). It is possible that a topographic high in this area, created as the southern forebulge of the Pyrenean orogen, assisted in directing the system that fed the Belsué-Atarés Fm. northwards, towards palaeovalleys and into the Jaca Basin.

As the Belsué-Atarés Fm. sediments entered the Jaca Basin it is inferred that the water depths they encountered in the SE Jaca Basin sector were quite shallow (above wave base) because proximal delta front conditions (FA5) were quickly established across much of the area, e.g. at Bara (Vol.2, p.32), Nocito (Vol.2, p.33), and Gabardiella (Vol.2, p.35). Indeed, sedimentation rates must have been high, and approximately equal to the subsidence rates in the synclines, as the proximal delta front depositional environment was fairly persistent for several millions of years, right up until the onset of the fluvial Lower Campodarbe Fm. Having said that, the patterns of facies and depositional environments in the SE Jaca Basin sector are actually quite complex,

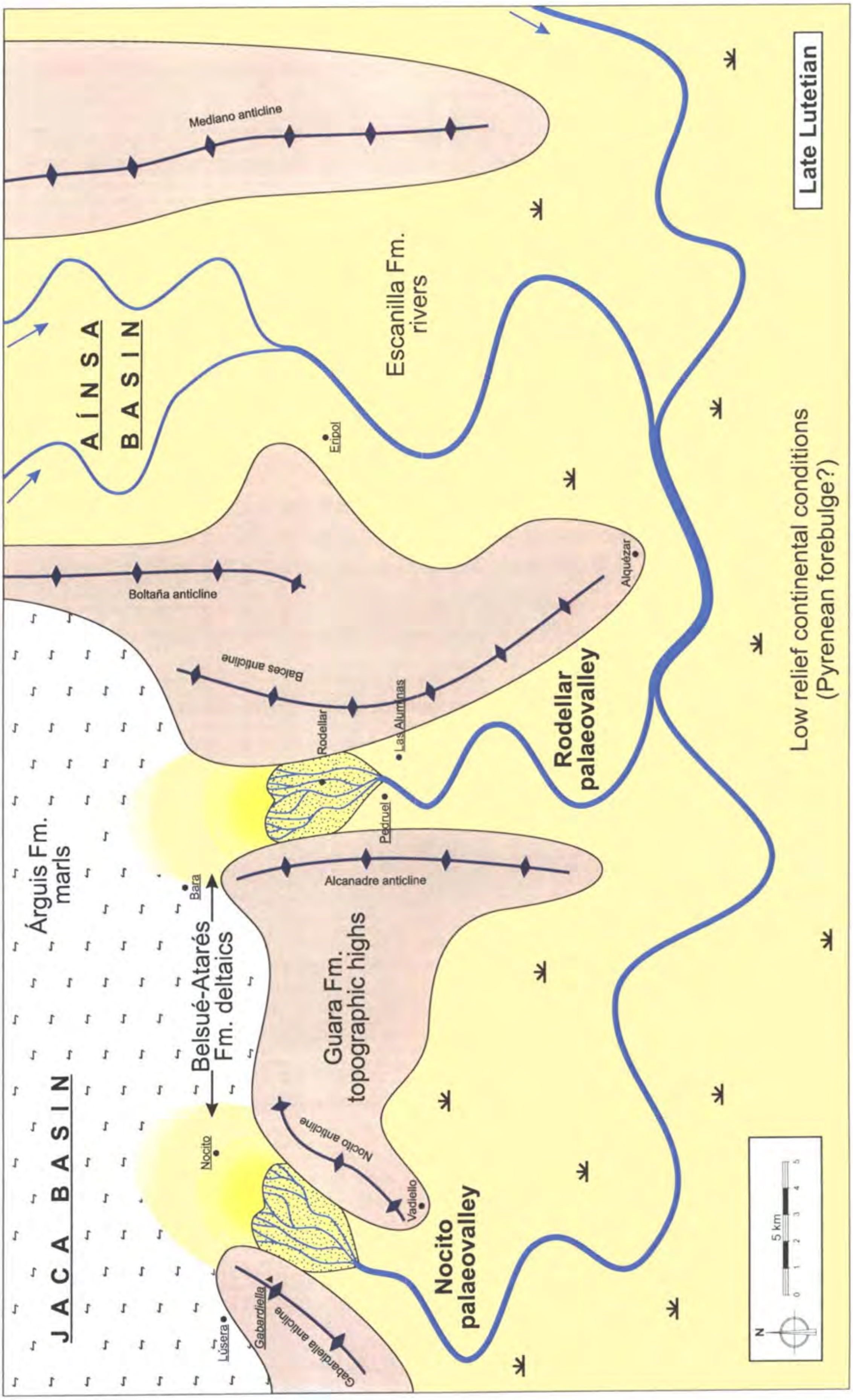


Fig. 8.9. Palaeogeography of the SE Jaca Basin–Aínsa Basin area during the late Lutetian.

largely because the influence of growing anticlines continued even once the sediments had entered the depositional basin.

8.5.3 Correlation between graphic logs

Fig. 8.10 is an almost W–E-orientated correlation panel covering the three long logs from the SE Jaca Basin sector: Bara, Nocito and Gabardiella. Included at the western end of the panel is the Lúsera log from the Southern Jaca Basin sector (Chapter 9), intended to aid correlation between the two areas. The Rodellar valley logs do not feature, as they are not sufficiently thick. The names of the different intervening anticlines are given along the base of the panel.

The Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary was used to determine the relative positions of the logs. This contact is sharp and distinctive, and has been shown by Hogan & Burbank (1996) to have formed near synchronously across other parts of the Jaca Basin. However, because of interfingering between the Belsué-Atarés Fm. and Lower Campodarbe Fm. in the SE Jaca Basin sector, it is clear that the boundary did not form synchronously across this area. This means that the relative vertical positions of the logs on the correlation panel could not simply be determined by 'hanging' them from the base of the Lower Campodarbe Fm. Instead, the mapping of Puigdefàbregas (1975; **Fig. 8.1**) was used to determine how the 'fingers' of each formation correlate between logs. Then, the purely stylistic and geologically meaningless convention that progradations of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary should be 'instantaneous' (i.e. drawn horizontal), whilst any retrogradations should be 'diachronous' (i.e. drawn diagonally up to the east) was applied. This convention was used because the progradations of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary are drawn horizontally on all other correlation panels in this work.

To summarise, the correlation panel is wholly stylistic, and while the vertical scale may be sediment thickness, this has no direct relationship to time. The formation boundaries and other lines of correlation noted merely indicate areas of the same facies association (depositional environment) on adjacent logs. These boundary surfaces and lines of correlation are most likely to be diachronous, and so are not necessarily key surfaces of any sort.

Good correlation exists between the Bara and Nocito logs. Both begin with around 40 m of sandy bioclastic limestones facies, which have a gradational contact with underlying Guara Fm. that is unique within the Jaca Basin (section **8.4.1**). At 62 m on the Bara log and 154 m on the Nocito log, a sudden change in depositional environment was noted. Below these two points, the sediments are identified on the correlation panel as 'Belsué-Atarés Fm. & Árguis Fm.'. This is not because the lithofacies were particularly marly, as the Árguis Fm. tends to be, but to maintain consistency with the formation divisions used further west in the Southern Jaca Basin sector (Chapter 9), where differentiating between the Árguis Fm. and Belsué-Atarés Fm. was not possible.

Above the 62 m and 154 m points on the Bara and Nocito sections is the Belsué-Atarés Fm. proper. The Belsué-Atarés Fm. successions on both logs consist of approximately 20 – 50-m-thick, equal-thickness oscillations between two pairs of facies associations: Upper shoreface and delta front sandstones (FA4) or proximal delta front channelised sandstones (FA5) alternate with poorly exposed and probably marl dominated packages, thought to be offshore–transition zone marls and sandstones (FA2) or lower shoreface sandstones (FA3). Between the two logs, the number of oscillations, their thicknesses and the heights at which they occurred were very similar – as indicated by the grey lines of correlation on **Fig. 8.10**. The dominance of FA5 in this part of the sections correlates westwards, across the Gabardiella anticline, into the FA5-dominated 'Prominent Sandstones of the Belsué-Atarés Fm.' that occur across the Southern Jaca Basin sector (Chapter 9).

The correlation panel (**Fig. 8.10**) also indicates that the incursion of terrestrial Lower Campodarbe Fm. sediments at 161 m – 340 m on the Bara log was reflected by a similarly thick and almost continuous package of FA5 (proximal delta front channelised sandstones) on the Nocito log. The mapping of Puigdefàbregas (1975; **Fig. 8.1**) indicates that the base of the Lower Campodarbe Fm. at the top of the Bara log could be 'tied into' the finger of Lower Campodarbe Fm. between 779 m – 888 m on the Nocito log. The regression of the formation boundary noted at the top of this package of Lower Campodarbe Fm. did not, however, reach as far back east as Bara (**Fig. 8.1**).

The Gabardiella log was positioned just to the east of the crest of the Gabardiella anticline. Despite the consequent greatly reduced thickness of the Belsué-Atarés Fm. present, the log does bear some similarities to the Nocito and Bara sections. For example, the first 57 m of the Gabardiella log is made up of marly sediments representing the 'Belsué-Atarés Fm. & Árguis Fm.'. Above this point, proximal delta front channelised sandstones (FA5) dominate, again with some alternations with finer and marlier facies associations.

8.5.3.1 Barrier effect of the Alcanadre anticline

A strong correlation exists between the Bara and Nocito logs – most likely because there were no growth structures in the area between the two sections. However, the Bara log does lie just to the NW of the Alcanadre N–S-orientated growth anticline which, according to the mapping of Puigdefàbregas (1975; **Fig. 8.1**) and the Bara log of this work (**Fig. 8.10**), exerted a strong control on the sedimentary architecture of the surrounding growth strata. Both the mapping and logging work indicate that the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary, which represents the change from marine to non-marine sedimentation i.e. the palaeo-coastline, became localised around the anticline crest whilst almost half a kilometre of sediment accumulated. Using sedimentation rates calculated further west (at Árguis, by Pueyo *et al.*, 2002), this localisation could have lasted for nearly 2 Myr.

De Boer *et al.* (1991) were the first to describe how a growing anticline may hold back a facies boundary in a progradational depositional system (section **8.3**). However, it was Bentham *et al.* (1992) who were the first to recognise the relevance of these ideas for this part of the Jaca Basin. The Alcanadre anticline was able to act as a barrier to progradation because the uplift of its crest and the subsidence of the synclines that flank it created an area of accommodation space flanked by a topographic high. Because the uplift and subsidence were ongoing, the Lower Campodarbe Fm. depositional system was not able to cross the structure westwards until sedimentation rates had exceeded the differential uplift rate of the crest of the anticline (relative to the floor of its syncline), and the 'excess' accommodation space filled in.

The Lower Campodarbe Fm. depositional system crossed the crest of the Alcanadre anticline twice – the first time it retrograded back eastwards. This facies trend is evidence of a change in one of the variables that had initially caused the formation boundary to remain localised around the crest of the structure. The key variables are related to tectonics, sea-level or sediment supply. The fact that repeated progradations and retrogradations were observed is evidence that the changes in one or more of these variables were cyclic.

8.5.3.2 Sedimentary cycles

The positioning of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary in the growth strata can be used to define two major cycles, each consisting of a progradational period and a retrogradational period. The stratigraphically lower cycle is best seen on the Bara log (Vol.2, p.32): at 161 m the boundary progrades westwards, at 340 m it retrogrades eastwards, and at 611 m it progrades back westwards again. Thus the total thickness of the cycle is 450 m, and by using the highly averaged sedimentation rates calculated further west (at Árguis, by Pueyo *et al.*, 2002 – see a justification for using this rate in section **4.3.2**), its repeat could be around 1.75 Myr.

Although the Bara cycle is reflected in the stratigraphy to the west at Nocito, the facies change that defines it is within marine strata, so is not as easily defined as the marine–non-marine facies change at Bara. However, once the Lower Campodarbe Fm. depositional system had finally breached the Alcanadre anticline, its westward progradation was held back once more by the Gabardiella anticline. This allowed a second, younger, cycle in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary to be deposited at Nocito. On the Nocito log (Vol.2, p.33 – 34): at 779 m the boundary progrades westwards, at 888 m it retrogrades eastwards, and at 1119 m it progrades back westwards again. Thus the total thickness of the cycle is 340 m, which would give a repeat time of around 1.33 Myr.

Smaller-scale cycles are also present within the syntectonic strata around Bara and Nocito. These are of the order of 10 – 100 m thick, and so could be roughly 40 – 400 kyr in duration. As has already been stated, these can be seen as the repetitive cycles between FA4 / FA5 (upper shoreface and delta front sandstones / proximal delta front channelised sandstones) and FA2 / FA3 (offshore–transition zone marls and sandstones / lower shoreface sandstones), which correlate well between the Bara and Nocito logs. Cycles of this smaller size also affect the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary on the Bara log. There are two such cycles, and each one is positioned immediately beneath the two large-scale Lower Campodarbe Fm. progradations that are described above (Vol.2, p.152 and p.157). Like the larger cycles, each smaller-scale cycle consists of a progradation and a retrogradation in the formation boundary.

The cause of the 1-Myr-order and 100-kyr-order cycles could be due to changes in one of, or some combination of, the following: eustatic sea-level, sediment supply, climate (Nijman, 1998), or rates of tectonic deformation – which could cause basin-wide uplift or subsidence, or affect the growth rate of the Alcanadre and Gabardiella anticlines. Changes in the growth rate of the anticlines would not be likely to cause the type of laterally extensive cycles observed (over 10 km), unless the changes in the growth rates occurred synchronously for both structures. Eustatic sea-level changes could be responsible as there were a number of sufficiently long-lived transgressions–

regressions whilst the Belsué-Atarés Fm. and Lower Campodarbe Fm. were being deposited (Haq *et al.*, 1987; **Fig. 2.20**). But away from these simple points, it is beyond the scope of this study to determine the mechanism behind these sedimentary cycles. At the very least, in-depth dating and sequence stratigraphic analysis would be required – this is an obvious area for future work.

8.5.3.3 Barrier effect of the Gabardiella anticline

The kilometre-scale Gabardiella anticline had a very strong effect on the syntectonic sediments that surround it: the Belsué-Atarés Fm. thins down to around one-third of its thickness on the crest of the structure, and the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary was held back by structure much in the same way as it was by the Alcanadre anticline. However, it is important to understand the syntectonic sediments that flank both sides of the Gabardiella anticline before the controlling effect that the structure had can be properly determined. The log immediately to the west of the anticline, at Lúsera, is part of the Southern Jaca Basin sector, and so described in Chapter 9. Because of this, the effect of the Gabardiella anticline, and the correlation between the SE Jaca Basin sector and the Southern Jaca Basin sector, will not be described in detail until the next chapter (section **9.5.1.4**).

8.6 Conclusions

The SE Jaca Basin sector contains probably the most important basinal sediment input point for the Belsué-Atarés Fm. The sediments were supplied by the Tremp–Graus Basin to the east and from the Escanilla Fm. fluvial system, which flowed from the Pyrenean axial zone, southwards along the Aínsa Basin. A topographic high to the south of the thrust front, possibly related to the south Pyrenean forebulge, may have assisted in directing the depositional systems northwards towards the Jaca Basin. The sediments gained entry into the basin through the south Pyrenean thrust front via the Nocito and Rodellar palaeovalleys. These features were formed as synclines between two pairs of actively growing, kilometre-scale, N–S-orientated anticlines. Although the palaeocurrent information in the vicinity of Nocito and Rodellar does not provide clear evidence for north-directed flow along the palaeovalleys, the fact that Belsué-Atarés Fm. is at its thickest, most sand-dominated, and most proximal-facies-dominated in these areas, almost certainly does.

Even once in the Jaca Basin, the progradation of the sediments of the deltaic Belsué-Atarés Fm., and the overlying fluvial Lower Campodarbe Fm., continued to be affected by the growing N–S-orientated anticlines associated with the thrust front. A particularly spectacular example of this was the holding back of the westward progradation of the Lower Campodarbe Fm. over the Belsué-Atarés Fm. by the Alcanadre and Gabardiella anticlines (which form the western sides of the Rodellar and Nocito palaeovalleys, respectively). This occurred because the subsidence in the synclines that flank the anticlines created an area of accommodation space that had to be infilled before the topographic high of the adjacent anticline crest could be overtopped.

As well as being held back by the anticlines, the progradation of the Lower Campodarbe Fm. over the Belsué-Atarés Fm. was interrupted by two, kilometre-scale regressions its lateral position. These regressions may be used to define two large-scale progradational–retrogradational cycles in the stratigraphy, 450 m and 340 m thick and 1.75 Myr and 1.33 Myr in duration. In addition, a number of smaller-scale progradational–retrogradational cycles in the formation boundary, of 10 – 100 m thickness and 40 – 400 kyr repeat times, were noted. Both these orders of cycles correlated well between the Nocito and Bara logs – a distance of nearly 10 km. The process responsible for the stratigraphic cycles is likely to be variations in relative sea-level and/or sediment supply, both of which may have a number of underlying causes.

8.7 Key Points

1. Sedimentary infill of the basin:

- As deltaic sedimentation was coming to an end in the Aínsa Basin (Sobrarbe Fm.), it was just beginning in the Jaca Basin (Belsué-Atarés Fm.).
- The Escanilla Fm. fluvial system, which flowed from the axial zone southwards along the Aínsa Basin, contributed to the Belsué-Atarés Fm. sediments.
- A large proportion of the Belsué-Atarés Fm. sands entered the Jaca Basin in its SE corner, via the Nocito and Rodellar palaeovalleys through the thrust front.
- In this part of the basin, the contact between the Guara Fm. and the overlying Belsué-Atarés Fm. was gradational over much of the area, except in the vicinity of the Gabardiella anticline, where a possible angular unconformity was developed.
- Proximal delta front conditions were rapidly established in this part of the basin, and largely persisted for most of the Belsué-Atarés Fm. deposition (around 4.9 Myr).

2. Structural configuration of the basin:

- Aside from the two palaeovalleys through it, the south Pyrenean thrust front acted as a barrier to sedimentary systems entering the Jaca Basin.
- The Boltaña anticline acted as a barrier throughout the deposition of the Belsué-Atarés Fm., preventing a direct connection between the Aínsa Basin and the Jaca Basin.

3. Influence of intrabasinal growth structures:

- The Gabardiella and Alcanadre anticlines acted as barriers to the westward progradation of the Belsué-Atarés Fm. and the Lower Campodarbe Fm.
- The Alcanadre anticline localised the base of the Lower Campodarbe Fm. (the palaeo-shoreline) in the vicinity of its crest for nearly 2 Myr.

4. Effect of sea-level changes:

- Two, 1-Myr-order, progradational–retrogradational cycles in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary were observed in this area.
- Numerous, smaller-scale, 100-kyr-order cycles in the Belsué-Atarés Fm.–Lower Campodarbe Fm. were also observed
- Both orders of cycles were laterally extensive for at least 10 km, between the Nocito and Bara logs, which is probably due to the lack of intervening growth structures.

The next chapter, Chapter 9, discusses the central portions of the southern margin of the Jaca Basin. In this area, a further three, kilometre-scale, N–S-orientated growth anticlines affected the deposition of the Belsué-Atarés Fm. These uplifting structures held back the progradation of siliciclastic facies, and led to the development of localised carbonate build-ups.

Chapter 9:
Southern Jaca Basin

9. Southern Jaca Basin

Contents

9. Southern Jaca Basin

9.1 Introduction

In recent years there has been considerable interest in the accurate analysis of growth strata in order to understand the coupling mechanisms between tectonics and sedimentation, or to determine fold kinematics or timings and rates of deformation (e.g. Gawthorpe & Hardy, 2002; Salvini & Storti, 2002; Ramos *et al.*, 2002; López-Blanco, 2002; Clevis *et al.*, 2004). This has inevitably involved much work on the subdivision of syntectonic successions into genetic units – a process that is also a fundamental element of sequence stratigraphy (e.g. Van Wagoner *et al.*, 1988). However, sequence stratigraphic concepts were first developed at passive margin settings, and so their application to tectonically active areas is far from straightforward. Whilst this problem has partly been solved for rift basins (e.g. Gawthorpe *et al.*, 1994), and foreland basins (e.g. Posamentier & Allen, 1993), the application of sequence stratigraphy to the infill of thrust-top basins has yet to be properly understood. The principle difficulty in thrust-top settings is the numerous growth structures that tend to compartmentalise the basin and strongly affect the syntectonic sedimentation, perhaps relegating sea-level to a second-order level of control.

The Jaca thrust-top basin, with its numerous, variously-orientated, kilometre-scale growth anticlines (Puigdefàbregas, 1975) should provide a world-class area for this new type of sequence stratigraphic study. Of particular interest will be the central portions of the southern basin margin – the focus of this chapter – where the relationships between 1000-m-thick syntectonic strata and a series of kilometre-scale, N–S orientated growth anticlines are superbly exposed. The growth anticlines form part of the External Sierras range of hills, which represent the thrust front on the southern side of the Pyrenees (Puigdefàbregas, 1975; Millán *et al.*, 1994).

During the last decade or so, numerous workers wishing to study growing structures and syntectonic sedimentation have visited this part of the Jaca Basin. Before the new data collected during the course of this work are presented in the latter half of this chapter, the previously published findings are summarised and reviewed. In section **9.2**, the results from studies that used the geometry of the growth strata to deduce the kinematics of the N–S-orientated growth folds are described. Section **9.3** gives a more detailed review of the two existing studies that have attempted to place some of the growth strata into a sequence stratigraphic framework (Millán *et al.*, 1994, and Castelltort *et al.*, 2003). The problem with these studies was that they gathered only a limited dataset, and made somewhat bold interpretations from it. The aim of this chapter is to utilise a comprehensive dataset, and the knowledge gained from work across the rest of the basin (chapters 4 – 8), to develop a complete understanding of the tectonic and sea-level controls of the deposition of the Belsué-Atarés Fm. in the Southern Jaca Basin sector.

In section **9.4**, the new sedimentological data collected from the Southern Jaca Basin sector during this work is presented. Included in this are almost 5 km of very detailed graphic logs, palaeocurrent studies, sediment compositional analysis and aerial photos. In section **9.5**, the affect of the N–S-orientated growth anticlines on the Belsué-Atarés Fm. is discussed, using a correlation panel constructed across the area. The evidence for changes in relative sea-level and the application of sequence stratigraphic concepts to the study of the growth strata are then examined.

9.2 Growth anticlines of the External Sierras

In order to understand the syntectonic sedimentation in the External Sierras area, it is important to first understand the geological structures and tectonic processes responsible for the development of the growth anticlines. Much of this has already been well covered in the published literature, and is briefly summarised below (sections **9.2.1**; see also the more detailed summary given in sections **2.4.1** and **2.4.2**). However, despite their well-studied nature, one of the most fundamental aspects of the growth anticlines – the mechanism responsible for their creation – is still a matter of much debate. The arguments for a halotectonic origin and a thrust-related origin are outlined in section **9.2.3**.

9.2.1 Tectonic regime and geological structure

The External Sierras, on the southern margin of the Jaca Basin, were created by the emergence of the Guarga thrust sheet (Holl & Anastasio, 1993). This thrust sheet moved on a basal detachment of Triassic (Keuper) evaporites (Millán *et al.*, 1994), and carried the Jaca Basin as a thrust-top basin (Hogan & Burbank, 1996). The External Sierras themselves are mostly composed of the Guara Fm. platform carbonates (section **2.4.3.2**), and the underlying Triassic (**Fig. 9.1**). Within the External Sierras are a series

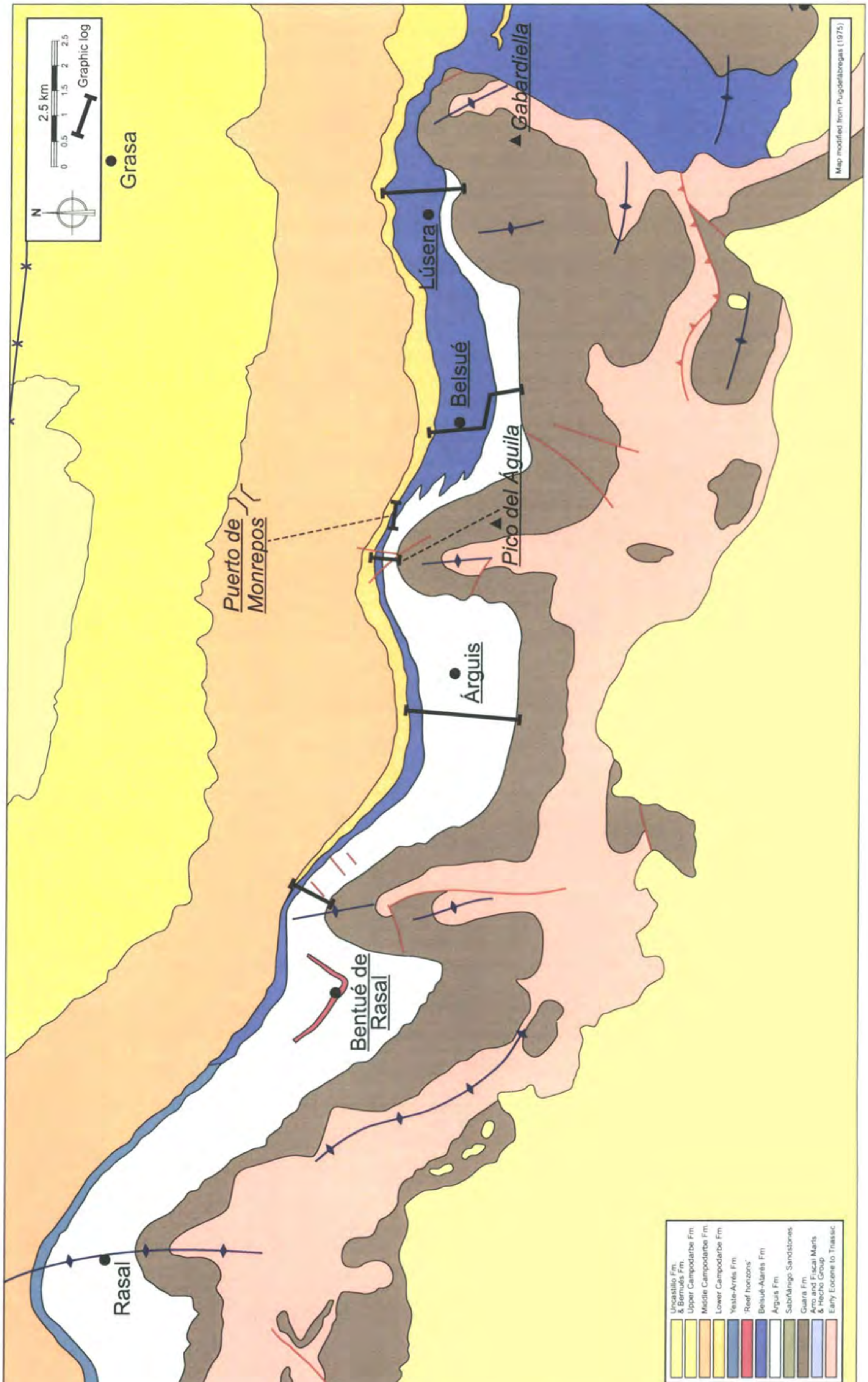


Fig. 9.1. Geological map of the Southern Jaca Basin, indicating the positions of the six graphic logs.

of kilometre-scale, N–S orientated, tight, symmetrical anticlines, separated by broad, flat-bottomed synclines (**Fig. 1.3**; Anastasio & Holl, 2001). These folds are classed as detachment folds as they formed via the Guara Fm. moving relative to the underlying Triassic evaporites. Whilst the folds were growing, syntectonic strata of the Árguis Fm. and Belsué-Atarés Fm. were deposited (Millán *et al.*, 1994; Castelltort *et al.*, 2003).

9.2.2 Origin of the folds of the External Sierras

Despite the considerable amount of research that has been completed on the anticlines of the External Sierras, there is still no agreement on the precise mechanism of their creation. Anastasio & Holl (2001) believe that the folds were created by halotectonics, involving movement of the Triassic evaporites that underlie the Guara Fm. (see also Holl & Anastasio, 1993). These authors state that a halotectonic origin is supported by the irregular fold geometries, the ubiquitous exotic strata along the basal detachment and fold cores, the synsedimentary timing of folding (as loading is thought to have caused the salt movement), palinspastic restorations, and by the fact that the folds stopped growing in the Early Oligocene, yet thrusting persisted along the thrust front until the Early Miocene (Hogan & Burbank, 1996; Meigs, 1997).

Martínez-Peña *et al.* (1995) believed that the folds of the External Sierras were thrust-related. These authors derived the palaeo-stress field of the Jaca Basin–Aínsa Basin–Tremp–Graus Basin area by analysing the orientation and sense of movement of over 2000 meso-scale faults. Their work showed that N–S folds of the External Sierras could have been created by the Eocene–Oligocene emplacement of the south Pyrenean central unit (SPCU) to the east of the Jaca Basin (**Fig. 8.6**). The folds would have initially formed as a series of frontal–oblique structures to the Guarga thrust sheet, but have been subsequently rotated clockwise as the SPCU advanced southwards.

Poblet & Hardy (1995) and Poblet *et al.* (1998) supported a thrust-related origin over the halotectonic mechanism of Anastasio & Holl (2001) because it seems likely that the Guara Fm. overburden is too thick, relative to the underlying evaporites, to have been pierced by movement of evaporites (Jackson & Talbot, 1994).

9.2.3 Thrust sheet rotation in the External Sierras

There is a good body of evidence that thrust sheet rotation about a vertical axis occurred during the emplacement of the Guarga thrust sheet (Puigdefàbregas, 1975;

McElroy, 1990; Millán *et al.*, 1992; Martinez-Peña *et al.*, 1995; Millán-Garrido, 1996; Hogan & Burbank, 1996; Pueyo *et al.*, 2000). This rotation affected the entire Jaca Basin, which was carried on top of the thrust sheet, and may have contributed to or caused the growth of the N–S-orientated anticlines in the External Sierras (Martínez-Peña *et al.*, 1995; Poblet & Hardy, 1995; Poblet *et al.*, 1998). Pueyo *et al.* (2002) used palaeomagnetic data gathered from the syntectonic strata flanking one of the growth anticlines of the External Sierras, the Pico del Águila growth anticline (**Fig. 1.3**), to quantify the total amount of thrust sheet rotation, and deduce how that rotation accumulated through time.

By comparing the palaeomagnetic directions calculated for numerous sites in the syntectonic strata with the magnetic reference direction for the Eocene (Dinarés, 1992), Pueyo *et al.* (2002) were able to calculate the amount of horizontal rotation that each syntectonic bed had undergone since it was deposited. Values varied from 46° clockwise at the base of the Árguis Fm., to 3° anticlockwise near the top of the Belsué-Atarés Fm. From these values, the authors were able to determine that the rotation rate varied from a high of 18.6°/Myr at the base of the Árguis Fm. to low of only 2.1°/Myr at the top of the Belsué-Atarés Fm. From this, the authors went on to reconstruct how the N–S anticlines in the External Sierras were progressively developed by the thrust sheet rotation (**Fig. 9.2**). If the bulk rotation value of 38° clockwise is removed from the present trend of the Pico del Águila anticline, it can be seen that the fold was orientated 135–315° (i.e. NW–SE) when it began to form.

Pueyo *et al.* (2002) acknowledged that thrust sheet rotation might have also been occurring before the deposition of the Árguis Fm. and Belsué-Atarés Fm., whilst the unstudied Guara Fm. was accumulating. The evidence for thrust sheet rotation did not however continue up into the Lower Campodarbe Fm., which lies above the Belsué-Atarés Fm. This was thought to be because the focus of the rotation had shifted westwards along the south Pyrenean thrust front to the western end of the External Sierras (Pueyo *et al.*, 2000). In that area, the rotation caused the development of the Santo Domingo anticline (**Fig. 1.3**), a kilometre-scale detachment fold and associated south-directed thrust system, during the Late Oligocene to Early Miocene (Garrido *et al.*, 1995).

The rotation of the Guarga thrust sheet and the associated Jaca thrust-top basin means that the orientations of structures, palaeocurrents and other directional features that lie within the basin on the thrust sheet may be different now to when they were first

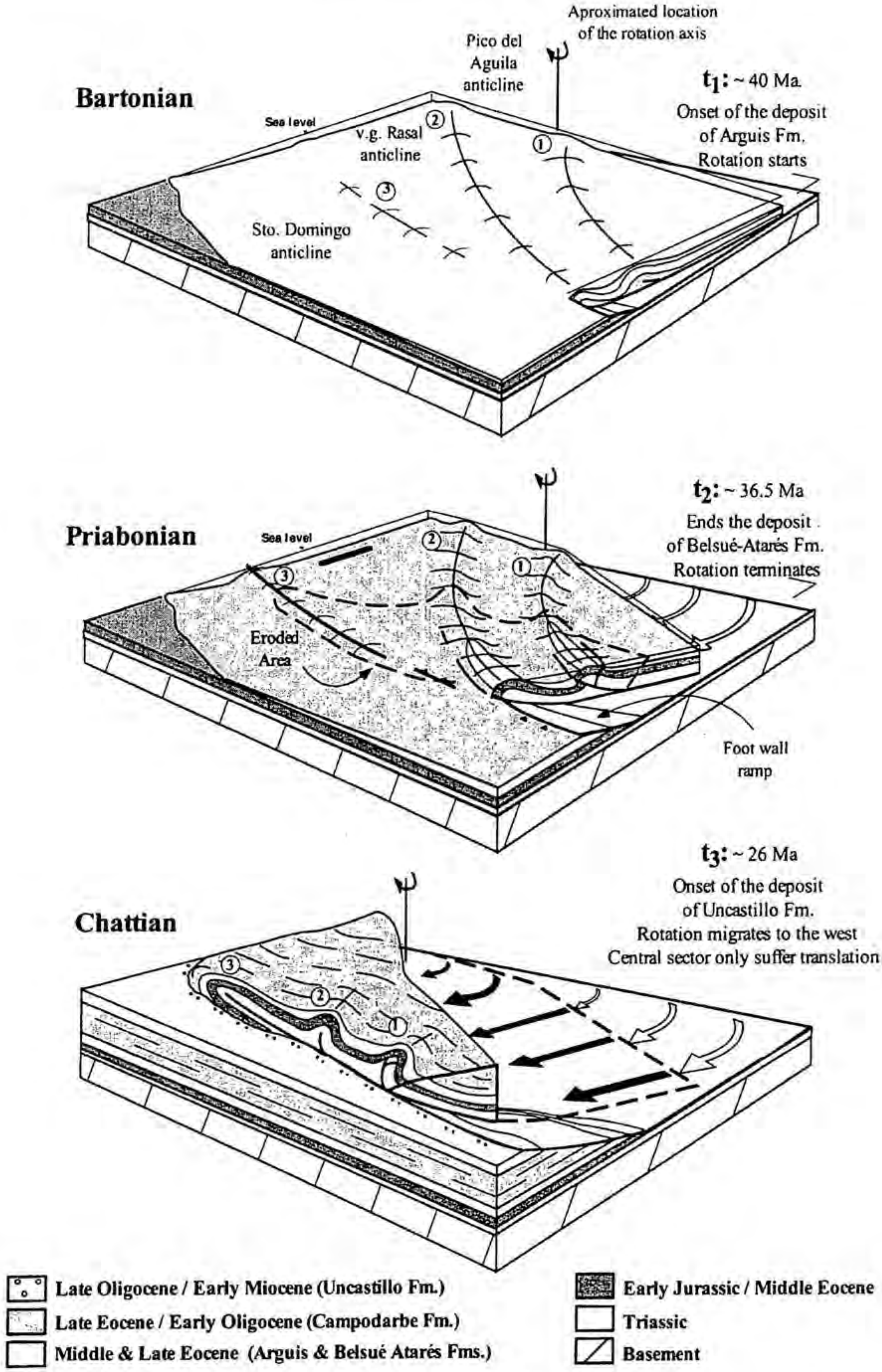


Fig. 9.2. A three-stage reconstruction of the rotation of the Guarga thrust sheet, and the creation of the N–S-orientated anticlines of the External Sierras. (From Pueyo *et al.*, 2002.)

formed, depending on when they formed. For a description of how this is dealt with in this work, see section **2.4.3.5**.

9.2.4 Pico del Águila anticline

The Pico del Águila anticline is one of the kilometre-scale, N–S oriented growth anticlines of the central External Sierras (**Fig. 1.3**). It has a tight, concentric (symmetrical) geometry, and is flanked by two box shaped synclines. The location of the anticline was controlled by a previously formed east-verging thrust that is currently folded into the core of the fold (Pueyo *et al.* 1997). The present-day orientation of the fold axis is plunging at 29° towards 353. The north-directed plunge is a consequence of the fold being located above a north-dipping footwall ramp on the Guarga thrust.

Whilst the Pico del Águila anticline was growing, the syntectonic sediments of the Árguis Fm. and, later, the Belsué-Atarés Fm. were deposited across the structure. The uplift of the fold potentially exerted a strong control on the facies and architecture of these syntectonic sediments (sections **9.4** & **9.5**). Numerous workers have used the geometry of the syntectonic strata to model the kinematics of the anticline and determine the mechanism by which it grew.

Poblet & Hardy (1995) applied a simple, 2D, geometrical method of reverse modelling to the western half of the Pico del Águila anticline. Their modelling method assumed that the growth strata were deposited horizontally and that fold uplift during the deposition of a particular bed can be given by subtracting the thickness of that bed in the hinge from the thickness in the flanking synclines. A down-plunge cross-section was constructed (**Fig. 9.3**), to allow the fold to be schematically represented as a kink-band (**Fig. 9.4**). The ages of various key surfaces in the syntectonic strata were interpolated from the palaeomagnetic data of Hogan (1993). If the limbs of the fold remained a constant length during growth (**Fig. 9.5**; De Sitter, 1956), Poblet & Hardy (1995) found that the present amount of uplift (1391 m) could have accumulated in 7.87 Myr, and ended at 34.8 Ma. A consequence of constant limb length growth is that the uplift rate of the fold would decrease through time (from a maximum rate of 0.31 mm/yr during the initial stages). Thus, although the youngest growth strata may be almost flat lying and exhibit near-constant thickness, this would not necessarily imply that tectonic activity had decreased.

Poblet & Hardy (1995) also produced a model that grew via a variable limb length (constant limb dip) mechanism (Dahlstrom, 1990; **Fig. 9.5**). Although they produced

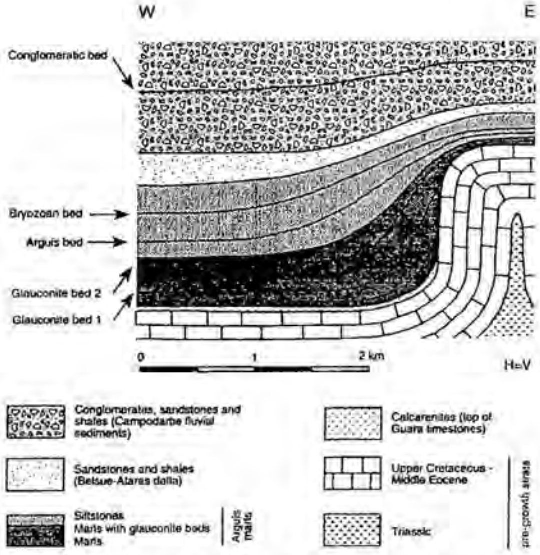


Fig. 9.3. Down-plunge cross-section through the western limb of the Pico del Águila growth anticline. (From Poblet & Hardy, 1995.)

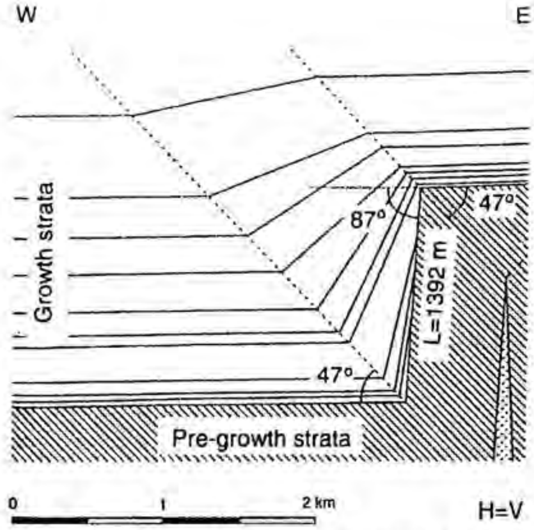


Fig. 9.4. Cross-sectional representation of the Pico del Águila anticline as a kink-band. (From Poblet & Hardy, 1995.)

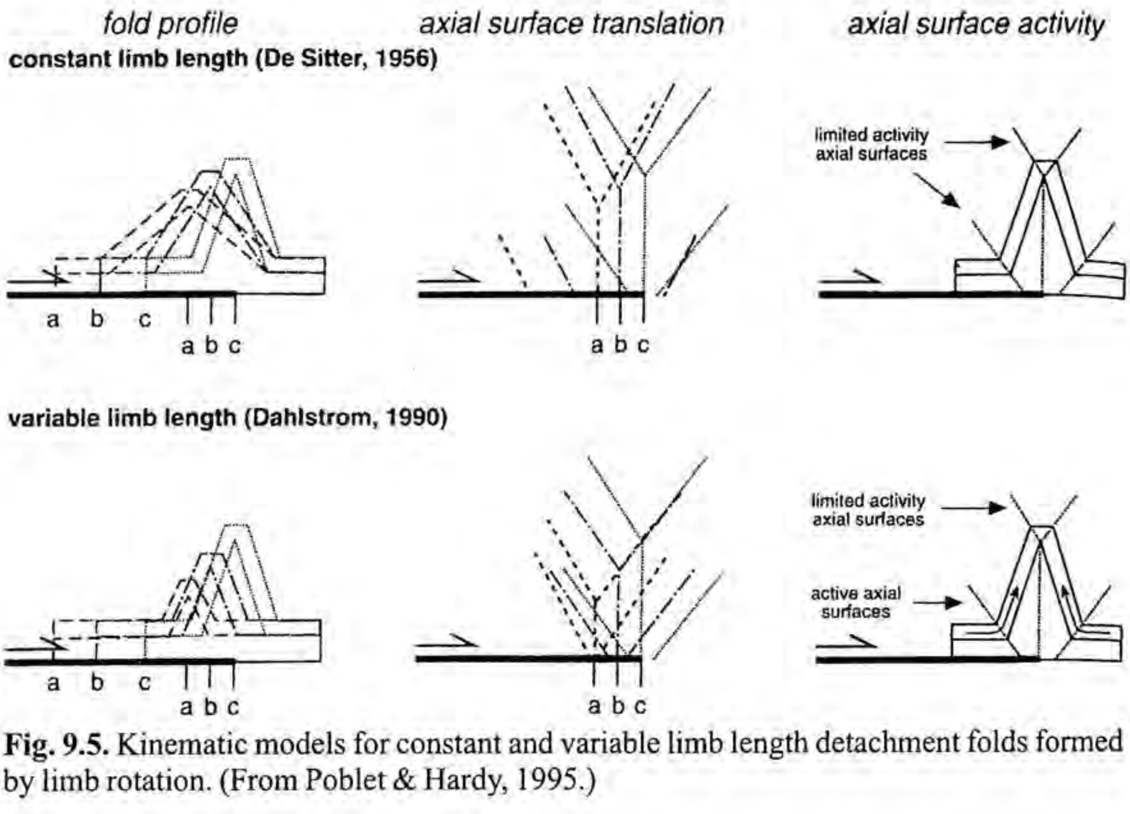


Fig. 9.5. Kinematic models for constant and variable limb length detachment folds formed by limb rotation. (From Poblet & Hardy, 1995.)

plots of the sequential development of the anticline for both of the growth mechanisms (**Fig. 9.6**), and compared them to the present day geometry (**Fig. 9.3**), the authors were unable to say which type of folding operated on the Pico del Águila anticline.

Pueyo *et al.* (1997) determined the folding mechanism of the Pico del Águila anticline by studying the anisotropy of magnetic susceptibility (AMS) within the surrounding growth strata. Magnetic susceptibility anisotropy arises because of the inherent magnetic anisotropy of certain rock-forming grains types, and the degree of their alignment. The AMS of a rock is studied by measuring its magnetic ellipsoid. In rocks that have acquired a fabric through deformation, there should be a systematic relationship between the strain ellipsoid and the magnetic ellipsoid.

Pueyo *et al.* (1997) used their AMS data to calculate shortening values for different layers within the growth strata around the Pico del Águila anticline, and compared their results to the depth that each layer was beneath the base of the Lower Campodarbe Fm. The authors found that, if the sedimentation rate was constant, as the amount of shortening accumulated through time, the amount the anticline grew as a result decreased exponentially. This result is consistent with the constant limb length model of fold growth proposed by Poblet & Hardy (1995).

9.3 Syntectonic sedimentation in the External Sierras

As explained in section **9.1**, the application of sequence stratigraphic concepts to tectonically active basins, and particularly structurally segmented thrust-top basins, is not straightforward and an area of ongoing research. The marine Árguis Fm. and Belsué-Atarés Fm. of the Jaca thrust-top basin together provide an excellent field example for this kind of research. Two separate groups of workers have already attempted to place the parts of these two formations that flank the N–S growth anticlines of the External Sierras into a sequence stratigraphic scheme (Millán *et al.*, 1994 and Castelltort *et al.*, 2003). Unfortunately, each study devised a completely different sequence stratigraphic framework for the same sedimentary succession. Consequently, the two studies went on to make differing inferences about how the anticlines of the External Sierras grew, how they affected the sedimentation, and what mechanism caused the sedimentary cycles that they observed. In this section, the two studies are reviewed in detail (sections **9.3.1** and **9.3.2**) and their relative merits assessed (section **9.3.3**).

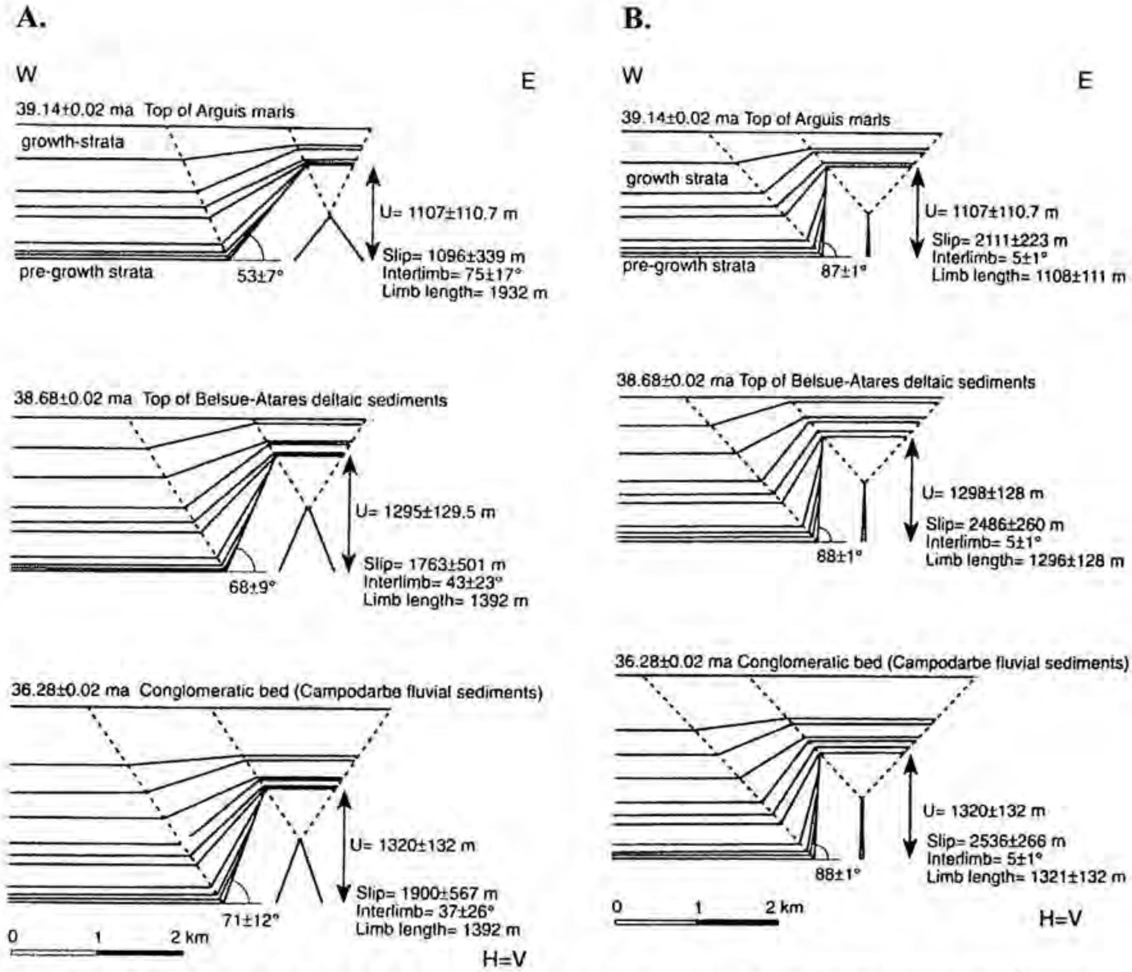


Fig. 9.6. Three-stage models of a possible kinematic evolution for the Pico del Águila anticline, for two different growth mechanisms: **A**. Constant limb length through time. **B**. Variable limb length through time. (From Poblet & Hardy, 1995.)

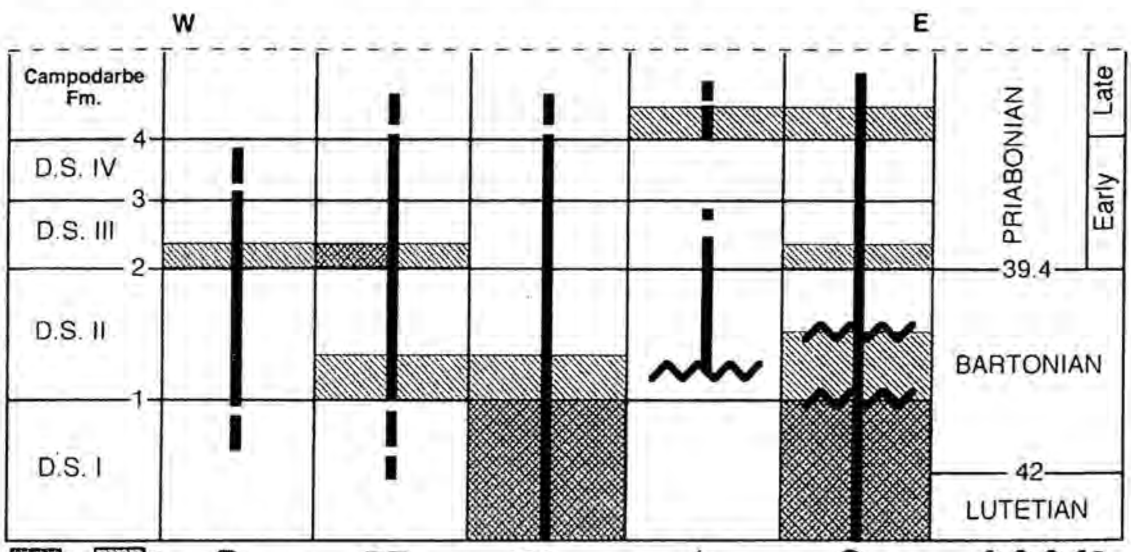


Fig. 9.8. The growth history of the anticlines, as derived by Millán *et al.* (1994) from their analysis of the growth strata. Key: vertical bars, uplift of anticline; pattern 1, onlap in growth strata; pattern 2, thinning and local onlap; wavy line 3, unconformity. Anticlines: R, Rasal; BR, Bentué de Rasal; PA, Pico del Águila; L, Lúsera; G, Gabardiella.

A third study, by Dreyer *et al.* (1999), into the sequence stratigraphy of the neighbouring thrust-top Aínsa Basin is also described (section **9.3.4**). The syntectonic marine deposits in this basin can be viewed as an older version of those found in the Jaca Basin (section **8.2**), although the nature of the Aínsa Basin perhaps made it more favourable for the application of sequence stratigraphic concepts.

9.3.1 Millán *et al.* (1994)

Millán *et al.* (1994) studied the full thickness of the Árguis Fm. and the Belsué-Atarés Fm. growth strata in the vicinity of the five growth anticlines of the central External Sierras – from the Rasal anticline in the west to the Gabardiella anticline in the east (**Fig. 1.3**). Their sequence stratigraphic framework (**Fig. 9.7**) consisted of four stacked depositional sequences (DS I – DS IV) of third-order magnitude (0.8 – 1.7 Myr long). Each was made up of a lower transgressive systems tract, formed by a thick wedge of marls, overlain by a highstand systems tract of shallow marine facies. The boundaries between the depositional sequences correspond to flooding surfaces, and were observed in the field as sharp lithological changes, onlapping relationships, and even unconformities.

DS I – DS II onlapped the Pico del Águila anticline and Bentué de Rasal anticlines respectively, whilst DS III overlapped both of them, but thinned markedly onto the fold crests. DS IV was unusual in nature between the villages of Bentué de Rasal and Belsué because in its lower half, instead of the transgressive marly facies normally present at the base of the sequence, cross-bedded siliciclastic facies were present instead.

The authors found evidence that many of the anticlines grew at the same time as one another (**Fig. 9.8**), contrary to the assertions of Puigdefàbregas (1975). The Pico del Águila and Gabardiella anticlines began to form prior to the first sediments of the Árguis Fm., grew continuously throughout the marine infilling of the Jaca basin, and may even have affected the lowermost Lower Campodarbe Fm. The Rasal, Bentué de Rasal and Lúsera anticlines were thought to have began their growth somewhat later.

The authors found that within each depositional sequence, the lower transgressive marly units had much greater thickness variations across the anticlines than the shallow-water siliciclastic units. The explanation offered was that each sequence began with a sudden increase in tectonic activity, causing a rapid deepening across the region, the creation of a flooding surface, and marl deposition. The increased tectonic activity also caused an increase in the growth rate of the anticlines, and hence greater thickness

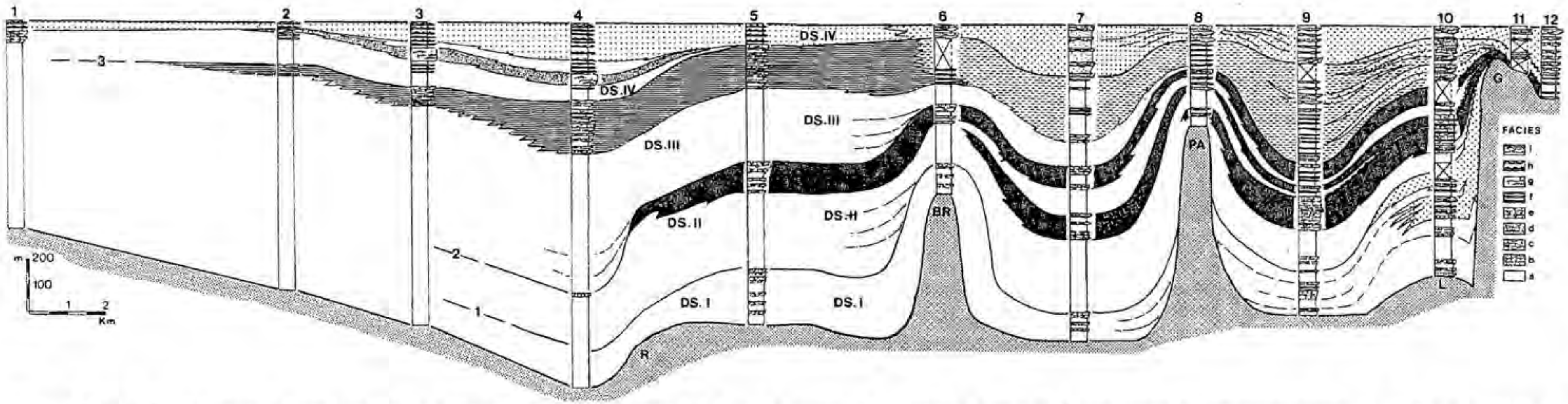


Fig. 9.7. W–E-orientated correlation and interpretation of graphic logs through the growth strata of the central External Sierras, by Millán *et al.* (1994). Log '1' is the equivalent to the Villalangua log of this work; '2', Triste log; '6', Bentué de Rasal log; '7', Árguis log; '8', Pico del Águila log; '9', Belsué log; '10', Lúsera log; '12', Gabardiella log. Their depositional sequences, consisting of transgressive (marls) and highstand (shallow marine facies) components, are marked as DS I to DS IV. The highstand parts of each DS are marked with different types of shading. Key to facies: a, blue marls; b, glauconitic sandy marls; c, skeletal wackestones to packstones; d, as for c, but sandy; e, as for c, but rich in bryozoans; f, skeletal marls bearing storm beds; g, coral boundstones; h, rippled sandstones with interlayered storm beds; i, cross-bedded sandstones and microconglomerates. Vertical exaggeration ×7.

variations in the syntectonic marls. The authors conceded that although it is possible that slower sedimentation rates during the marl deposition were responsible for the more pronounced thickness variations, this would not explain the generation of the observed sequences. Finally, the authors felt that the depositional sequences were not caused by eustatic sea-level changes because their timings did not correlate with the eustatic sea-level curve of Haq *et al.* (1987).

9.3.1.1 Comments on Millán *et al.* (1994)

The validity of the work of Millán *et al.* (1994) depends wholly on the sequence stratigraphic framework that they erected. The basis of this is presented as a long correlation panel, with facies and their interpretation overlain (**Fig. 9.7**). Although some additional explanation is offered in the text as to why their sequence boundaries (flooding surfaces) have been placed where they have, it is often not obvious why other major facies changes were not chosen as sequence boundaries as well.

The absence of a lowstand systems tract in the defined depositional sequences is not explained by the authors. It is not surprising that lowstand deposits are absent from the proximal (eastern) end of the section, where sediment bypass and erosional sequence boundary formation would be expected during times of lowstand in a conventional sequence stratigraphic setting (Van Wagoner *et al.*, 1988). However, lowstand deposits are not found at the distal (western) end of the section either, where conventional sequence stratigraphic wisdom predicts that they should be.

Another point arising from their correlation panel (**Fig. 9.7**) that is not explained in the text, is why DS II has up to three laterally extensive units of highstand-type shallow-water carbonate and siliciclastic facies, separated by transgressive-type marls, at the eastern end of the section. These features could represent higher order cycles, but the authors do not suggest a reason why they are not seen in the other depositional sequences, or a possible driving force for them.

A fundamental problem with the sequence stratigraphic interpretation presented by Millán *et al.* (1994) is that it does not take account of the three-dimensional nature of the geological situation. A conventional sequence stratigraphic interpretation of a passive margin setting can be adequately described on a 2D cross-section, parallel to depositional dip. However, this is not the case in the External Sierras, where the third dimension is very important. For instance, an E–W orientated cross-section through the growth anticlines will inevitably fail to feature potential subaerial sediment source areas on the thrust front to the south, or describe the way that the growth anticlines pass out northwards into the basin. Both of these factors could, however, have a very significant effect on facies development and stratigraphy.

The authors state that the lower boundary of DS II is represented by a low-angle angular unconformity to the east of Lúsera, and include a photograph to demonstrate this (**Fig. 9.9A**). However, this photograph is very misleading. Firstly, the upper, almost horizontal beds fall into the 'Prominent Sandstones of the Belsué-Atarés Fm.' of this work (section **9.4.1**), so should be considered to belong to DS III or DS IV by the authors, and not DS II. Secondly, due to foreshortening, it is not obvious from the photograph that the lower dipping beds are several hundreds of metres in front of the upper, horizontal beds. The lower beds dip because they are closer to the Gabardiella anticline and older, so have been tilted more. In the field, the beds in the gap in the photo can clearly be seen to progressively and continuously decrease in dip upwards (**Fig. 9.9B**). In other words, this photograph does not depict an angular unconformity.

Despite the fact that the authors state that each depositional sequence begins with a flooding surface, they also state that between the villages of Bentué de Rasal and Belsué, the base of DS IV consists of cross-bedded siliciclastic facies of a delta lobe, overlying the carbonate middle and inner ramp facies of the previous sequence. It does not seem reasonable to interpret the surface between the two as being a flooding surface, as the authors do, because an abrupt influx of siliciclastic material into an area is more likely to be due to a sudden fall in sea-level rather than a rise.

Millán *et al.* (1994) asserted that their depositional sequences had a tectonic origin, yet failed to present any compelling evidence for this. They argued that the greater thickness variations in the transgressive marly facies across the anticlines were because of increased tectonic activity causing the transgressive periods and increasing the anticline growth rates. Yet they went on to concede that if the marls were deposited at a lower sedimentation rate than the highstand siliciclastics, and that if tectonics proceeded at the same rate, then the same disparity in thickness variations would be produced. They dismissed this model because it did not explain the origins of their depositional sequences, although variations in several other basinal parameters could be responsible for these. Although the authors went on to reject eustatic sea-level changes as being the root cause of their sequences, the palaeomagnetic dating (Hogan, 1993) they use to demonstrate the non-correlation with eustatic sea-level curves is not sufficiently accurate to prove this.

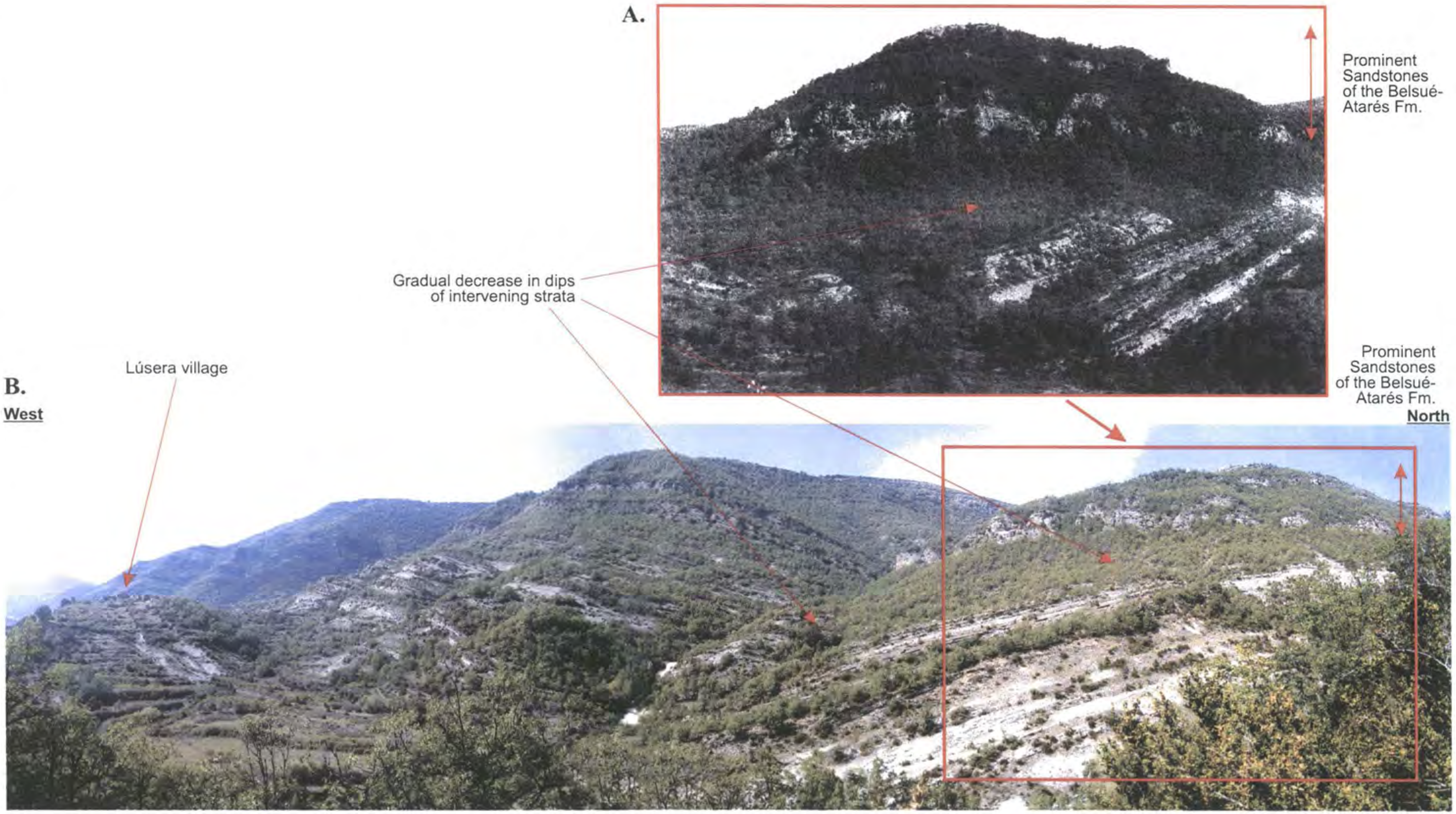


Fig. 9.9. Photos of the area east of Lúsera village. **A**. Evidence of an "angular unconformity between DS I and DS II", presented by Millán *et al.* (1994). **B**. Photomontage depicting a gradual decrease in the dips of the growth strata that are meant to have been cut by the angular unconformity.

9.3.2 Castelltort *et al.* (2003)

Castelltort *et al.* (2003) studied the growth strata that flank the Pico del Águila anticline in the central External Sierras (**Fig. 1.3**). The sections they studied ran between the top of the Guara Fm. and the base of the 'Ralla de las Tinas bed' of the Belsué-Atarés Fm. (Puigdefàbregas, 1975) – referred to as the 'Prominent Sandstones of the Belsué-Atarés Fm.' in this work (section **9.4.1**). In other words, they chose not to study the complete marine infill of the Jaca Basin, terminating their work mid-way through the Belsué-Atarés Fm., and covering only DS I – DS III of Millán *et al.* (1994).

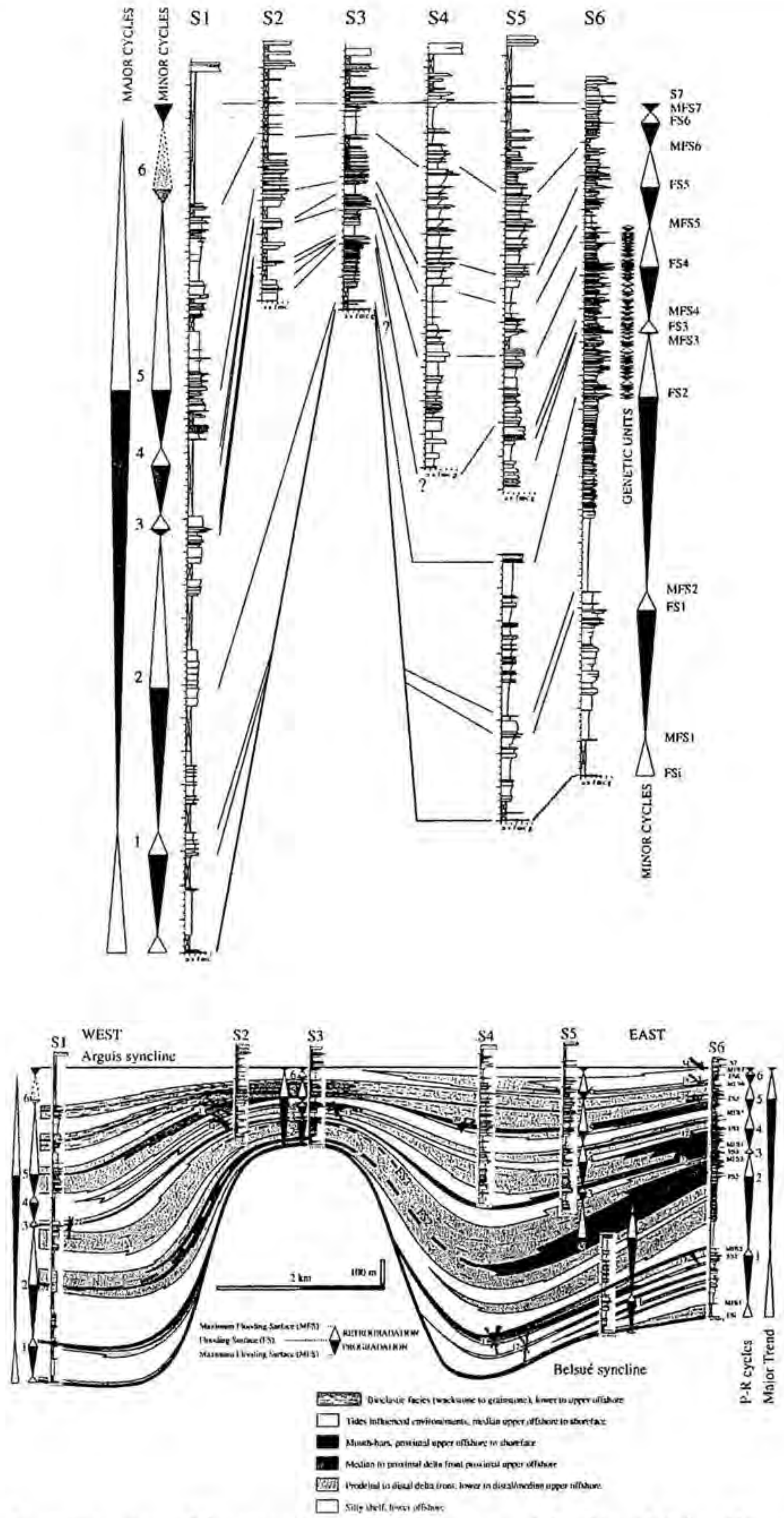
Castelltort *et al.* (2003) interpreted a completely new sequence stratigraphic framework from their data (**Fig. 9.10**). They identified three orders of cycles, divided by maximum flooding surfaces. The highest order cycles were termed 'genetic units', and were from several tens of centimetres up to 30 m thick. Next were 'minor cycles', 5 – 450 m thick, totalling six in number, and each consisting of progradational and retrogradational sub-cycles. The minor cycles made up one-and-a-bit 'major cycles', which were 300 – 1100 m thick.

The geometry and sedimentary facies of the genetic units was found to depend on their position relative to the anticline, suggesting that the growing structure exerted a controlling influence on them. Within the minor cycles, the progradational sub-cycles tended to be highly condensed onto the hinge of the anticline, whilst the retrogradational sub-cycles tended to have a more homogeneous thickness distribution. A similar trend was also noted in the major cycle. The authors also found that the growth of the anticline deflecting local palaeocurrents away from the regional NW-directed trend, towards the north.

The authors used the magnetostratigraphy of Hogan & Burbank (1996), the biostratigraphic data of Sztràkos & Castelltort (2001), and the assumption of a constant sediment accumulation rate between data points, to put absolute ages to their sequence-dividing maximum flooding surfaces. They found that genetic units were less than 100 kyr in duration, minor cycles 100 kyr – 1.8 Myr, and the major cycle 4 Myr long. The authors went to show that the uplift rate of the anticline decreased continuously through time, from about 750 to 200 m/Myr – this is consistent with the AMS work of Pueyo *et al.* (1997) and the constant limb length fold growth model of Poblet & Hardy (1995; section **9.2.4**).

From their chronostratigraphic constraints and analysis of vertical facies changes, Castelltort *et al.* (2003) showed that accommodation space was being created almost

A.



B.

Fig. 9.10. Interpretation of the growth strata that surround the Pico del Águila anticline, presented by Castelltort *et al.* (2003), featuring their proposed three orders of depositional sequences. Log 'S1' is the equivalent to the Árguis log of this work; 'S3', Pico del Águila log; 'S5', Belsué log. **A**. Graphic logs with inferred cycles indicated. **B**. Interpretations of the depositional environments and the sequence stratigraphic framework.

continuously across the entire area, even on the crests of the anticlines, implying regional scale relative sea-level rise. As would be expected, they found that the retrogradational parts of their minor cycles tended to form during times of rapid accommodation space creation, whereas the progradational parts of the minor cycles formed during periods of slow accommodation space creation or reduction. They did not find any systematic relationship between the timings of minor cycles and the variations in anticline crestal uplift rate – some minor cycles occurred during periods of continuous uplift.

9.3.2.1 Comments on Castelltort *et al.* (2003)

In a similar way to the work of Millán *et al.* (1994), the validity of the work of Castelltort *et al.* (2003) hinges entirely on the sequence stratigraphic framework that they erected. The basis of this they present as a correlation panel, featuring their sedimentary logs, with their interpretation overlain (**Fig. 9.10**). It is not at all obvious from these figures why the maximum flooding surfaces, which divide up their minor cycles, have been located as they have – many do not seem to correlate with any particular changes in the beds marked on the logs. There also appears to be a number of levels where there are obvious changes in the beds on the logs that could have been interpreted as a maximum flooding surface, but have not been. As with Millán *et al.* (1994), the approach of using a two-dimensional sequence stratigraphic model to understand a three-dimensional situation is undoubtedly a problem.

Castelltort *et al.* (2003) were quite selective in the strata that they studied. They did not look at the sediments around the four other growth anticlines of the central External Sierras, and they did not interpret the upper half of the Belsué-Atarés Fm. (Prominent Sandstones or 'Ralla de las Tinas bed'), even though their logs apparently extended up through it (**Fig. 9.10**). On the correlation panel, minor cycles 4 and 6 in log S1, to the west of the structure, are inferred in areas of zero exposure. Log S1 is the equivalent of the Árguis log of this work (section **9.4.2**), and in the experience of this author, the few unexposed parts of this area are usually revealed laterally as being almost entirely marly. Beds with even moderate sand content tend to stand proud of the recessive weathering and frequently poorly exposed marls, and it is not thought that there are sufficient quantities of 'drift' deposits in the area to cover over significant sections of sandy lithology. Thus, it is felt unlikely that these unexposed areas actually contain the necessary quantities of sandy marls and sandstone beds to justify the interpretation that each represents a whole minor cycle.

Using data drawn from various dating methods, the authors calculated that the time span of their genetic units was up to 100 kyr, and that their minor cycles were 100 kyr – 1.8 Myr long. They did not however state why the two should be considered as different orders of cycle, rather than just a continuum of varying cycle repeat times. Also, some of the defined minor cycles have very different thicknesses between the western and eastern synclines either side of the Pico del Águila anticline (**Fig. 9.10**). For example, minor cycle 5 is three times thicker in the west than in the east, yet the authors did not offer any explanation for this.

Crucial to much of the analysis of Castelltort *et al.* (2003) into the way the fold grew were their calculations of accommodation space and its variation through time. These relied upon estimates of palaeobathymetry derived from the facies that they interpreted. However, many of the facies could have been deposited at a very wide range of water depths. For example, their Table 2 (Castelltort *et al.*, 2003) states that flooding surface FS1 in log S5 could have formed at between 10 and 90 m water depth. Error bars such as these gave rise to large uncertainties in their calculated values of accommodation space variation. This in turn brings into question their subsequent deductions on the controlling effects that accommodation space generation and anticline crestal uplift had on the depositional sequences. Other questionable assumptions in their calculations include a constant sediment accumulation rate between data points, and a constant sediment supply rate through time.

9.3.3 Millán *et al.* (1994) vs. Castelltort *et al.* (2003)

The interpretations of Millán *et al.* (1994) and Castelltort *et al.* (2003) cannot both be correct, because the two studies defined completely different sequence stratigraphic frameworks from the same growth strata (compare **Fig. 9.7** and **Fig 9.11**). The cycles of Millán *et al.* (1994) were delineated by flooding surfaces and consisted of a marly transgressive systems tract, overlain by a mixed bioclastic / siliciclastic highstand systems tract. The cycles of Castelltort *et al.* (2003) were delineated by the deepest facies (i.e. maximum flooding surfaces), and consisted of a shallowing-up highstand systems tract, a mixed bioclastic / siliciclastic lowstand systems tract, and a retrogradational transgressive systems tract. Castelltort *et al.* (2003) identified six sedimentary cycles in the same vertical stack of strata that Millán *et al.* (1994) identified three – yet it is not simply a case of two of the Castelltort *et al.* (2003) cycles fitting into one of the Millán *et al.* (1994) cycles.

The conclusions drawn by both sets of authors were also completely at odds. Millán *et al.* (1994) felt that their depositional cycles were driven by episodic tectonic activity. They said that active tectonics led to subsidence and marl deposition across the area, with the marls thinning markedly onto the crests of the rapidly uplifting anticlines. As tectonics slowed, a more even thickness of mixed bioclastic / siliciclastic sediments was laid down. On the other hand, Castelltort *et al.* (2003) asserted that tectonics was a continuous process at the scale of the cycles. These authors said that their cycles resulted from variations in accommodation space, driven by regional changes in relative sea-level. They explained the thinning of the retrogradational sub-cycles onto the hinge of the anticline as having occurred because during periods of slow long-term, regional accommodation creation, progradation would be more favoured on the anticline crest than in the synclines.

The crux of the interpretations of both papers is the validity of their sequence stratigraphic framework, yet neither paper presents a convincing argument for exactly how each sedimentary cycle was identified and delineated. Indeed, neither works actually present any primary sedimentological evidence that laterally extensive, repetitive sedimentary cycles actually exist within the marine growth strata that flank the External Sierras. Furthermore, neither paper shows any consideration for the three-dimensional nature of the structures and the sediments that were deposited around them. On the strengths of the data presented, it seems that neither of the papers is more likely to be correct than the other.

Section **9.5.3**, below, uses the primary sedimentological data collected during the course of this work to assess whether any laterally extensive sedimentary cycles can actually be identified within the Árguis Fm. and the Belsué-Atarés Fm. of southern Jaca Basin sector, and hence which, if either, of the studies reviewed here is correct. Section **9.3.4**, immediately below, looks at the one example of marine growth strata from a thrust-top basin that have apparently been successfully placed into a sequence stratigraphic framework.

9.3.4 Dreyer *et al.* (1999)

Dreyer *et al.* (1999) devised a sequence stratigraphic framework for the Eocene Sobrarbe Fm. deltaic succession of the Aínsa Basin (section **8.2**). The studied succession was deposited whilst the Aínsa thrust-top was undergoing active deformation, in much the same way that the 5-Myr-younger (Bentham *et al.*, 1992) Belsué-Atarés Fm. was in the Jaca Basin (**Fig. 2.20**). The authors found erecting a sequence stratigraphic framework difficult because facies associations often interfingered, thicknesses were highly variable, the expression of stratigraphic surfaces commonly varied laterally, and the resolution of biostratigraphic constraints were poor. Nevertheless, a basin-wide interpretation of the stratigraphy was arrived at (**Fig. 9.11**).

Dreyer *et al.* (1999) subdivided the stratigraphy of the Sobrarbe Fm. into four 'composite sequences', each around 0.75 Myr long, and separated by major regressive unconformities. Each composite sequence consisted of a basal lowstand portion, overlain by transgressive and highstand components, and was thought to have been driven by relative sea-level changes due to episodic movements on the Aínsa Basin sole thrust. The nature of each composite sequence was strongly dependant on its position relative to the growth anticlines. Each one could also be subdivided into 3 – 7 'minor cycles', that were 10 – 45 m thick, bounded by maximum flooding surfaces and coarsened upwards.

Repeated episodes of thrusting during Middle to Late Eocene times caused deformation across the entire South Pyrenean foreland basin area, including the formation of the Arcusa growth anticline in the Aínsa Basin. Each tectonic episode caused uplift of the anticline crest and regressive unconformity (sequence boundary) formation in the crestal growth strata, but also coeval subsidence in the flanking synclines and flooding surface formation in the synclinal growth strata. The variable polarity of each individual sequence boundary (i.e. have both transgressive and regressive parts) is the key difference between the sequence stratigraphic interpretation of the Sobrarbe Fm. presented by Dreyer *et al.* (1999) and conventional passive margin sequence stratigraphy, in which sequence boundaries have the same polarity along their entire length (Van Wagoner *et al.*, 1988).

9.3.4.1 Sequence stratigraphy in the Aínsa and Jaca basins

Dreyer *et al.* (1999) devised a sequence stratigraphic framework that fits with the vast majority of the facies architecture of the Sobrarbe Fm. of the Aínsa Basin (**Fig. 9.11**). Unlike the work of Millán *et al.* (1994) and Castelltort *et al.* (2003), there are no obvious stratigraphic surfaces that have remained unexplained.

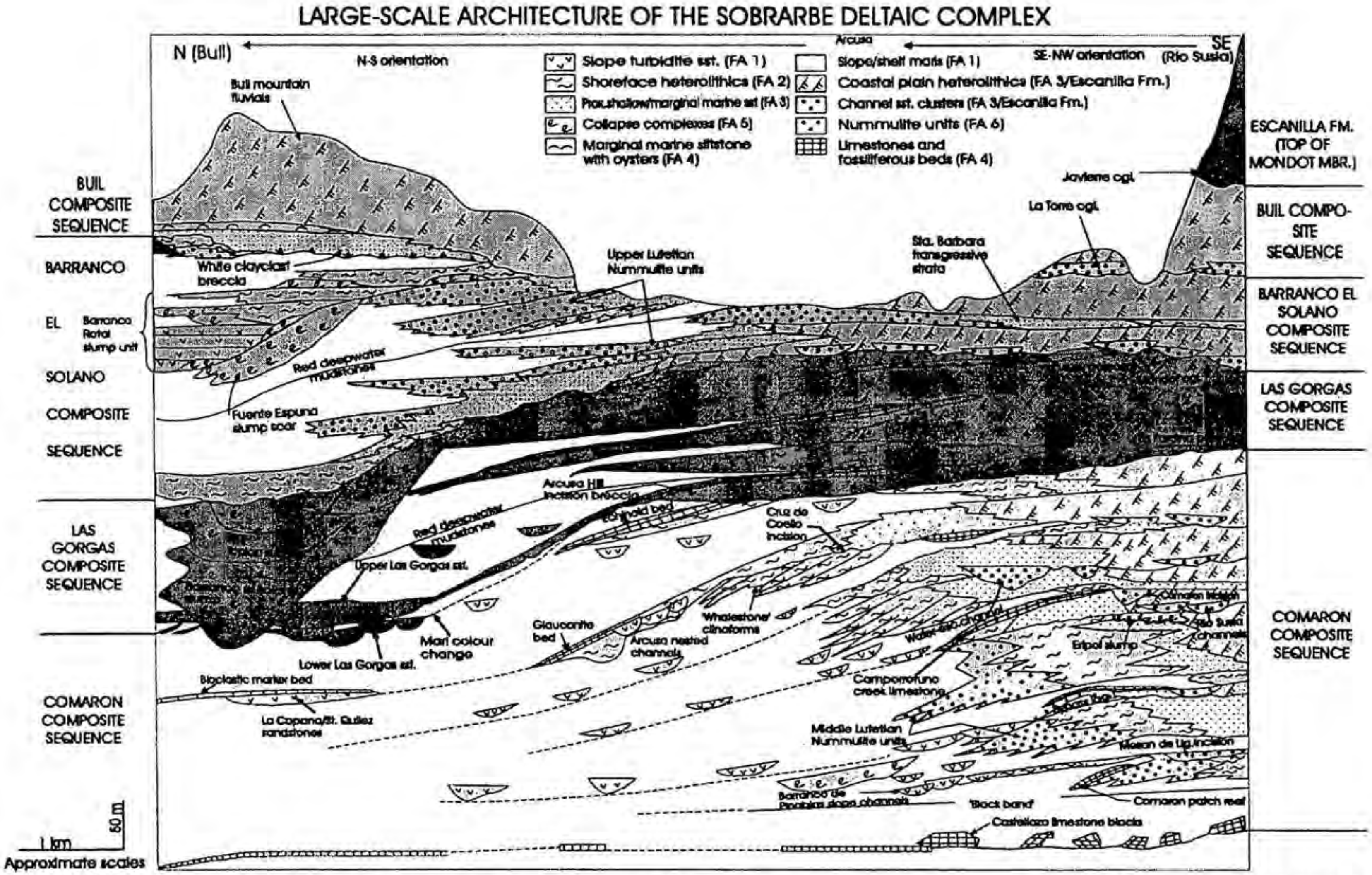


Fig. 9.11. Summary diagram of the syntectonic strata of the Aínsa Basin, presented by Dreyer *et al.* (1999), and featuring the four composite sequences that they interpreted.

There are a number of reasons why the Aínsa Basin might have proven a better choice of active thrust-top basin, than the Jaca Basin, to apply passive margin sequence stratigraphic concepts to. Firstly, at 25 km by 40 km, the Aínsa Basin covers a five times smaller area than the 100 km by 50 km Jaca Basin. This allowed Dreyer *et al.* (1999) to include the whole of the basin within their sequence stratigraphic framework. Secondly, the Arcusa anticline is the only significant growth anticline in the Aínsa Basin. This structure has only around 200 m of relief, and is orientated N–S i.e. more-or-less parallel with the NNW-directed bulk sediment progradation direction, meaning that it had only a limited impact on the progradation of the deltas of the Sobrarbe Fm. Despite this relatively simple basin configuration, Dreyer *et al.* (1999) stated that "the construction of a stratigraphic framework [was] a formidable task".

Over in the Jaca Basin, the growth anticlines are much larger (close to 1000 m of relief in several cases), much more numerous (eight in total along the southern basin margin alone), probably grew at different times, and many are orientated as N–S barriers cutting across the west- to WNW-directed bulk sediment progradation direction. Thus, these growth anticlines probably had a much greater impact on the progradation of the Belsué-Atarés Fm. deltas along the Jaca Basin than the Arcusa anticline did on the Sobrarbe Fm. of the Aínsa Basin. It is therefore hardly surprising that the extremely complex facies architecture of the syntectonic strata of the Jaca Basin has so far proven impossible to fit into a convincing sequence stratigraphic framework.

9.4 Graphic logs of the Southern Jaca Basin sector

The numerous, spectacularly exposed, kilometre-scale growth anticlines that had a strong control on the deposition of the syntectonic Árguis Fm. and Belsué-Atarés Fm. have made this area of the Jaca Basin by far the most popular part to publish on. Sections **9.2** and **9.3**, above, summarised, reviewed and integrated the findings of many of the more recent studies. Now, with the current level of understanding properly established, from this point onwards a new, thorough and comprehensive dataset collected as part of this work is presented and interpreted.

This sector of the field area lies about 20 km south of the town of Sabiñánigo, around the villages of Árguis and Belsué (**Fig. 9.1**). Six graphic logs were completed through the entire thicknesses of the Árguis Fm. and the Belsué-Atarés Fm. The locations of the logs are indicated on **Fig. 9.1**, and each is also reproduced, in both summary and original full-scale version, in the appendices in Vol.2.

Log name	Summary log	Original log
Lûsera	Vol.2, p.36 – 37	Vol.2, p.174 – 184
Belsué	Vol.2, p.38 – 39	Vol.2, p.185 – 195
Monrepos	Vol.2, p.40	Vol.2, p.196 – 197
Pico del Águila	Vol.2, p.41	Vol.2, p.198 – 201
Árguis	Vol.2, p.42 – 43	Vol.2, p.202 – 215
Bentué de Rasal	Vol.2, p.44	Vol.2, p.216 – 223

Each log begins in the underlying Guara Fm., passes through the full thickness of the Árguis Fm. and the Belsué-Atarés Fm., and ends in the overlying Lower Campodarbe Fm. The only exception to this is the relatively short Monrepos log, which followed a road cut through the upper portions of the Belsué-Atarés Fm. The Árguis Fm. and Belsué-Atarés Fm. were deposited syntectonically, whilst the underlying Guara Fm. and older units were being deformed into a series of N–S-trending anticlines (section **9.2**). Thus, these two formations display great thickness variations between logs close to the fold crests and logs in the flanking synclines, and a variety of onlap and overlap relationships with the folds.

This section, section **9.4**, outlines the fundamental characteristics of the syntectonic strata of the area, such as facies and facies associations, stratal geometries, palaeocurrents, and sediment composition. In section **9.5**, the interpretation of this data, and the construction of a correlation panel across the area, should allow the key questions raised in the current literature to be answered, such as: how did the anticlines control the facies architecture, is there any evidence for sea-level cycles, and can sequence stratigraphic concepts be applied to the infill of this active thrust-top basin?

9.4.1 Discriminating between the formations

In this area of the Jaca Basin, there are two formally defined syntectonic marine formations above the Guara Fm. – the Árguis Fm. and the Belsué-Atarés Fm. (Puigdefàbregas, 1975; **Fig. 9.1**). However, from my own field observations there does not seem to be a usable set of criteria to define the boundary between the two. In other areas of the Jaca Basin the two may be distinguished using facies associations – the Árguis Fm. tends to be composed of FA1 and FA2, and little else. The problem in this sector is that marly (FA1 and FA2) and sandy (FA3 and FA4) facies associations occur throughout many of the logs, in contrast to the more ordered coarsening-upwards succession seen in other areas. Thus, in this sector, the Árguis Fm. and the Belsué-Atarés Fm. have not been distinguished on the logs or the correlation panel.

Puigdefàbregas (1975) informally subdivided the Belsué-Atarés Fm. on the southern margin of the Jaca Basin, referring to its uppermost portions as the 'Ralla de las Tinas bed'. These uppermost portions consist of a sharp-based and near continuous package of proximal delta front channelised sandstones (FA5), which may be several hundreds of metres thick and is readily recognised on all logs across the sector. In this study, this package is referred to as the 'Prominent Sandstones of the Belsué-Atarés Fm.', and is marked as such on all logs and the correlation panel.

9.4.2 Facies, facies associations and facies architecture

In terms of facies and facies associations, there are few similarities between the logs of this sector. All begin with marly facies, but some then remain marly for the rest of the succession (Bentué de Rasal, Árguis), whereas others oscillate between sandy and marly facies (Pico de Águila, Belsué, Lúsera). The most obvious similarity in terms of facies is that all logs end with roughly 60 – 300 m of proximal delta front channelised sandstones (FA5; section **3.3.5**) of the Prominent Sandstones (section **9.4.1**). In four of the logs (Árguis, Pico del Águila, Monrepos and Belsué), these are overlain with around 10 – 20 m of marginal marine clays and sandstones (FA6; section **3.3.6**). All sections end with the distinctive fluvial sandstones and floodplain fines / red soils of the Lower Campodarbe Fm. (FA11 / FA12; section **3.3.11** / section **3.3.12**).

The Lúsera log (Vol.2, p.36 – 37 & p.174 – 184), the most easterly in this sector, is situated in the syncline between the large Gabardiella anticline to the east, and the smaller Lúsera anticline to the west. It begins with an unusual 38-m-thick package of upper shoreface and delta front sandstones (FA4; section **3.3.4**; Vol.2, p.174). These beds are very rich in miscellaneous shell fragments, plus a few red-coloured quartz pebbles. Above, the log is largely composed of offshore–transition zone marls and sandstones (FA2; section **3.3.2**) and lower shoreface sandstones (FA3; section **3.3.3**). However, at 362 m, a 23-m-thick, sharply-bounded, laterally extensive (over several hundreds of metres) package of FA5 is present (Vol.2, p.177). Besides a 6-m-thick package of the same facies association higher up the same log (Vol.2, p.179), isolated packages of FA5 are not seen on any of the other logs in this sector. Further up this section, a few beds of sandy bioclastic limestones facies are present (FA7; section

3.3.7). The Lúsera log finishes with by far the thickest package of Prominent Sandstones in this sector – around 289 m (Vol.2, p.36 – 37 & p.182 – 184).

Moving 4.7 km to the west, the next section encountered is the Belsué log (Vol.2, p.38 – 39 & p.185 – 195). This section is situated about 7 km to the west of the small Lúsera anticline, and 3 km to the east of the large Pico del Águila anticline. It is primarily composed of sand dominated facies – mostly lower shoreface sandstones (FA3) and upper shoreface and delta front sandstones (FA4). This log also contains packages of intensively symmetrically rippled sandstones facies (section **3.2.6**) that reach 30 m thick (Vol.2, p.188 – 193), making them by far the thickest found in the whole of the Belsué-Atarés Fm. The sandstones of this log are notable for being particularly rich in *Nummulites*.

The next log, lying 1.5 km to the west, is the short Monrepos log (Vol.2, p.40 & p.196 – 197). This log is perched on the eastern flank of the Pico del Águila anticline, and took advantage of a road-cut offering a 107-m-thickness of superb exposure, most of which is occupied by the Prominent Sandstones of the Belsué-Atarés Fm. This unit is characterised by many stacked beds of coarse, cross-bedded sandstones facies (section **3.2.8**; Vol.2, p.196), belonging to the facies association proximal delta front channelised sandstones (FA5). Marl rip-up clasts and pebbles are abundant in many of the beds.

Just over 1 km to the west, the Pico del Águila log (Vol.2, p.41 & p.198 – 201) is situated on the very crest of the Pico del Águila anticline. This log is only 297 m thick up to the base of the Lower Campodarbe Fm., compared to the two logs in the flanking synclines that are 1014 m and 1256 m thick in the same stratigraphic interval. Although this log is slightly sandier than most of the others, by far the most notable thing about it is the great thickness (88 m) of carbonate ramp limestones (FA7) present (Vol.2, p.199 – 200). The majority of this thickness is made up of bioclastic limestones facies (section **3.2.9**), with lesser amounts of sandy bioclastic limestones facies (section **3.2.10**). Within these carbonate beds, oysters and oyster colonies are abundant, and much more common than in all other logs of this sector.

The Árguis log (Vol.2, p.42 – 43 & p.202 – 215) was located 3.3 km to the west of the previous log, in the western syncline of the Pico del Águila anticline. This section is marl dominated, being composed almost entirely of offshore–transition zone marls and sandstones (FA2; Vol.2, p.42 – 43), and has a much lower proportion of sandy facies than the logs to the east of the Pico del Águila anticline. However, between 541 m and 549 m, there is an unusual, laterally extensive (over several hundreds of metres) bed of upper shoreface and delta front sandstones (FA4), isolated in the FA2 marls (Vol.2, p.207). Immediately overlying this bed is 18 m of marls and silts containing a very abundant but highly unusual trace fossil, never previously identified (R. Goldring, pers. comm., 2003; section **3.2.3.1**). This trace fossil is almost unique to this package, making only a few isolated appearances across the whole of the rest of the Jaca Basin.

Finally, the westernmost section is the Bentué de Rasal log (Vol.2, p.44 & p.216 – 223), situated 3.3 km west of the Árguis log, on the crest of the Bentué de Rasal anticline. This log contains the lowest proportion of sandy facies in this sector, being largely composed of offshore marine marls (FA1; section **3.3.1**). Between 300 m and 440 m, there are a number of thin (around 1 m) and thick (up to 32 m) packages of bioclastic limestones facies (Vol.2, p.219 – 220), representing carbonate ramp limestones (FA7). The lithologies and fossil assemblages present in these are reminiscent of the limestones that occur above the crest of the Pico del Águila anticline 6.6 km to the east.

To the west of the Bentué de Rasal anticline is one final growth structure – the Rasal anticline, located near the village of Rasal (**Fig. 1.3**). However, exposure hereabouts is poor, and it was not felt that the quality of logs likely to be produced would contribute much to the understanding of this area. Reconnaissance work revealed the Belsué-Atarés Fm. & Árguis Fm. interval to be composed of marly and carbonate facies, with no obvious siliciclastics until a few tens of metres of the capping Prominent Sandstones of the Belsué-Atarés Fm. are reached.

In summary, the Árguis Fm. and Belsué-Atarés Fm. in this sector of the Jaca Basin contain sediments deposited in a wide range of marine environments. In the 'Belsué-Atarés Fm. & Árguis Fm.' interval, these are: offshore marine (FA1), offshore–transition zone (FA2), lower shoreface (FA3), upper shoreface (FA4), limited amounts of proximal delta front (FA5), and carbonate ramp (FA7). The carbonate ramp limestones (FA7) are almost exclusively found above the crests of the anticlines of the External Sierras. In the Prominent Sandstones interval, the environment of deposition is primarily proximal delta front (FA5), but with some marginal marine (FA6) sediment present on some sections. Overlying this on all sections are the fluvial sandstones and floodplain fines / red soils (FA11 / FA12) of the Lower Campodarbe Fm.

9.4.3 Sediment onlap around the Pico del Águila anticline

Fig. 9.12 depicts an aerial photo of the Pico del Águila anticline (**Fig. 9.12A**), and a simple interpretation of the trends in the growth strata that surround it (**Fig. 9.12B**). If

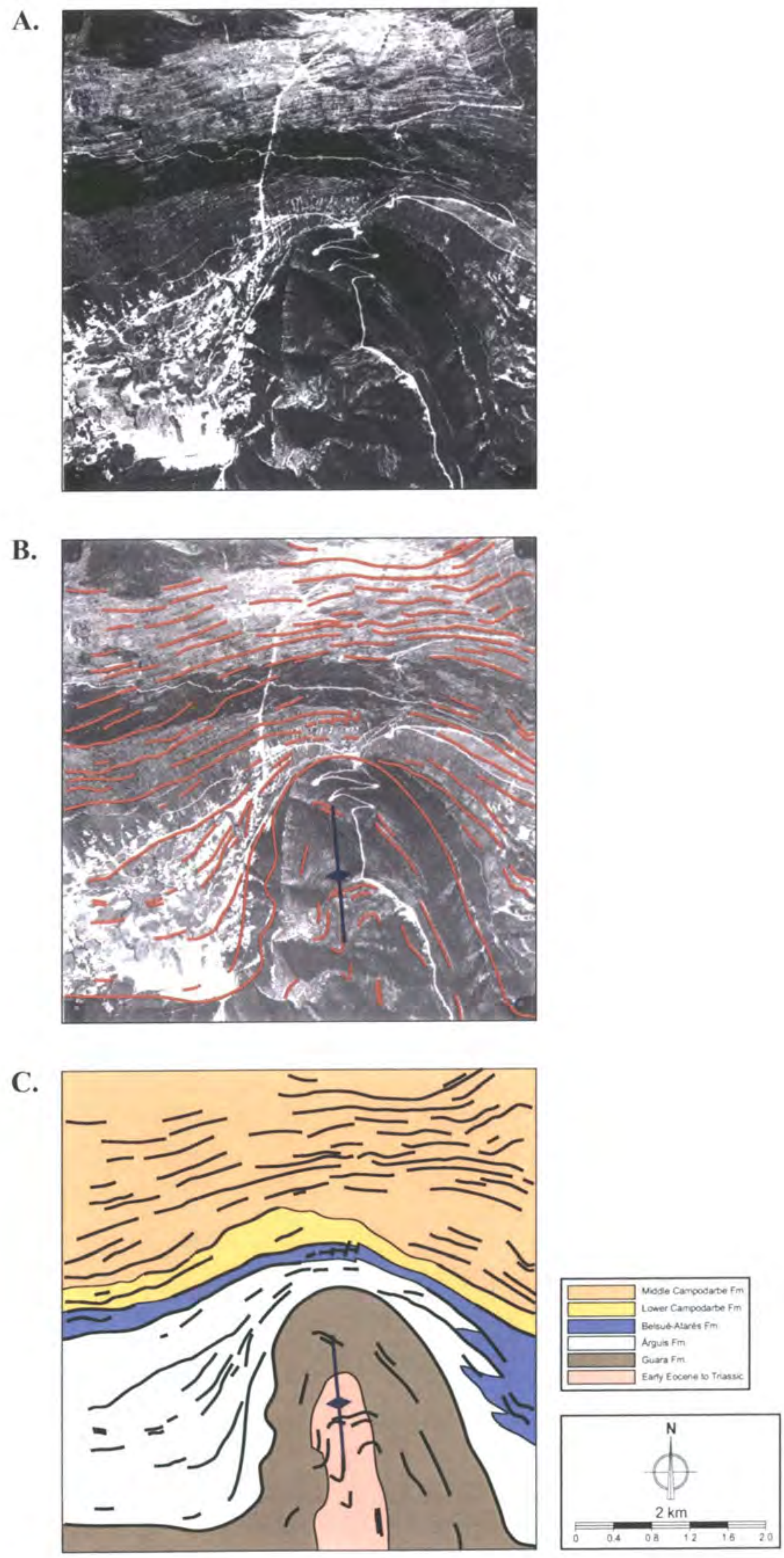


Fig. 9.12. Sediment onlap and overlap around the Pico del Águila anticline. **A**. Aerial photo. **B**. Interpretation. **C**. Interpretation superimposed on geological map of Puigdefàbregas (1975).

this interpretation is added to the geological mapping of Puigdefàbregas (1975), then it can be seen how the growth of the structure affected the syntectonic strata from the various formations (**Fig. 9.12C**). Fortunately, the land topography and the dips of the syntectonic strata are distributed almost symmetrically about the structure, with the line of symmetry being parallel to the N–S-orientated axis of the fold. Because of this it is possible to make direct comparisons between the stratal geometries and thicknesses viewed on the aerial photo / map (**Fig. 9.12**) between either side of the fold, without having to compensate for topographic or dip effects.

Several onlap terminations can be seen in the lower half of the Árguis Fm., whilst in the upper half the strata appear to overlap the structure. The mapping of Puigdefàbregas (1975) indicates that the Belsué-Atarés Fm. partially passes over the Pico del Águila anticline, thinning onto the crest, and then becoming a little thicker again in the western syncline. However, the majority of the thickness of the Belsué-Atarés Fm. is indicated on the Puigdefàbregas (1975) map as changing laterally into the Árguis Fm. in the vicinity of the eastern limb of the structure. From field study, it is not obvious what criteria were used to define this relationship. It is however clear from the interpretation of the aerial photo that the actual strata crosscut the formation boundary as initially mapped.

The stratal trends in the Lower Campodarbe Fm. and Middle Campodarbe Fm. are harder to interpret. The Lower Campodarbe Fm. is notably thicker to the west of the crest of the Pico del Águila anticline. The strata of the Middle Campodarbe Fm. appear to define a large-scale progressive unconformity: the fanning within the strata opens towards the east, seemingly indicating that the eastern portion was tilted downwards with respect to the west. The fulcrum of this apparent progressive unconformity would be more-or-less directly above the crest of the Pico del Águila anticline.

The onlapping relationship between the growth strata of the lower half of the Árguis Fm. and the Pico del Águila anticline indicates that the structure had significant positive topographic relief on the seafloor during the deposition of these units. The overlapping relationships that characterise the upper half of the Árguis Fm. and the Belsué-Atarés Fm. indicate that the anticline did not have a significant topographic relief during these times. This may suggest that the anticline initially grew rapidly, outstripping the sedimentation rate, before slowing, but could also indicate than an initial low sedimentation rate increased through time whilst the uplift rate remained constant. Correct interpretation of this particular stratal geometry would require dating of the growth strata (see Pueyo *et al.*, 2002, and Castelltort *et al.*, 2003).

It is inferred from the stratal patterns in the Lower Campodarbe Fm. and Middle Campodarbe Fm. of this area that large-scale tectonic processes, such as tilting, were occurring in the External Sierras. There does not however seem to be any evidence for continued growth of the Pico del Águila anticline itself. To properly understand these complex stratal patterns would however require a much more thorough investigation.

9.4.4 Palaeocurrents

The palaeocurrent trends across most of the logs in this sector are quite similar (**Fig. 9.13**). The majority of the palaeocurrent readings were taken from symmetrical ripples – their abundance indicating that wave reworking was an important process in this part of the Jaca Basin. The Árguis, Pico del Águila, Monrepos and Belsué logs are dominated by a palaeocurrent trend of W–E- to WNW–ESE-directed wave rippling. In the west, the marl dominated Bentué de Rasal log did not yield any palaeocurrent information. In the east, the Lúsera log, whilst featuring the common WNW–ESE wave rippling trend, also has an unusual N–S-orientated flow direction, defined by wave rippling and some N-directed unidirectional flow (Vol.2, p.36 – 37).

The W–E- to WNW–ESE-directed wave rippling is parallel to the synclinal axis of the Jaca Basin (**Fig. 1.3**), but close to perpendicular to the trend of the N–S-orientated growth anticlines of the External Sierras. With the exception of Lúsera, most sections have very similar palaeocurrent trends, irrespective of their positioning relative to the N–S growth anticlines. It therefore seems likely that the wave rippling in this part of the basin followed a trend along the WNW–ESE-orientated Jaca Basin syncline, and was not affected by the N–S anticlines. It can be inferred from this that the N–S anticlines did not have sufficient topographic relief above the sea floor to deflect the palaeocurrents caused by wind-generated waves during the deposition of the Belsué-Atarés Fm.

The N–S-directed wave rippling and N-directed unidirectional currents recorded at Lúsera are, however, harder to explain. The unidirectional currents could indicate that the Lúsera and Gabardiella anticlines, which flank this log to the east and west respectively, did have sufficient topographic expression on the sea floor to affect the current flow in the area. Or perhaps the N-directed unidirectional flow could have originated from potential subaerially exposed source areas within the External Sierras to the south of Lúsera.

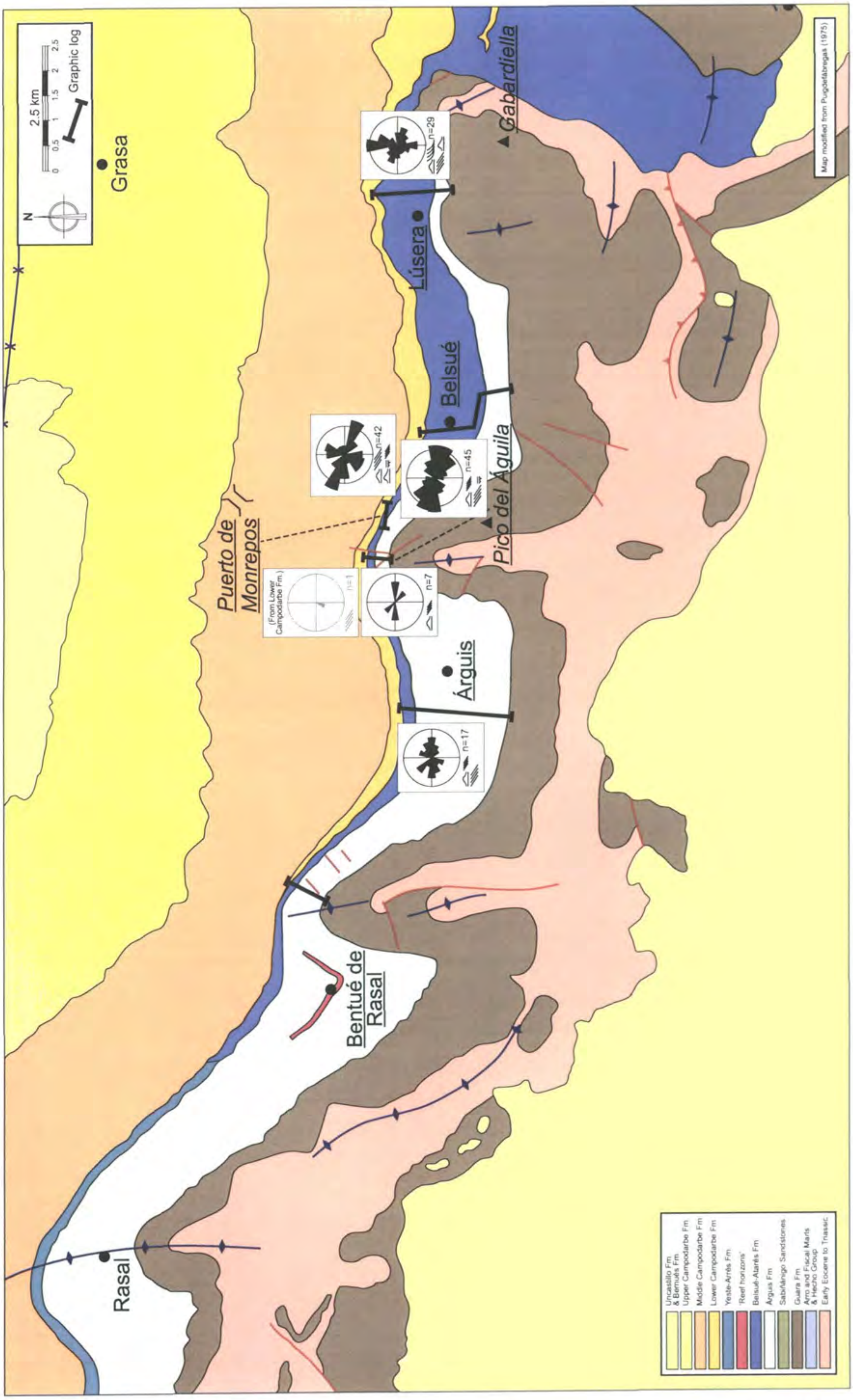


Fig. 9.13. Geological map of the Southern Jaca Basin, with palaeocurrent rose diagrams for each log.

9.4.5 Sediment composition

Samples were collected from several fine–medium sandstone beds during the logging process, and their compositions analysed. **Fig. 9.14** shows the composition data for Árguis and Lúsera as it was felt that these two logs – 11 km apart and separated by the kilometre-scale Pico del Águila growth anticline – would be the most likely to have differing sediment compositions. The make-up of samples from the other four logs were also analysed, but are not included on **Fig. 9.14** for clarity and because they are little different to those of the first two logs. It was also noted that all samples had a very similar texture when viewed down the microscope – poorly sorted, angular grains.

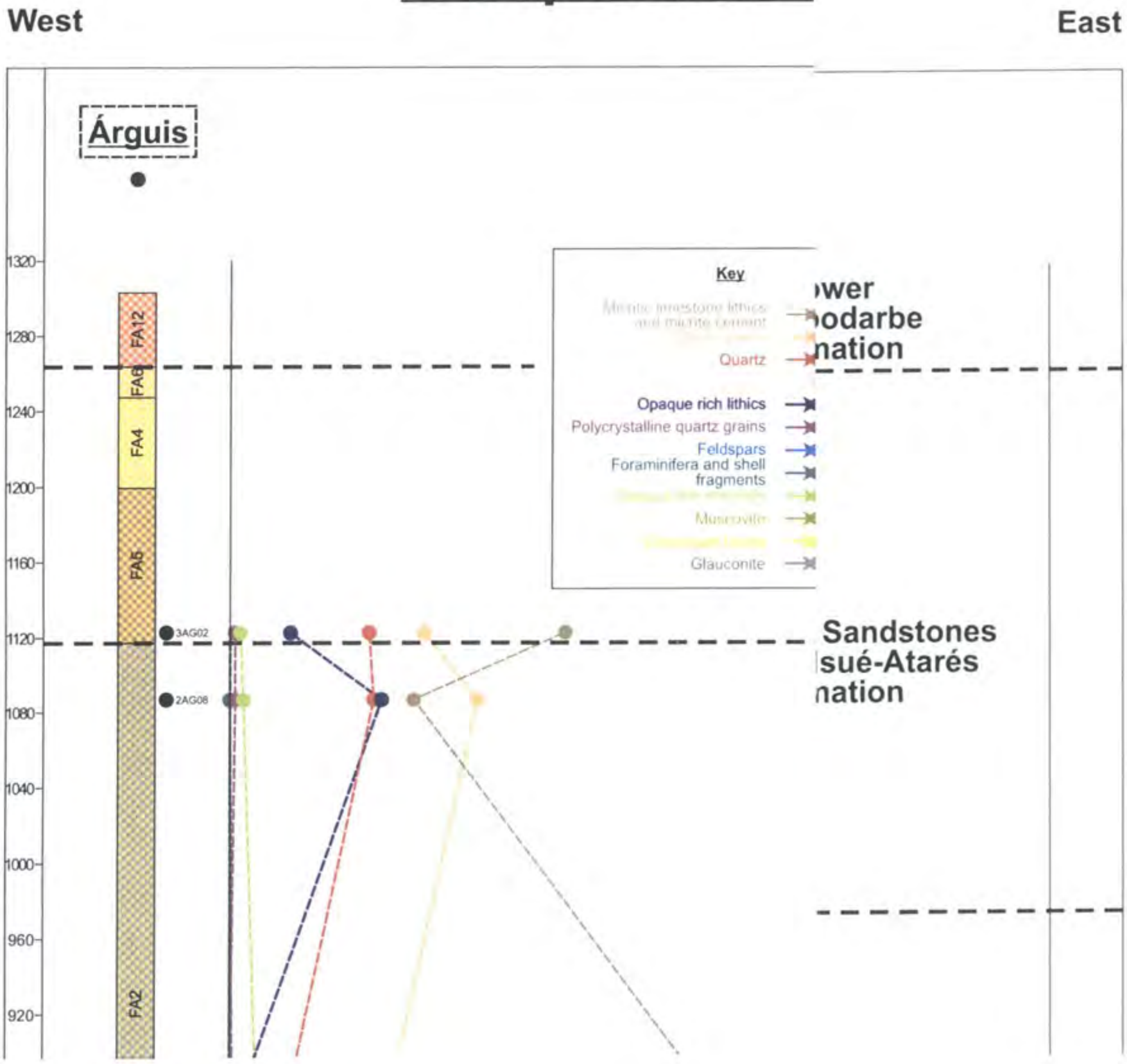
The sediments of Lúsera contain a higher percentage of calcite grains (30.8% average) than the Árguis samples (20.6% average), which contain more micritic limestone lithics and micrite cement (45.9% average vs. 36.9% average). This is consistent with the Lúsera section being dominated by sandy lithologies whilst the Árguis log is dominated by marly ones. Beyond this trend, however, there does not seem to be any further systematic variations in the composition data, either between or within the logs. Even the Prominent Sandstones, which correlate extremely well across the area, do not seem to have a particularly similar composition between the two sections. Such variable compositions may reflect variations in the make-up of the sediment being supplied and/or fluctuating depositional processes that preferentially sorted out different grain types.

Both logs contain, at various heights, a few percent of 'exotic' minerals and grains such as opaque-rich lithics, polycrystalline quartz grains, opaque iron minerals, muscovite, and chloritised biotite. These must originate from igneous and metamorphic rocks, and so imply that this sector of the Jaca Basin was being fed sediment partly sourced from the internal zone of the Pyrenean mountain belt (Jones, 1997).

9.5 Correlation, interpretation and discussion

Section **9.4** covered the fundamental aspects of the marine growth strata of the Southern Jaca Basin sector. This section, section **9.5**, takes these fundamentals and builds upon them, aiming towards answering some of the key questions in the study of marine growth structures and the application of sequence stratigraphic concepts to active thrust-top basins.

Composition I



This section begins by discussing the correlation, or in fact the lack of correlation, between the six graphic logs (section **9.5.1**). It goes on to discuss how the three major growth anticlines are largely responsible for this lack of correlation (sections **9.5.2** – **9.5.5**), and the mechanisms by which this may have occurred (section **9.5.6**). Against this background of local (and regional) tectonic control on depositional sequences, some previous authors have found evidence of a sea-level control – this finding is assessed using the newly collected dataset (section **9.5.7**). Finally, the key question of whether it is possible to apply sequence stratigraphic concepts to this part of the Jaca Basin, and so to active thrust-top basins in general, is discussed (section **9.5.8**).

9.5.1 Correlation between graphic logs

Fig. 9.15 is an almost W–E-orientated correlation panel covering all six logs from the Southern Jaca Basin sector. Included at the eastern end of the panel is the Gabardiella log from the SE Jaca Basin sector, intended to aid correlation between the two areas. All logs are 'hung' from the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary. This contact is sharp and distinctive, and has been shown by Hogan & Burbank (1996) to have formed more or less synchronously in some parts of the Jaca Basin. The most recent and well-constrained palaeomagnetic dates, derived by Pueyo *et al.* (2002), have been included at their appropriate heights alongside the Árguis log. Along the base of the panel, the names of the different growth anticlines are given.

However, it should be remembered that the cyclical progradations and retrogradations in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary observed in other parts of the basin (Chapter 4 and Chapter 8) indicate that this surface did not form synchronously across the entire area. Furthermore, because palaeomagnetic dates are only available for one section in this area (Árguis), the correlation panel had to be constructed purely on the basis of facies. Thus, because of the lack of chronological constraint, the correlation panel should be considered to be wholly stylistic. Whilst the vertical scale may be sediment thickness, this has no direct relationship to time. The formation boundaries and other lines of correlation noted merely indicate areas of the same facies association (depositional environment) on adjacent logs. These boundary surfaces and lines of correlation are most likely to be diachronous, and so are not necessarily key surfaces of any sort.

Within the main body of the Belsué-Atarés Fm. & Árguis Fm., it is difficult to laterally correlate between any of the logs – quite simply, adjacent logs do not look very much like one another. There are however a few general trends across the area that may be observed. Firstly, the logs in the east tend to be much more sand-rich and contain coarser grades of sand than those logs further west, which are very much marl-dominated. The division between the sand-dominated and marl-dominated areas seems to be the Pico del Águila anticline. Secondly, with the exception of a small thickness (less than 10 m) on the Lúsera log, carbonate ramp limestones (FA7) are restricted to the Bentué de Rasal and the Pico del Águila logs i.e. to above the crests of two of the three, kilometre-scale growth structures.

By far the strongest correlation between logs in this sector occurs outside the main body of the Belsué-Atarés Fm. & Árguis Fm. – the Prominent Sandstones of the Belsué-Atarés Fm. form a sharp-based and highly distinctive package that is clearly visible on all logs. The thickness of the Prominent Sandstones varies quite profoundly between the crests of the anticlines and in the adjacent synclines. For example, the Prominent Sandstones are 289 m thick at Lúsera, but only 40 m thick above the crest of the Pico del Águila anticline, 7.5 km to the west. Overlying the Prominent Sandstones, and forming a second highly distinctive and readily correlatable contact, is the Lower Campodarbe Fm.

The correlation between particular pairs of logs is discussed in more detail in the following sections, which discuss the controlling effects that the three, kilometre-scale, N–S-orientated growth anticlines exerted over the deposition of the syntectonic Árguis Fm. and Belsué-Atarés Fm.

9.5.2 Influence of Pico del Águila anticline

The Pico del Águila anticline is inferred to have strongly controlled the depositional systems of the Belsué-Atarés Fm. & Árguis Fm. interval because, as the correlation panel (**Fig. 9.15**) and composition data (section **9.4.5**; **Fig. 9.14**) clearly indicate, the thickness, lithology and facies of the growth strata change profoundly across the structure. To the east, the Belsué-Atarés Fm. & Árguis Fm. interval of the Belsué log is 917 m thick, and dominated by sands throughout. To the west of the structure on the Árguis log, the Belsué-Atarés Fm. & Árguis Fm. interval is 1109 m thick, and dominated by marls. On the crest of the structure, the Belsué-Atarés Fm. & Árguis Fm. interval is condensed to only 257 m thick – about one-quarter of its synclinal thickness – and uniquely thick beds of carbonate ramp limestones (FA7) are present.

In order to have this controlling effect, the structure must have had some degree of positive topographic relief above the sea floor during deposition. Indeed, the growth strata from the lower half of the Árguis Fm. onlap the flanks of the anticline (**Fig. 9.12**) – evidence that the structure did have significant topographic relief, preventing sediment deposition on its crest (section **9.4.3**). However, stratigraphically higher growth strata from the rest of the Árguis Fm. and the Belsué-Atarés Fm. overlap the fold (**Fig. 9.12**; Poblet & Hardy, 1995). Despite this, the Pico del Águila anticline continued to affect thickness and facies throughout the rest of the Árguis Fm. and Belsué-Atarés Fm. deposition. Thus, it seems likely that the lack of non-deposition on the crest of the structure in the higher stratigraphic levels was a product of increased sedimentation rates, perhaps due to an increase in the amount of sediment being supplied to the basin.

Throughout the deposition of the Belsué-Atarés Fm. & Árguis Fm. interval, the positive topographic relief associated with the growing Pico del Águila anticline apparently acted as a barrier to the general westward progradation of the regional depositional system (Puigdefàbregas, 1975). It prevented the sand rich lower shoreface (FA3) and uppers shoreface and delta front (FA4) depositional environments of the Belsué section in the east from crossing the structure westwards and reaching the marl dominated offshore–transition zone (FA2) environment in the west at Árguis. The relief of the structures was also sufficient to enable the production of 88 m of more-or-less continuous limestones above the fold crest. This probably occurred because of crestal uplift, elevating the seafloor into better sunlight conditions and/or into less turbid waters than adjacent areas. It is, however, important to remember the three-dimensional nature of the situation – although it is not possible to see how far northwards the Pico del Águila anticline persists for, it is likely that at some point further towards the basin centre, sands sourced from the east were able to pass westwards around the 'nose' of the structure, likely also preventing carbonate production on the fold crest.

To the west of the Pico del Águila anticline, the Belsué-Atarés Fm. & Árguis Fm. interval on the Árguis log is made up of approximately 1000 m of the very marly offshore–transition zone marls and sandstones (FA2). However, isolated right in the middle of these is a 15-m-thick package of upper shoreface and delta front sandstones (FA4; 534 m – 549 m; Vol.2, p.207). The facies present in this package are reminiscent of the sandy lithologies that occur to the east of the Pico del Águila anticline at Belsué and Lúsera. It seems possible that this isolated sandy unit was indeed sourced from the east, perhaps overlapping the crest of the anticline during a period of tectonic quiescence and zero uplift. NW-directed palaeocurrent measurements taken from cross-bedding in this package do lend some weight to this idea (Vol.2, p.207). However, although the make-up of the sand in this package was analysed, the compositions of the sands to the east of the anticline are, unfortunately, too variable to prove an eastern origin for this isolated western sand package (section **9.4.5**; **Fig. 9.12** – compare sample 2AG04 on the Árguis log to samples from the Lúsera log).

The thickness of the Prominent Sandstones of the Belsué-Atarés Fm. was strongly affected by the Pico del Águila anticline, varying from 97 m in the syncline to the east of the structure, down to 40 m on the crest, and then up to 146 m in the western syncline. However, it does not seem as though the facies were as strongly affected as they were within the Belsué-Atarés Fm. & Árguis Fm. interval below. The Prominent Sandstones are principally composed of the same facies (medium, cross-laminated sandstones facies and coarse, cross-bedded sandstones facies), of the same facies association (FA5: proximal delta front channelised sandstones) across this entire sector. Perhaps the only systematic variation is that in the west, the sandstone grainsizes tend to be a finer (fine–medium sand is the average grainsize at Árguis vs. medium–coarse sand at Lúsera), and have fewer rip-up clasts and pebbles present: compare 1109 m – 1256 m on the Árguis log (Vol.2, p.213 – 215) with 800 m – 1089 m on the Lúsera log (Vol.2, p.182 – 184). However, it is not clear whether these east–west variations are due to the Pico del Águila anticline, or in fact represent a proximal–distal relationship.

The affect that the Pico del Águila anticline had on the Lower Campodarbe Fm. is not obvious, largely because the whole thickness of the formation was not logged, so any thickness variations are not apparent. No systematic facies or facies association variations were apparent either (**Fig. 9.15**). It has already been suggested that fold uplift ceased around the time that the Lower Campodarbe Fm. began to form (Hogan & Burbank, 1996). Indeed, beds of medium, cross-bedded coloured sandstone facies were recorded above the crest of the anticline on the Pico del Águila log (308 m – 329 m, Vol.2, p.201). This facies is thought to represent dunes and bars of a fluvial channel (section **3.2.20.2**), and it seems very unlikely that a river would be localised above the crest of an anticline if that anticline was still growing.

9.5.3 Influence of the Bentué de Rasal anticline

The Bentué de Rasal anticline lies at the western end of the Southern Jaca Basin sector (**Fig. 1.3**). On the Bentué de Rasal log, situated above the crest of the anticline, the Belsué-Atarés Fm. & Árguis Fm. interval (up to the base of the Prominent

Sandstones) is 622 m thick (**Fig. 9.15**). It is dominated by the siliciclastics-free pure marls facies, of the offshore marine marls (FA1) facies association. Also found in the crestal succession are several thick (up to 32 m) packages of carbonate ramp limestones (FA7; 300 m – 440 m, Vol.2, p.219 – 220). The only other significant thicknesses of FA7 in this sector are seen above the crest of the Pico del Águila anticline.

In contrast, on the Árguis log, 3.3 km to the east of the fold crest in the eastern syncline, the Belsué-Atarés Fm. & Árguis Fm. interval is 1109 m thick, and dominated by the offshore–transition zone marls and sandstones (FA2) facies association. To the west of the structure, the Belsué-Atarés Fm. & Árguis Fm. interval is though to be a similar thickness to that at Árguis (**Fig. 9.1**; Puigdefàbregas, 1975; Millán *et al.*, 1994), and is dominated by offshore marine marls (FA1). Thus, it seems as though this anticline affected the Belsué-Atarés Fm. & Árguis Fm. interval in a very similar way to the Pico del Águila anticline 6.6 km to the east. The ongoing uplift of the structure acted as a barrier to the westward progradation of the silts and fine sands of the FA2 depositional environment. On the crest of the structure, only about one-half of the synclinal thickness of the Belsué-Atarés Fm. & Árguis Fm. interval was deposited, and the production of several thick beds of carbonate material occurred.

The stratigraphically higher Prominent Sandstones of the Belsué-Atarés Fm. are only 60 m thick on the crest of the Bentué de Rasal anticline, yet are 146 m thick at Árguis in the syncline to the east. However, despite this significant thinning, the facies within the Prominent Sandstones do not obviously vary between the synclinal and crestal areas. This was also the case with the Pico del Águila anticline in the east. Within the Lower Campodarbe Fm. above the crest of the Bentué de Rasal anticline, two, 4-m-thick beds of medium, cross-bedded coloured sandstone facies were recorded. These are thought to represent a fluvial channel (section **3.2.20.2**), and as with the Pico del Águila anticline, their presence seems to suggest that fold growth had ceased by the time of their deposition.

Thus, the Bentué de Rasal anticline affected the growth strata that surround it in much the same way that the Pico del Águila anticline affected its adjacent syntectonic beds.

9.5.4 Correlation with the SE Jaca Basin sector

The Gabardiella anticline marks the eastern boundary of the Southern Jaca Basin sector – to its east lies the SE Jaca Basin sector (Chapter 8). The correlation panel for this sector (**Fig. 9.15**) also features the westernmost log from the SE Jaca Basin sector, intended to help integrate the analysis of the two areas. It should be noted that if the left-hand end of the correlation panel for the SE Jaca Basin (**Fig. 8.10**) is folded over, this section can be placed on top of the Southern Jaca Basin panel (**Fig. 9.15**) to create a continuous section that covers both areas.

As explained in section **9.1**, palaeomagnetic dates are only available for one section in this area. Furthermore, it was only possible to locate one aerial photo (section **9.4.3**), and the very rough terrain and the sometimes patchy exposure meant that the walking out of beds was rarely possible. For these reasons, correlation between the Southern and SE Jaca Basin areas, across the Gabardiella anticline, could only be achieved by looking at the similarities in the facies and facies associations between the logs belong to the two areas

The Gabardiella log lies just to the east of the crest of the Gabardiella anticline. After the first 57 m, the log features two significant packages of proximal delta front channelised sandstones (FA5), topped off by a further thick package (132 m) of FA5 (Vol.2, p.35 & p.170 – 173). These packages are very reminiscent of the Prominent Sandstones of the Belsué-Atarés Fm. noted on the Lúsera log, just 2.9 km to the west, and so have been correlated with one another on the correlation panels (**Fig. 8.10**; **Fig. 9.15**). The lowermost 57 m of the Gabardiella log is largely composed of offshore–transition zone marls and sandstones (FA2), and is reminiscent of the Belsué-Atarés Fm. & Árguis Fm. interval from the logs further to the west, and so these have been correlated accordingly also.

Moving eastwards, the Belsué-Atarés Fm. on the Bara log (Vol.2, p.32) and the Nocito log (Vol.2, p.33 – 34) is, after the lowermost 100 m or so, is dominated by FA5, with some intervening packages of FA2, FA3 and FA4. As with the Gabardiella log, the FA5 packages are reminiscent of the Prominent Sandstones identified to the west of the Gabardiella anticline, and so the two have also been correlated (**Fig. 8.10**; **Fig. 9.15**). Again, similar to the Gabardiella log, the lowermost 154 m of the Nocito log and 46 m of the Bara log are reminiscent of the Belsué-Atarés Fm. & Árguis Fm. interval identified to the west of the fold, and so the correlation of these two has also been made.

9.5.5 Influence of the Gabardiella anticline

Now that the correlation across the Gabardiella anticline of the subdivisions of the syntectonic strata has been established, it is possible to identify the effects that the growth of the structure had on the coeval sedimentation in the area. The correlation panels (**Fig. 8.10**; **Fig. 9.15**) indicate that the fold profoundly affected the thicknesses of the various syntectonic units. For example, to the east of the structure, at Nocito, the complete syntectonic marine succession (including the Árguis Fm. and the Belsué-Atarés Fm., but excluding the 'finger' of the Lower Campodarbe Fm.) is 1011 m thick; on the crest of the structure at Gabardiella the marine succession is 297 m thick; to the west at Lúsera this interval is 1090 m thick.

As well as thicknesses of the syntectonic units, the structure had a profound effect on the distribution of the facies associations (**Fig. 8.10**; **Fig. 9.15**). To the east of the fold at Nocito, the section consisted of 154 m of marl rich FA2 – FA3, followed by 857 m of sand dominated FA5 (but with FA2, FA3 and FA4 intervals). In the middle of this log there is also a 109-m-thick progradational 'finger' of continental facies associations (FA11 / FA12) of the Lower Campodarbe Fm. (Vol.2, p.166 – 167). This unusual feature extends for about 5 km laterally (Puigdefàbregas, 1975; **Fig. 8.3**), yet fails to pass westwards across the Gabardiella anticline. In contrast to the FA5 dominated Nocito log, to the west of the structure at Lúsera, the marine succession consists of a marl dominated 800 m of FA2 – FA3, followed by just 289 m of sand dominated FA5.

Thus, it seems as though the Gabardiella anticline, like the Pico del Águila and Bentué de Rasal anticlines to the west, acted as a barrier to the general westward progradation of depositional environments (facies associations). In this case, the Gabardiella anticline held back the upper shoreface and delta front (FA4), proximal delta front (FA5) and fluvial (FA11 / FA12) environments, allowing offshore–transition zone (FA2) and lower shoreface (FA3) conditions to persist in the west for much of the Árguis Fm. and Belsué-Atarés Fm. times. Eventually, towards the end of the marine phase of the basin, the proximal delta front (FA5) environment breached the crest of the structure and prograded westwards. Some time after, the fluvial (FA11 / FA12) environment of the Lower Campodarbe Fm. did the same. This breaching of the crest of the structure may reflect higher sedimentation rates associated with the more proximal depositional environments, or may have occurred simply because the uplift rate of the structure was slowing.

So, the uplift of the Gabardiella anticline, like the Pico del Águila and Bentué de Rasal anticlines to the west, caused reduced sedimentation on its crest and acted as a barrier against the progradation of more proximal depositional environments. The only major difference between the effects that this structure had, compared to those of the other two, is that limestones were not deposited above the crest of the Gabardiella anticline.

9.5.6 Growth anticlines as barriers to progradation

Section **8.3** discussed the work of De Boer *et al.* (1991), who described how a growing anticline my have a barrier effect and cause the vertical localisation of an otherwise progradational facies boundary. In section **8.5.3.1**, the ideas presented by De Boer *et al.* (1991) were used to explain how the Alcanadre anticline of the SE Jaca Basin sector (**Fig. 1.3**) was able hold back the westward progradation of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary for about 1.5 – 2 Myr (**Fig. 8.10**). However, from the work presented in this chapter on the Gabardiella, Pico del Águila and Bentué de Rasal anticlines (**Fig. 9.15**; sections **9.5.2**, **9.5.3** and **9.5.5**), it has become apparent that every one of the N–S-orientated growth folds of the External Sierras acted as a barrier to the progradation of the syntectonic sediments. Not only was the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary affected, but so were all the other siliciclastic depositional environments (facies associations) that are well represented in this area.

Fig. 9.16 summarises the distribution of facies associations within the Árguis Fm., Belsué-Atarés Fm. and lowermost Lower Campodarbe Fm. across the Southern and SE Jaca Basin sectors. Although the correlation is based on similarities in facies associations, a degree of chronological control can be derived from the palaeomagnetic dates of Pueyo *et al.* (2002), which are cited next to the Árguis log. It is clear from this figure which of the facies associations (or groups of facies associations) were held back by which of the growth anticlines. It can also be seen on this figure that all of the facies associations (or groups) simultaneously underwent a major westward progradation, in some cases breaching the crests of the barrier structures, at around 37.5 Ma (Pueyo *et al.*, 2002). This could be evidence of a relative sea-level change, and is discussed in the next section.

9.5.7 Evidence for sea-level cycles

As noted above and indicated on **Fig. 9.16**, all of the major siliciclastic marine facies associations (deposition environments) found in the Southern and SE Jaca Basin sectors underwent a major progradational–retrogradational cycle towards (or at) the top of the Belsué-Atarés Fm. The resulting cycle in the syntectonic strata begins at around 900 – 1000 m on the vertical scale on **Fig. 9.16**, and so was deposited at about 37.5 Ma at Árguis (Pueyo *et al.*, 2002). The first part of the cycle is a rapid westward progradation of all major siliciclastic facies associations, varying in magnitude from about 1 km westwards in the west at Bentué de Rasal, to around 12 km westwards in the east at Bara.

Prior to this progradation, each of the major siliciclastic facies association was held in a fixed horizontal position, vertically aggrading behind one of the four, kilometre-scale growth anticlines. The rapid progradation that followed represents a time when each of the facies associations, apparently simultaneously, was able to breach the crests of the growth folds that had previously held them back, and shift rapidly in a basinward direction. As shown on **Fig. 9.16**, the facies associations (or pairs of facies associations) and the folds that they were initially held back by, but then breached during the progradational event, are (from west to east):

- FA2 breached the crest of the Bentué de Rasal anticline, and prograded 1 km westwards across FA1.
- FA3+FA4 breached the crest of the Pico del Águila anticline, and prograded 3 km westwards across FA2.
- FA5 breached the crest of the Gabardiella anticline, and prograded 6 km westwards across FA3+FA4.
- FA11+FA12 (of the Lower Campodarbe Fm.) breached the crest of the Alcanadre anticline, and prograded 12 km westwards across FA5 (of the Belsué-Atarés Fm.).

The westward progradation of each of the major siliciclastic facies associations was followed by each retrograding back eastwards by 2 – 5 km. This retrogradational phase was brought to an end by a second major phase of progradation, dated as occurring at 37.2 Ma at Árguis (Pueyo *et al.*, 2002). The time gap between the two progradational events can be used to define a stratigraphic cycle of approximately 0.3 Myr duration. This second major progradation event was, like the first, seemingly rapid, as proximal delta front channelised sandstones (FA5) lie directly on top of offshore–transition zone marls and sandstones (FA2) at Árguis and offshore marine marls (FA1) at Bentué de Rasal (**Fig. 9.16**). There is no evidence for any intervening lower shoreface sandstones (FA3) or upper shoreface and delta front sandstones (FA4), and nor is there any evidence that these facies associations had been deposited and then eroded. This trend of westward progradation continued for at least 0.6 Myr, when the fluvial sandstones (FA11/FA12) of the Lower Campodarbe Fm. prograded across the Árguis section (Pueyo *et al.*, 2002).

Three possible causes of the facies association progradation and retrogradation are outlined and discussed below:

- A sudden fall in eustatic sea-level, followed by a rise. The palaeomagnetic dates of Pueyo *et al.* (2002) have been used to correlate the progradational–retrogradational stratigraphic cycle with the eustatic sea-level curves of Haq *et al.* (1987; **Fig. 2.20**). However, this seems to show that there were no large enough fluctuations in global sea-level at the right time to cause the kilometre-scale shifts in the facies associations.
- A sudden increase in the sediment supply rate, followed by a decrease. This would not seem to be a likely explanation of the rapid facies association shifts because changes in sediment supply tend to occur gradually. Furthermore, the compositional data did not contain any evidence of sediment supply changes (section **9.4.5**).
- A sudden basin-wide uplift event, followed by subsidence. Such changes could occur because of variations in the activity of the thrust that underlies the Jaca Basin.

Therefore, the cause of the 0.3 Myr long, progradational–retrogradational facies association cycle (beginning with the facies associations first breaching the crests of the growth anticlines) is most likely to have been a basin-wide uplift event, followed by basin-wide subsidence.

9.5.8 Application of sequence stratigraphic concepts

In the syntectonic marine and lowermost non-marine strata of the Southern and SE Jaca Basin sectors, there are two well defined progradational–retrogradational cycles in the facies associations (**Fig. 9.16**). Both had durations of the order of 1 Myr and caused kilometre-scale shifts in the lateral positions of the facies boundaries. Furthermore, both are though to have been caused by changes in relative sea-level, due to basin-wide uplift and subsidence events. The younger of the two (described above, section **9.5.7**), affected each of the major siliciclastic facies associations across the area, and is though to have lasted for 0.3 Myr (up to the base of the next progradation). The older of the two affected the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary in the vicinity of the

Bara log (section **8.5.3.2**), and is thought to have lasted for around 1 Myr. It is also thought that the progradation at the base of this older cycle may correlate with the progradation of FA3+FA4 over FA2 in the lower halves of the Belsué and Lúsera sections about 15 km to the west (**Fig. 9.16**).

However, in the syntectonic marine strata to the west of the Gabardiella anticline, Millán *et al.* (1994) identified four stacked depositional sequences, separated by flooding surfaces, of 0.8 – 1.7 Myr duration (section **9.3.1**). In the syntectonic strata around the Pico del Águila anticline, Castelltort *et al.* (2003) interpreted a wholly different sequence stratigraphic framework, consisting of six 'minor cycles', 5 – 450 m thick and 100 kyr – 1.8 Myr in duration (section **9.3.2**). No evidence to support either of these interpretations of further large-scale cycles in the syntectonic marine strata to the west of the Gabardiella anticline was found in the data collected during the course of this work (**Fig. 9.16**).

Castelltort *et al.* (2003) also found evidence of higher order repetitive 'genetic units', which were up to 30 m thick and 100 kyr in duration. Cycles of this order were also noted by this work, but only in the Nocito and Bara logs of the SE Jaca Basin sector (Chapter 8; section **8.5.3.2**). Here the cycles consist of repetitive oscillations between FA4 / FA5 and FA2 / FA3 that correlate well across the 10 km between the Bara and Nocito logs, and lateral shifts in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary around the Bara section.

Laterally extensive, 100-kyr-order repetitive cycles were not, however, found in the syntectonic strata around the Pico del Águila anticline that Castelltort *et al.* (2003) studied, or indeed in any of the syntectonic marine strata to the west of the Gabardiella anticline. Although it is possible to observe oscillations of approximately this order between more distal and more proximal facies associations on some of the sections in this area, these do not correlate with adjacent sections. One of the fundamental requirements of a sequence stratigraphic framework is laterally correlatable stratigraphic cycles, delineated by chronostratigraphic (key) surfaces (Van Wagoner *et al.*, 1988). Without these, the predictive value of the sequence stratigraphic framework is lost, and its whole validity is brought into question. This work did not find evidence of such features throughout the bulk of the syntectonic strata to the west of the Gabardiella anticline, and so the sequence stratigraphic analysis of Millán *et al.* (1994) and Castelltort *et al.* (2003) must be called into question.

However, laterally correlatable stratigraphic cycles of 100-kyr-order were observed in the syntectonic marine sediments to the east of the Gabardiella anticline, in an area unstudied by Millán *et al.* (1994) or Castelltort *et al.* (2003). It is thought that a strong correlation exists between these cycles on the Nocito and Bara logs because of the lack of intervening growth structures. Further west, the numerous, kilometre-scale growth anticlines are believed to have prevented the deposition of recognisable, laterally correlatable stratigraphic cycles of 100-kyr-order. However, in this area a larger scale, lower order cycle of 1-Myr-order repeat time was observed. It was felt that this cycle was reflected in the stratigraphy, whereas ones of 100-kyr-order were not, because the magnitude and duration of the shift in facies associations related to it were sufficient to overcome the background 'noise' in the stratigraphy (created by local controls on sedimentation e.g. the growth of individual anticlines). Furthermore, the base of the cycle represents the time when the crests of the anticlines had been breached and so were no longer acting as barriers to progradation.

Thus, it has been shown that it is not possible to apply sequence stratigraphic concepts to the majority of the marine strata in the Southern and SE Jaca Basin sectors, and especially in areas that are in close proximity to the N–S-orientated growth anticlines. However, this is not to say that it is impossible to successfully apply sequence stratigraphic concepts to any thrust-top basin. The Jaca Basin, and particularly the External Sierras area, is particularly structurally complex, and has a relatively complicated history of tectonic deformation and sedimentary events (section **2.4**; **Fig. 2.20**). Dreyer *et al.* (1999), for example, was able to successfully place the syntectonic marine infill of the Aínsa Basin into a sequence stratigraphic framework (section **9.3.4**). The reason for their success, however, is thought to be that the Aínsa Basin is much simpler structurally, having only one major growth anticline. Importantly, this anticline was orientated parallel to the bulk sediment transport direction in the basin, and so would not have been able to inhibit facies association progradation or the development of laterally extensive stratigraphic cycles, in the way that the growth folds of the External Sierras did in the Jaca Basin.

9.6 Conclusions

The kilometre-scale, N–S-orientated growth anticlines of the External Sierras strongly affected the deposition of the syntectonic Árguis Fm. and Belsué-Atarés Fm. in the Southern and SE Jaca Basin sectors. On the crests of the structures the total thickness of marine sediment accumulated was reduced to as little as one-quarter of that in the flanking synclines, and in some cases, thick carbonate units were formed. For much of the marine infill phase of the basin, the N–S-orientated structures acted as barriers to the general WNW-directed progradation of the major siliciclastic facies associations (depositional environments). Each facies association tended to vertically aggrade behind a particular growth anticline, the more distal facies associations in the west, and the more proximal ones in the east.

At 37.5 Ma (on the Árguis section), a basin-wide uplift event caused a fall in relative sea-level, and a rapid 1 – 12 km westward progradation of all major facies associations, across the crests of the growing structures that had previously acted as barriers. This was followed by basin-wide subsidence and facies association retrogradation of 2 – 5 km. Then, at 37.2 Ma (at Árguis), a second major facies association progradation occurred, causing proximal delta front channelised sandstones (FA5) to be lain directly on top of offshore marine marls (FA1) at Bentué de Rasal. This progradation continued at least until 36.6 Ma (at Árguis), when the Lower Campodarbe Fm. prograded across the area. Once it had crossed the Gabardiella anticline, the Lower Campodarbe Fm. was not affected by the more westerly growth anticlines, implying that uplift had ceased by this time.

Two major progradational–retrogradational cycles of the order of 1-Myr duration have been defined in the syntectonic strata of the Southern and SE Jaca Basin sectors. The younger began with the breaching of the crests of the anticlines, described above, whereas the older affected the Belsué-Atarés Fm.-Lower Campodarbe Fm. boundary in the vicinity of the Bara section. In the Nocito–Bara area, the lack of intervening growth anticlines allowed the deposition of recognisable, laterally extensive, 100-kyr-order cycles in the syntectonic Belsué-Atarés Fm. However, laterally extensive cycles of this order were not seen to the west of the Gabardiella anticline, because the intervening growth anticlines exerted too strong an effect on the sedimentation.

These finding do not support the previous sequence stratigraphic interpretations of the marine syntectonic strata of this area that were proposed by Millán *et al.* (1994) and Castelltort *et al.* (2003), and imply that such interpretations of sediments to the west of the Gabardiella anticline are inappropriate. Sequence stratigraphy is thought to fail in this part of the Jaca Basin because of the complex structural and sedimentary history, and because the N–S-orientated growth anticlines were ideally orientated to act as perpendicular barriers to sediment progradation. Sequence stratigraphic concepts may, however, still be useful in less heavily deformed thrust-top basins, such as the Aínsa Basin.

9.7 Key Points

1. Sedimentary infill of the basin:

- The Árguis Fm. and the Belsué-Atarés Fm. have a gradational boundary in this area.
- The Prominent Sandstones are a progradational package of proximal delta front channelised sandstones (FA5) that cap the Belsué-Atarés Fm. in this area.

2. Structural configuration of the basin:

- Depositional systems did not cross the southern margin of the basin (the south Pyrenean thrust front), aside from via the Rodellar and Nocito palaeovalleys.

3. Influence of intrabasinal growth structures:

- The syntectonic marine strata were drastically thinned onto the crests of the N–S-orientated anticlines, down to as little as one-quarter of their synclinal thickness.
- Thick carbonate packages (up to 88 m) accumulated above the crests of the Pico del Águila anticline and Bentué de Rasal anticline anticlines.
- Because the anticlines were orientated near perpendicular to the bulk sediment progradation direction, they were able to act as barriers, causing all major siliciclastic facies associations to vertically aggrade for much of the marine phase.
- The growth anticlines did not affect the facies or progradation of the Lower Campodarbe Fm., implying that the uplift had ceased by this point.

4. Effect of sea-level changes:

- At 37.5 Ma (at Árguis), a fall in relative sea-level, due to basin-wide uplift, caused all facies associations to breach the crests of the anticlines that had been holding them back, and prograde westwards by 1 – 12 km.
- This was followed by a 0.3-Myr-long rise in relative sea level, due to basin-wide subsidence, causing all facies associations to retrograde eastwards by 2 – 5 km.
- A second rapid facies association progradation occurred at 37.2 Ma (at Árguis), and lasted at least until 36.6 Ma, when the Lower Campodarbe Fm. prograded across the area unimpeded.
- Two 1-Myr-order progradational–retrogradational cycles were observed in the syntectonic marine strata of the area.

- Laterally extensive 100-kyr-order cycles are seen in the syntectonic marine strata in the Nocito–Bara area, where there are no intervening growth anticlines.
- Stratigraphic cycles of 100-kyr-order were not observed to the west of the Gabardiella anticline, bringing into question the sequence stratigraphic interpretations of Millán *et al.* (1994) and Castelltort *et al.* (2003).
- Sequence stratigraphy does not work in this part of the Jaca Basin because of the complex geological history and the barrier effect exerted by the N–S-orientated growth anticlines.

The next chapter, Chapter 10, integrates the findings from each of the separate sectors of the Jaca Basin (chapters 4 – 9), to produce a complete understanding of the development of the basin from the first syntectonic growth strata to the onset of terrestrial conditions. They key findings regarding the controls of structurally defined basinal sediment input points, intrabasinal growth structures, and relative sea-level changes are summarised, and comparisons to analogous basins from other parts of the world are made.

Chapter 10:
Discussion and Conclusions

10. Discussion and Conclusions

Contents

10. Discussion and Conclusions

10.1 Introduction

The relationships between the syntectonic marine strata of the Jaca Basin and an array of kilometre-scale, compressive tectonic structures are superbly exposed. This area therefore provides a rare and world class opportunity to study the poorly understood effects that growing structures may have upon shallow marine depositional systems in compressional basin settings. This final chapter aims to bring together all work on the controls on sedimentation and evolution of the basin that have been discussed so far, to draw conclusions, and determine the wider importance of this work.

This chapter begins with a summary and integration of the findings from all the separate parts of the basin, as discussed in the preceding chapters (section **10.2**). The wider implications of these findings for several different aspects of geological research are then detailed (section **10.3**), and comparisons are made with other case studies and geological systems (section **10.4**). Lastly, the conclusions of this study are stated (section **10.5**), and some suggestions for future work are given (section **10.6**).

10.2 Key findings from the Jaca Basin

This section summarises the key findings of this work, in four separate sub-sections. Each sub-section represents a particular area of geological research, and corresponds to one of the sub-sections in the Key Points section found at then end of chapters 4 – 9. The subsections focus on: the sedimentary infill of the basin (section **10.2.1**), the structural configuration of the basin (section **10.2.2**), the influence of intrabasinal growth structures (section **10.2.3**), and the effect of sea-level changes (section **10.2.4**). Lastly, section **10.2.5** summarises the key findings of this work.

10.2.1 Sedimentary infill of the basin

The syntectonic sediments of the Jaca Basin studied in this work belong to the Árguis Fm., the Belsué-Atarés Fm. and the Yeste-Arrés Fm., and were deposited in a diverse range of shallow marine depositional environments. The majority of the marine sands of the basin belong to the Belsué-Atarés Fm. and were transported by the Jaca

Basin axial deltaic system. This depositional system was fed by a number of sediment input points through the structurally defined basin margins, and prograded along the synclinal basin axis towards the WNW. The ubiquitous presence of exotic grain types in the sands of the Belsué-Atarés Fm., such as chloritised biotite, indicate that the Pyrenean axial zone contributed sediment to all parts of the Jaca Basin (Hirst & Nichols, 1986; Jones, 1997).

The deposition of syntectonic marine strata in the Jaca Basin began at 41.5 Ma (Pueyo *et al.*, 2002), when a regional rise in sea-level – the Biarritzian transgression – caused the drowning of the Guara Fm. carbonate platform (Puigdefàbregas, 1975; **Fig. 2.20**). In the SE corner of the basin, the Guara Fm. was rapidly overlain by the proximal delta front channelised sandstones (FA5) of the Belsué-Atarés Fm., whereas across the rest of the basin, offshore marine marls (FA1) of the Árguis Fm. formed (**Fig. 10.1**).

The basin continued to subside near continuously for its entire marine phase, which lasted for about 5 Myr (Hogan & Burbank 1996; Pueyo *et al.*, 2002). However, the subsidence rate was closely matched by the sediment accumulation rate, causing facies associations (depositional environments) to vertically aggrade. For example, in the SE corner of the basin, proximal delta front channelised sandstones (FA5) built up a near continuous 1000 m of thickness, whilst a similar amount of offshore marine marls (FA1) accumulated at the distal western end of the basin (**Fig. 10.1**).

At 37.5 Ma (Hogan & Burbank 1996; Pueyo *et al.*, 2002), the first major westward progradation of facies associations occurred, with a near instantaneous basinward shift of up to 12 km. At the same time, proximal delta front channelised sandstones were deposited for the first time in the northern basin margin area. At 37.2 Ma, a second major progradation occurred in the southern basin margin area, with facies associations shifting westwards once more by up to 15 km. This progradation was again seemingly near instantaneous, as proximal delta front channelised sandstones (FA5) were deposited directly on top of the offshore marine marls (FA1) at Bentué de Rasal (**Fig. 10.1**) with a non-erosional relationship. Also occurring at 37.2 Ma, the proximal delta front (FA5) environment of the northern basin margin area was superseded by fan delta front conglomerates (FA9) of the Santa Orosia fan delta.

The syntectonic marine infilling of the Jaca Basin ended at 36.6 Ma (Pueyo *et al.*, 2002), when the fluvial systems (FA11/FA12) of the Lower / Middle Campodarbe Fm. prograded rapidly across the basin (Jolley, 1987), and the Santa Orosia alluvial fan (FA10) evolved from the fan delta (**Fig. 10.1**).

10.2.2 Structural configuration of the basin

Because the Jaca Basin was an entirely marine basin at the time of deposition of the Belsué-Atarés Fm., it was unable to generate its own siliciclastic sediment. Therefore, the entry of external depositional systems into the basin would have been one of the principal controls on the distribution of siliciclastic facies associations. The entry of such systems would have been controlled by the basin margin topography, which was most probably strongly influenced by structural configuration of the basin margins. For this reason, emphasis was placed upon understanding the margins of the basin during the course of this work.

The northern margin of the Jaca Basin was defined by a series of WNW–ESE-trending thrusts and related folds during the deposition of the Belsué-Atarés Fm. (**Fig. 1.3**). The Belsué-Atarés Fm. is exposed along the 100 km length of this margin, and typically consists of distal marine and marginal marine facies associations, indicating a lack of a proximal siliciclastic supply (**Fig. 10.1**). Throughout the area, palaeocurrent indicators are dominated by NNE–SSW-directed wave-rippling, reflecting oscillatory marine currents that were directed against a WNW–ESE-orientated shoreline of uplifting basin margin structures (**Fig. 10.2**). It is evident that the northern margin structures were uplifting during the deposition of the Belsué-Atarés Fm. because the sediments thin markedly onto the flanks of some of the margin anticlines. However, two basinal sediment entry points existed through the northern margin during Belsué-Atarés Fm. times. Towards the eastern end of the margin, the conglomerates of the Santa Orosia fan delta, partly sourced in the Pyrenean axial zone, were transported into the basin (**Fig. 1.3**). The second entry point was at the very western end of the northern basin margin, where the sands of the Martes deltaic system, also partly sourced in the axial zone, flowed into the basin (**Fig. 1.3**).

The eastern margin of the Jaca Basin was defined by the 26-km-long, 4-km-across Boltaña anticline during Belsué-Atarés Fm. times (**Fig. 1.3**). This structure is thought to have acted like a barrier, preventing sediment being carried over its crest and into the Jaca Basin. Evidence for this comes from the fact that immediately to the west of the structure, the Belsué-Atarés Fm. is dominated by marls and clays rather than sands (**Fig. 10.1**). Other workers have shown that active uplift of the Boltaña anticline deflected depositional systems that operated to the east of the structure, in the Aínsa Basin, before (Sobrarbe Fm.; Jones, 1997; Dreyer *et al.*, 1999), during (Escanilla Fm.; Bentham *et al.*,

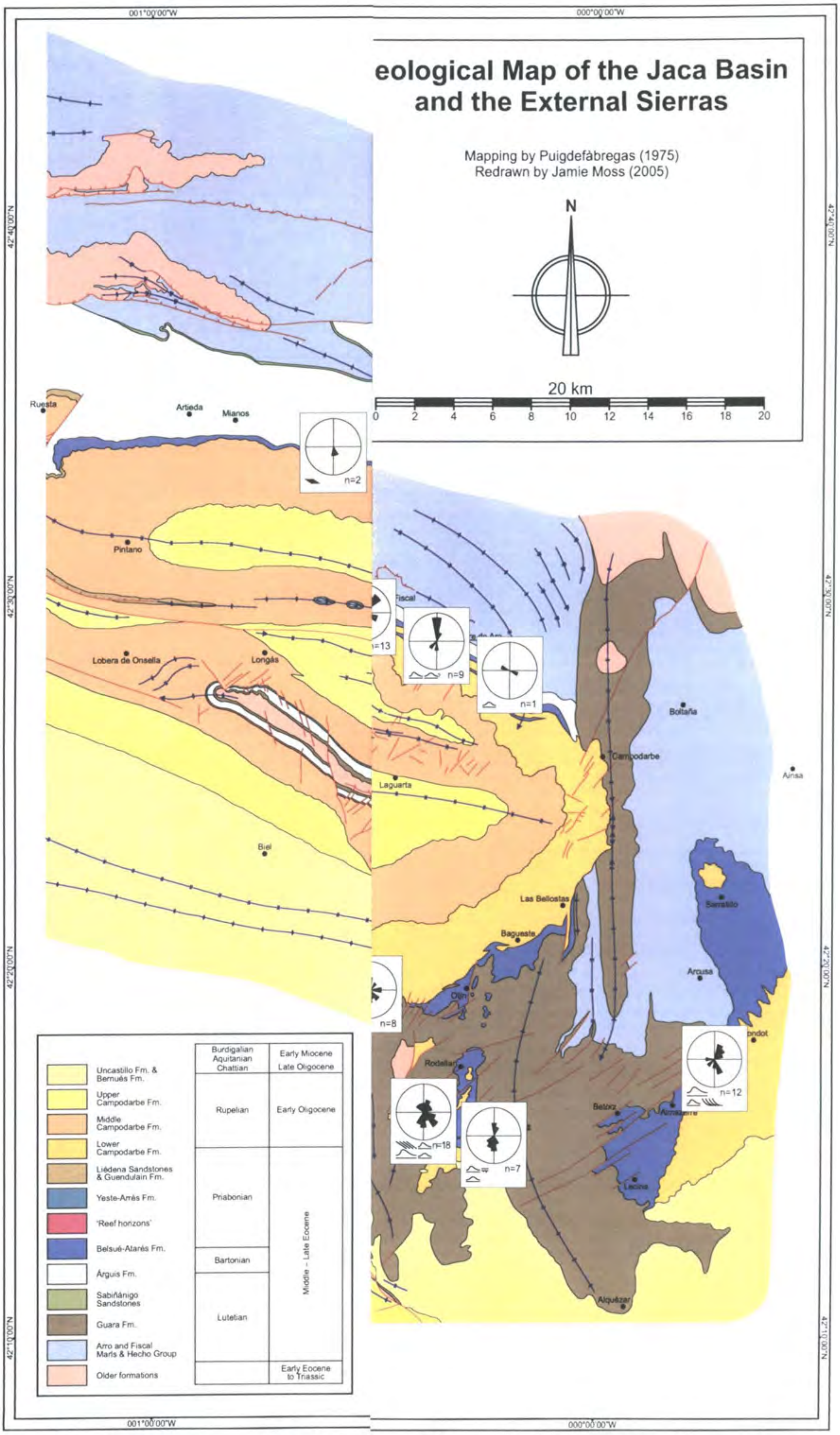


Fig. 10.2. Geological map of the Jaca Bm. and Yeste-Arrés Fm. Total readings = 553.

1992; Jones, 1997), and after (Lower Campodarbe Fm.; Jolley, 1987) the deposition of the Belsué-Atarés Fm.

Whilst the Belsué-Atarés Fm. was being deposited, the southern basin margin was defined by the WNW–ESE-orientated emergence of the Guarga thrust sheet (Anastasio & Holl, 2001), representing the south Pyrenean thrust front. The Belsué-Atarés Fm. thins markedly onto structures related to this frontal thrust, indicating a syntectonic relationship. Palaeocurrent indicators along the southern basin margin are strongly dominated by WNW–ESE-directed wave rippling (**Fig. 10.2**), which is thought to reflect marine oscillatory flow directed parallel to the synclinal basin axis. Along the western half of the southern basin margin area, the syntectonic marine sediments are dominated by marls rather than sands, indicating that external siliciclastic depositional systems did not cross the southern basin margin in that area.

At the eastern half of the southern basin margin area, however, the Belsué-Atarés Fm. is thicker, coarser grained, and contains a higher proportion of proximal facies associations than in any other part of the basin. This is because much of the sand of the Belsué-Atarés Fm. is inferred to have entered the basin at this point, via two, 2–3-km-wide, synclinal palaeovalleys through the thrust front. The more westerly of these is the Nocito palaeovalley, which is flanked by the Gabardiella and Nocito anticlines (**Fig. 1.3**). Approximately 14 km to the east is to Rodellar palaeovalley, flanked by the Alcanadre and Balces anticlines. Like all siliciclastic sediments in the Jaca Basin, the sand that was delivered through these palaeovalleys contains grains that could only have come from the Pyrenean axial zone (Hirst & Nichols, 1986; Jones, 1997). It is therefore thought that these sediments were delivered to the southern margin of the Jaca Basin by the southward-flowing Escanilla Fm. fluvial system of the Aínsa Basin to the east (Dreyer *et al.*, 1999), possibly via a northwards deflection by the south Pyrenean forebulge lying somewhere to the south.

Unlike the other three basin margins, the western end of the Jaca Basin was not delineated by a structurally controlled topographic high during Belsué-Atarés Fm. times. Instead, the basin is thought to have simply been open towards the Bay of Biscay in this direction.

To summarise, the configuration of the margins of the Jaca Basin exerted a very strong control on the distribution of facies associations within the basin, via a series of structural highs and lows that acted, respectively, as barriers and input points for external siliciclastic depositional systems.

10.2.3 Influence of intrabasinal growth structures

As well as the barrier effect exerted by the uplifting structurally defined basin margins, the depositional systems of the Belsué-Atarés Fm. were affected by a number of kilometre-scale, intrabasinal growth structures. These structures can be divided into two groups – those related to the northern basin margin, and those related to the southern basin margin (**Fig. 1.3**). A syntectonic relationship between each growth structure and the Belsué-Atarés Fm. was evident from the fact that the sediments thinned markedly onto the crests of the structures, sometimes down to as little as one-quarter of their thickness in the intervening synclines (**Fig. 10.1**).

The growth structures of the northern margin area consist of two anticlines that are directly related to the WNW–ESE-trending thrusts and folds of the northern basin margin itself (**Fig. 1.3**). The more easterly of the two, the Río Basa anticline, prevented the upper shoreface and delta front sandstones (FA4) of the Jaca Basin axial deltaic system from reaching marl dominated areas to the north of the structure for much of the Belsué-Atarés Fm. times (**Fig. 10.1**). It was only when the Santa Orosia fan delta began to deliver sediment into the basin, at 37.5 Ma (Hogan & Burbank, 1996), that depositional systems were able to pass across the crest of this structure. Approximately 24 km to the west, the Binacua anticline caused a drastic thinning of the Belsué-Atarés Fm. and carbonate ramp limestones (FA7) accumulated on its crestal area (**Fig. 10.1**).

The growth structures of the southern margin area consist of a series of eight, N–S-orientated anticlines that are related to the emergent Guarga thrust sheet (**Fig. 1.3**). These structures may have been formed by ramps on the thrust plane (Martínez-Peña *et al.*, 1995; Poblet & Hardy, 1995; Poblet *et al.*, 1998), then have been rotated, or may have been produced by halotectonics (Anastasio & Holl, 2001). Whichever is the case, the growing structures acted as barriers to the westward progradation of facies associations of the Belsué-Atarés Fm. (**Fig. 10.1**). Each of the major facies associations tended to vertically aggrade behind one of these N–S-orientated growth structures, with the more proximal environments being held back in the east, and the more distal ones being trapped further west. This situation was maintained during the accumulation of around 800 m of strata or about 4 Myr of time (Pueyo *et al.*, 2002), until a major progradational event simultaneously breached the crests of each of the growth structures at 37.5 Ma (Pueyo *et al.*, 2002). In addition to acting as barriers, localised carbonate ramp limestones (FA7) were deposited above the crests of the Pico del Águila and Bentué de Rasal anticlines (**Fig. 10.1**).

To summarise, the intrabasinal growth anticlines of the Jaca Basin exerted a very strong control on the distribution of facies associations within the basin, by acting as barriers to the perpendicular progradation of all siliciclastic facies associations and by causing reduced siliciclastic sedimentation and the deposition of carbonate units in the crestal areas.

10.2.4 Effect of sea-level changes

Not only was the progradation of facies associations in the Jaca Basin controlled by the intrabasinal growth structures, it was also affected by changes in relative sea-level. The evidence for this is the numerous, rapid lateral shifts in the positioning of facies associations within the syntectonic marine strata. In the far NE corner of the Jaca Basin, two progradational–retrogradational cycles in the position of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary (the palaeo-shoreline) were observed (**Fig. 10.1**). Each cycle involved around a 10 km shift in the position of the boundary, and was approximately 250 m thick, which is thought to correspond to a cycle repeat time (period) of the order of 1 Myr (Pueyo *et al.*, 2002). The progradation at the base of the second cycle seems to correlate westwards into a major facies association progradation in the region of the Santa Orosia fan delta (**Fig. 10.1**). This progradation involved the sudden arrival of proximal delta front channelised sandstones (FA5) in the area, and is thought to represent the first time that a major depositional system was able to pass over the crest of the Río Basa growth anticline. In addition to the 1-Myr-order stratigraphic cycles, also observed were a few smaller scale, higher order cyclic shifts in the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary. These had a thickness of around 25 m, which is thought to correspond to repeat times of the order of 100 kyr.

In the southern basin margin area, two progradational–retrogradational cycles in the lateral positioning of the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary were readily observed in the Nocito–Bara area (**Fig. 10.1**). Each cycle was 300 – 500 m thick, and so thought to have a repeat time of the order of 1 Myr (Pueyo *et al.*, 2002). The younger of the two cycles correlates westwards with a 1 – 12 km basinward progradation of all facies associations that occurred at 37.5 Ma (Pueyo *et al.*, 2002), and represents the first breaching of the crests of the N–S-orientated southern margin growth anticlines (**Fig. 10.1**). The progradation was followed by a 2 – 5 km facies association retrogradation that lasted for 0.3 Myr (Pueyo *et al.*, 2002). This was capped by a further, very rapid progradation that was responsible for depositing proximal delta front channelised sandstones (FA5) directly on top of offshore marine marls (FA1), with a non-erosional relationship, at Bentué de Rasal (**Fig. 10.1**). In addition to the 1-Myr-order stratigraphic cycles, a few smaller scale, higher order cycles in stratigraphy were observed in the Bara–Nocito area (**Fig. 10.1**). These cycles were laterally extensive and correlatable over 10 km, which is thought to be because of the lack of intervening growth anticlines. Laterally correlatable cycles of this order were not seen in the syntectonic marine strata from other parts of the southern basin margin area.

The rapid lateral shifts in facies associations (depositional environments) recorded in some parts of the basin are thought to have been caused by changes in relative sea-level, due to basin-wide subsidence / uplift events. Changes in eustatic sea-level are not thought to have been responsible, as the sea-level curves of Haq *et al.* (1987) do not show any rises or falls of sufficient magnitude during this time period (**Fig. 2.20**). Changes in climate or sediment supply are not thought to be responsible either, as these would be expected to have had a more gradual effect on the stratigraphy, yet some of the progradations were apparently almost instantaneous. The major facies association progradation at 37.5 Ma, which for the first time breached the crests of many of the growth structures in both the northern and southern basin margin areas (the Bentué de Rasal, Pico del Águila, Gabardiella and Río Basa anticlines), is also believed to have been due to a fall in relative sea-level. This event is not thought to have been caused by a cessation of anticline uplift because facies associations that were not directly abutting against growth folds were also affected – for example, the Belsué-Atarés Fm.–Lower Campodarbe Fm. boundary at the eastern end of the basin, in the vicinity of the villages of Lardiés on the northern margin and Bara on the southern margin (**Fig. 10.1**).

To summarise, relative sea-level changes in the Jaca Basin were caused by basin-wide uplift and subsidence events, and exerted a strong control on the distribution of facies associations, producing rapid shifts in their lateral positions.

10.2.5 Summary of the key findings

This work on the syntectonic marine sediments of the Jaca Basin has shown that:

- Local tectonic factors were the principal control on the distribution of facies associations (depositional environments); they included:
    - The structural configuration of the basin margins, which acted as barriers to extrabasinal depositional systems or provided basinal sediment input points.

  - Intrabasinal growth structures, which acted as barriers to the progradation of sediment once it had entered the basin.
- Relative sea-level changes were relegated to a second-order level of control, although they did cause rapid, kilometre-scale shifts in facies associations.

10.3 Implications of key findings

The key findings of this work, summarised above, have considerable implications for the study of marine growth strata and the infill of thrust-top basins. Although attempts to document the controls on stratigraphic cycles in the syntectonic marine infill of thrust-top basins are rarely documented in the published literature, those studies that have endeavoured to do this have placed their syntectonic strata into sequence stratigraphic frameworks (Millán *et al.*, 1994; Dreyer *et al.*, 1999; Castelltort *et al.*, 2003). However, this work has shown that, in this thrust-top basin, sediment input points and intrabasinal growth structures were the principal controls on the lateral distribution of facies associations through time (sequence development), and that relative sea-level was relegated to a second-order level of control. For this reason, conventional passive margin sequence stratigraphic concepts, in which relative sea-level is the primary control on sequence development (Van Wagoner *et al.*, 1988), should not be applied to syntectonic strata in other thrust-top basins without prior consideration of potential structural controls on deposition. These ideas could be of great importance for hydrocarbon exploration in thrust-top basins or in reservoir rocks deposited across marine growth structures.

However, this work has also demonstrated that the marine infill of a thrust-top basin may be so complex and 'three dimensional' that it could be almost impossible to erect a detailed sequence stratigraphic model that takes proper account of all sediment input points and intrabasinal growth structures. In the future, numerical modelling similar to that of Clevis *et al.* (2004) may be of great assistance in dealing with complicated geological situations like that of the Jaca Basin.

This work has shown that the nature and geometry of the syntectonic strata of the Jaca Basin varied enormously across each of the growth structures. For example, the eastern flank of the Pico del Águila anticline (**Fig. 1.3**) largely consists of well bedded sandstones (**Fig. 10.1**), with limestones and marly sandstones on the crest, and monotonous, poorly bedded marls on the western flank. Lateral variations in the syntectonic strata such as these should be an important consideration to those workers who wish to reconstruct the kinematics of growth structures from the syntectonic strata that surround them (Poblet & Hardy, 1995; Masaferro *et al.*, 2002; Casas-Sainz *et al.*, 2002; Gawthorpe & Hardy, 2002; Salvini & Storti, 2002; Rafini & Mercier, 2002). Many such studies make assumptions about the invariance of sedimentary processes operating across growing structures that this work has demonstrated to be overly simplistic.

In conclusion, this work has shown how the distribution of facies associations in an actively evolving thrust-top basin may be complex and essentially unpredictable using conventional wisdom. However, some new ideas as to what the principal controls on the facies associations were have been presented. These will be of great relevance to any work that aims to understand the nature of marine growth strata or the infill of active thrust-top basins.

10.4 Comparisons to analogous geological systems

Aside from examples from the other south Pyrenean thrust-top basins (e.g. De Boer *et al.*, 1991; Dreyer *et al.*, 1999; López-Blanco *et al.*, 2003), in the published literature there are no known examples of shallow marine depositional systems that have been directly affected by intrabasinal compressive growth structures. Virtually all studies into syntectonic marine strata describe situations where ongoing tectonic activity within the structures of the margins of a basin gave rise to cyclic activity within the basinal depositional system, often a fan delta (e.g. Marzo & Anadón, 1988; Boorsma, 1992; López-Blanco, 1993; Dorsey *et al.*, 1995; Burns *et al.*, 1997; López-Blanco *et al.*, 2000; Marzo & Steel, 2000; Benvenuti, 2003; Sohn & Son, 2004). Many of these studies use cycles within the stratigraphy to study the tectonic evolution of the basin margins and assess the relative importance of sea-level controls (Clevis *et al.*, 2004, and references therein).

One exception to this is the work of Ferguson & McClay (1997) and McClay *et al.* (2000) into the Mahakam fold belt and delta of Borneo, Indonesia. The key aspects of this area, and its similarities and differences with the Jaca Basin system, are discussed in section **10.4.1**. Section **10.4.2** describes the comparatively well-understood controls that intrabasinal compressive growth structures may have on fluvial depositional systems – and what ideas can be applied from this research to that on shallow marine systems.

10.4.1 Growth folds of the Mahakam delta

Ferguson & McClay (1997) and McClay *et al.* (2000) studied the Mahakam fold belt and associated Mahakam delta of the Kutai Basin, Borneo, Indonesia (**Fig. 10.3A**). Since the Miocene, the Mahakam delta has prograded across the evolving fold belt, and continues to do so to the present day (**Fig. 10.3B–C**). The authors used interpretations of a large quantity of seismic and borehole data from across the ancient deposits of the delta to propose a new model for the structural and stratigraphic evolution of the area (**Fig. 10.3C**). Cross-sections were constructed, balanced and sequentially restored, and scaled physical modelling was undertaken.

The Mahakam fold belt consists of a number of long, linear, asymmetric, thrust-fault bounded detachment anticlines, which are 2 – 5 km wide and separated by broad, open synclines (**Fig. 10.3C**). In this way, they are quite similar to the N–S-orientated anticlines of the External Sierras in the Jaca Basin. The Mahakam delta prograded in a direction perpendicular to the orientation of the crests of the structures, much like the Belsué-Atarés Fm. deltas did in the Jaca Basin. Furthermore, and again like the Jaca Basin, the deformation that created the anticlines propagated in the same direction as the sediment progradation, over time.

However, unlike the External Sierras area of the Jaca Basin, McClay *et al.* (2000) were able to demonstrate that the progradation of the wedge of siliciclastic sediments of the Mahakam delta strongly affected the deformation of the underlying basement, contributing to the development of the anticlines. It was found that the differential loading by the prograding siliciclastic wedge caused movement in a substrate of mobile shales, forming a series of up-dip extensional faults. When the area was subjected to regional tectonic compression, the extensional faults were reactivated as reverse faults, producing a series of detached uplift anticlines that affected the ongoing progradation of the delta. Although a similar model has been proposed for the Jaca Basin by Anastasio & Holl (2001), this has largely been ignored in subsequent work by authors who believe that the basement in the External Sierras did not contain sufficient mobile deposits to have been deformed in this way.

Unfortunately, McClay *et al.* (2000) did not look at the affects that the growing structures had upon distribution of facies associations within the Mahakam delta. However, Ferguson & McClay (2000) did study the delta top fluvial channel sandstones of the ancient delta deposits, and found that their paths had been deflected by the uplifting anticlines, towards structural low points.

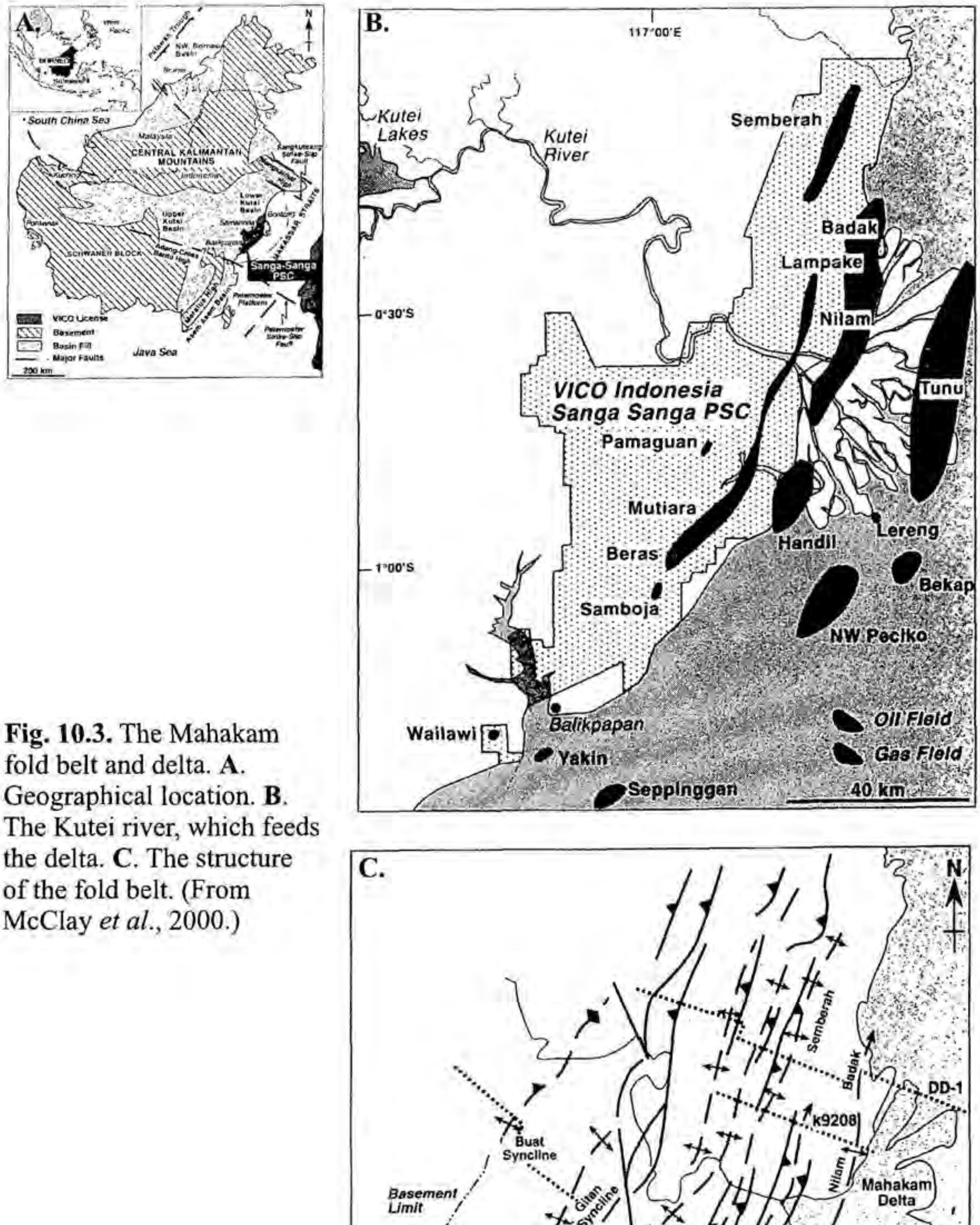


Fig. 10.3. The Mahakam fold belt and delta. **A**. Geographical location. **B**. The Kutei river, which feeds the delta. **C**. The structure of the fold belt. (From McClay *et al.*, 2000.)

In conclusion, although the work of McClay *et al.* (2000) and Ferguson & McClay (1997) did not look in detail at the structural controls on the deltaic facies associations, it did however show that the interaction between a marine depositional system and a growing structure may operate in both directions – that the sedimentation may affect the development of the structures. This important result has largely been forgotten about in recent work on the Jaca Basin.

10.4.2 Growth structures and fluvial systems

The effects that growing intrabasinal compressive structures have on fluvial systems are much better covered in the literature than for shallow marine or deltaic systems (e.g. Jolley *et al.*, 1990; Burbank *et al.*, 1996; Simpson, 2004; Ghassemi, 2005). It may be possible to draw an analogy between the effects that growing structures have on rivers and that which they have on deltas, as both situations involve a depositional system that is sensitive to topography. However, in order to do this it is necessary to only consider rivers that cannot erode through uplifting structures in their path (for example, because the uplift rate it too great), as marine depositional systems in areas of net sediment accumulation will not have any significant erosive power.

Jones (2004) summarised a number of ways in which a non-erosive fluvial system may react to the uplift of a structure and the development of positive topographic relief across its path (**Fig. 10.4**). In the simplest case, where a river meets an uplifting structure at a perpendicular angle, the river will tend to flow parallel to the trend of the structure until it reaches the tip point, whereupon it may resume its original course (**Fig. 10.4A**). However, if the river drains in a direction that is parallel to the trend of the uplifting structure, then its course may not be affected (**Fig. 10.4E**). Where two or more structures meet and interfere with one another, a structural low point may be created and exploited by the course of the river (**Fig. 10.4B–D**). Jones (2004) went on to point out that growing structures deflecting river systems may have an important effect on the stratigraphy of a depositional basin, especially if the structures responsible are large and the deflection is of the order of tens of kilometres.

The importance of the work summarised by Jones (2004) for the syntectonic marine sediments of the Jaca Basin lies not only in the fact that a non-erosive depositional system will be deflected by uplifting structures in their path, but in emphasising the importance of the three-dimensional nature of the geological situation. For instance, once a river has been deflected by a growing structure, it may or may not

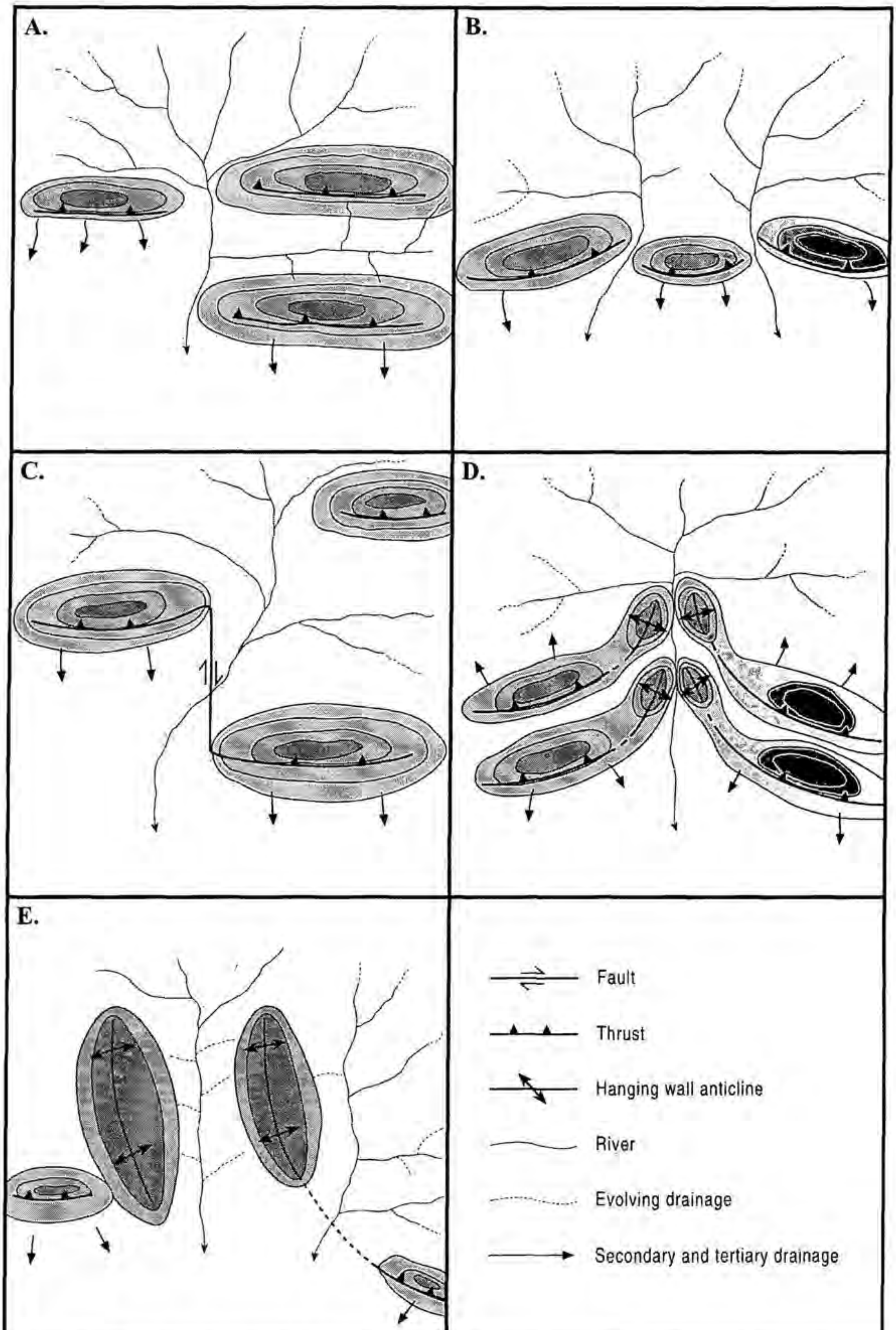


Fig. 10.4. The ways in which a non-erosive river may respond to the uplift of geological structures across its course. For a detailed explanation, see text. (From Jones, 2004.)

resume its original course when the tip point is passed, or may be captured by any structural low points encountered along the way. The three-dimensional nature of the N–S-anticlines of the External Sierras has not been given any consideration in previous interpretations of the area (Millán *et al.*, 1994; Castelltort *et al.*, 2003). For example, it is not known how the anticlines pass northwards towards the centre of the basin (**Fig. 1.1**), where the tip points are, and whether the deflected Belsué-Atarés Fm. was able to resume its otherwise blocked westward progradation at some point. Whilst the linear nature of the Belsué-Atarés Fm. outcrops in the Jaca Basin make attaining a three-dimensional understanding difficult, this does not mean that the third dimension can be ignored in geological models.

10.5 Conclusions

This work provides a detailed account of the tectonic controls on shallow marine sedimentation in an active thrust-top basin – a subject matter that has only very rarely been addressed in the published literature. The Jaca Basin became a discrete thrust-top basin in the late Lutetian (Middle Eocene) with the emergence of the Guarga thrust sheet, upon which the basin is detached. From 41.5 Ma, the distal (western) portions of the basin were infilled with the offshore marine marls of the Árguis Fm., whilst the sands of the Belsué-Atarés Fm. deltaic system were being deposited in the eastern portions of the basin. Ongoing southwards displacement on the Guarga thrust sheet caused numerous, variously orientated, kilometre-scale compressional growth structures to form within and along the margins of the basin whilst the marine sedimentation was occurring. The effect that the growth of these structures had on the marine depositional processes is the subject matter of this work.

With the exception of the western basin margin, all the margins of the Jaca Basin were defined by tectonic structures during Belsué-Atarés Fm. times: the northern margin was formed by WNW–ESE-trending thrusts and related folds; the eastern margin was marked by the kilometre-scale thrust-related Boltaña anticline; and the southern margin was delineated by the emergent front of the Guarga thrust sheet. Each of these structures was actively uplifting during Belsué-Atarés Fm. times, and so the basin margins tended to act as barriers, preventing external depositional systems from entering. However, two synclines through the southern margin (the Nocito and Rodellar palaeovalleys) and structural low points of uncertain origin through the northern margin (Martes and Santa Orosia systems) allowed sands and conglomerates sourced from the

Pyrenean axial zone to enter the basin. Because the Jaca Basin was an entirely marine basin and unable to generate its own siliciclastic sediment, the entry of external sand- and pebble-bearing depositional systems had profound effect on the style of sedimentation in the basin.

Once in the basin, the transport and deposition of the externally sourced sands was strongly affected by a number of kilometre-scale growth anticlines. The uplift of each of these structures tended to deflect siliciclastic sediments, blocking the progradation of depositional systems across the structures, and favouring reduced sediment accumulation and carbonate formation on the uplifting crestal areas. The growth folds of the northern basin margin area were related to the WNW–ESE-trending margin defining structures, and prevented the sands of the Jaca Basin axial deltaic system from reaching the marl dominated areas at the very northern edge of the basin. The growth folds of the southern basin margin area were related to the underlying Guarga thrust and were oriented N–S, so prevented the westward progradation of the various depositional environments of the Jaca Basin axial deltaic system.

The first time that basin-wide relative sea-level changes had a profound affect on the stratigraphy across the Jaca Basin was at 37.5 Ma, and was caused by a basin-wide uplift event. The resulting fall in relative sea-level allowed each of the depositional environments of the axial deltaic system that had previously been prevented from prograding, to breach the crests of the barrier anticlines and shift basinward by up to 12 km. Within the syntectonic strata, another two basin-wide progradational events were identified, and between them, periods of retrogradation. These basin-wide progradational–retrogradational cycles involved several hundreds of metres of thickness of strata, and so had repeat times of the order of 1 Myr. In areas away from the growth structures, cycles in the stratigraphy of tens of metres of thickness were also observed. These had repeat times of the order of 100 kyr, and were laterally extensive for up to 10 km. Importantly however, these higher order cycles could not be traced through the syntectonic strata that was directly affected by the growth anticlines.

This work has therefore shown that the primary controls on the distribution of marine depositional environments in the Jaca thrust-top basin were the growing tectonic structures – both of the basin margins, and intrabasinal. The effects of relative sea-level changes, although sometimes very significant, were relegated to a second order level of control. For this reason, it is inappropriate to try to place the infill of thrust-top basins such as the Jaca Basin into a conventional sequence stratigraphic framework. Perhaps only numerical modelling work will be able to take account of the various controls and three-dimensional complexities of these types of situations.

The finding of this study will be of relevance to workers operating in a number of different areas of geological research, such as: those who study basin dynamics, and wish to understand the controls on sedimentation in thrust-top settings; hydrocarbon exploration geologists, who aim to predict the distribution and quality of sands in compressional basins; and structural geologists, who use the geometry of syntectonic strata to reconstruct the kinematics of growth structures.

10.6 Suggestions for future work

During the course of this project, a number of unstudied aspects of the syntectonic marine strata of the Jaca Basin have become apparent, and a number of questions further to the original aims of this work have arisen. These are detailed below, in an approximate order of increasing work required and/or difficulty in addressing them:

- Some of the most inaccessible and/or poorly exposed outcrops of the Belsué-Atarés Fm. were not studied during the course of this work (**Fig. 1.2**). Of these, the area that would probably have been the most useful to visit is the remote region to the east of Bara and the north of the Rodellar palaeovalley, in the SE corner of the basin. This area could help further the understanding of the role of the Rodellar palaeovalley as a major basinal sediment input point. Other potentially useful unstudied places to visit are the poorly exposed area around the Rasal anticline, which is the westernmost of the N–S-orientated growth anticlines of the External Sierras (**Fig. 1.3**), and the heavily wooded area to the west of Martes deltaic system at the western end of the northern basin margin.
- As was done in the better-exposed southern basin margin area, it would be useful to log the full thickness of the Árguis Fm. along the northern basin margin. This could help identify the initiation of uplift in the northern margin growth anticlines, and better constrain the changes in thickness and facies associations across the structures.
- This work has emphasised the importance of sediment entry points through the structurally defined basin margins. Although the southern margin entry points are known to have formed as synclines between growth anticlines trending perpendicular to the thrust front, the reason for the existence of the northern margin

entry points is unknown. To add to the understanding of this margin, future work could use detailed mapping and structural analysis to determine why the northern entry points are located where they are.

- This work took the important step of integrating study of the evolution of the Aínsa Basin, which is considered to have existed 'further up' the south Pyrenean axial sediment dispersal system, with that on the Jaca Basin. Because of the linkages of this sort between the these two basins, and indeed between all the south Pyrenean thrust-top and foreland basins, it would be beneficial if future work also had a broader scope, rather than focusing on just one of the thrust-top basins.
- One of the key aspects of this work was determining how the sediments of the Belsué-Atarés Fm. entered the basin, which is partly dependant on where the sediments originally came from. Because of this, future work would benefit from a better identification of the detrital grains that make up the Belsué-Atarés Fm. sands, perhaps tracing them back to particular parts of the Pyrenean axial zone or other source areas.
- In order to increase the confidence in the correlations between adjacent logs, from which many of the controlling effects of the growth structures have been deduced, it would be very useful to supplement the existing palaeomagnetic dating (Hogan & Burbank, 1996; Pueyo *et al.*, 2002). Such work could lead to the positive identification of key, chronostratigraphic surfaces in the parts of the basin that are not subdivided by the major growth structures. If this proved possible, then the first properly constrained sequence stratigraphic interpretation of the marine syntectonic strata could be undertaken.
- Clevis *et al.* (2004) demonstrated the value of three-dimensional stratigraphic forward numerical modelling for predicting the infill of a foreland basin being subjected to fluctuating sea-level and tectonic activity. Although the Clevis *et al.* (2004) model contained a number of sediment input points and axial (deltaic) and transverse (alluvial fan) depositional systems, like the Jaca Basin, it did not however feature intrabasinal growth structures such as those studied in this work. Therefore, an obvious area for future work would be to extend the numerical modelling of Clevis *et al.* (2004) to include variously orientated, kilometre-scale growth anticlines, to see what effect they had on the synthetic stratigraphy and what the primary controls on sequence development were.
- When extending the numerical modelling of Clevis *et al.* (2004), it would be advantageous if the new models also took account of the effect that the load exerted

by a prograding siliciclastic wedge may have on the growth of structures that it is prograding over, as indicated may happen by McClay *et al.* (2000).

- As mentioned above, because of the approximately linear nature of the outcrops of the Belsué-Atarés Fm. in the Jaca Basin, the three-dimensional aspects of the geological situation during Belsué-Atarés Fm. times are poorly understood. For example, it is not known how far the growth structures of the External Sierras extend towards the basin centre, or whether there were in fact other growth structures in the middle of the basin. The Belsué-Atarés Fm. is buried beneath the Campodarbe Group across much of the basin (**Fig. 1.1**), so the best way to study its three-dimensional nature and search for further growth structures would be to shoot a 3D seismic survey across the basin. It would also be useful to drill boreholes and collect core from the buried Belsué-Atarés Fm. in order to find out the distribution of facies associations within it.
- Finally, in order to increase the understanding of the effects that intrabasinal compressional growth structures may have on shallow marine depositional systems, it would be very useful to find and study other examples from across the globe (in addition to the other south Pyrenean examples). As described above, the Mahakam fold belt and delta would be an ideal place for further investigation as that system has many similarities with the External Sierras and the Belsué-Atarés Fm.

It is hoped that this work on the Belsué-Atarés Fm. of the Jaca Basin has contributed to the general understanding of marine thrust-top basins and tectonic controls on sedimentation, especially the role of structurally defined basin margins and intrabasinal growth structures, and will aid further research in these areas.

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Appendix I:
Key Figures

Appendix I: Key Figures

This appendix contains the most important figures of this thesis, presented in ascending numerical order. They are unbound so that they may be easily referred to at any point, and compared with one another. In the main text, these figures are denoted by being **underlined**.

Contents

Facies association cross-section for the Southern and SE Jaca Basin

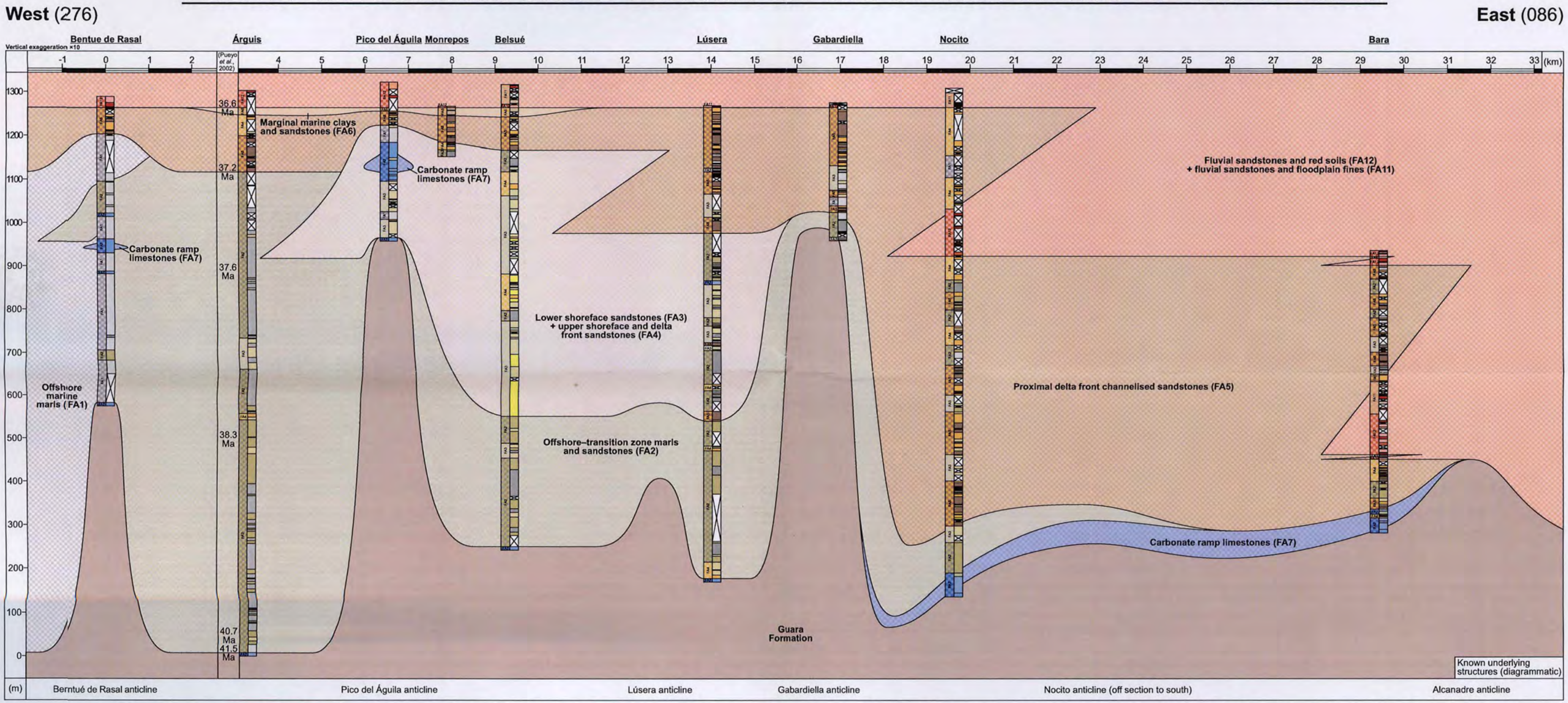

Fig. 9.16. A vertical cross-section depicting the dominant facies associations (depositional environments) for the Southern and SE Jaca Basin sectors. The correlation is diagrammatic, and the boundaries depicted only represent changes in depositional environment, so are not necessarily key surfaces or isochrons. Includes palaeomagnetic dates from Pueyo *et al.* (2002). Section has a 10° clockwise kink between the Lúsera and Gabardiella logs. A horizontal scale is given along the top of the figure, and the vertical exaggeration ×10.

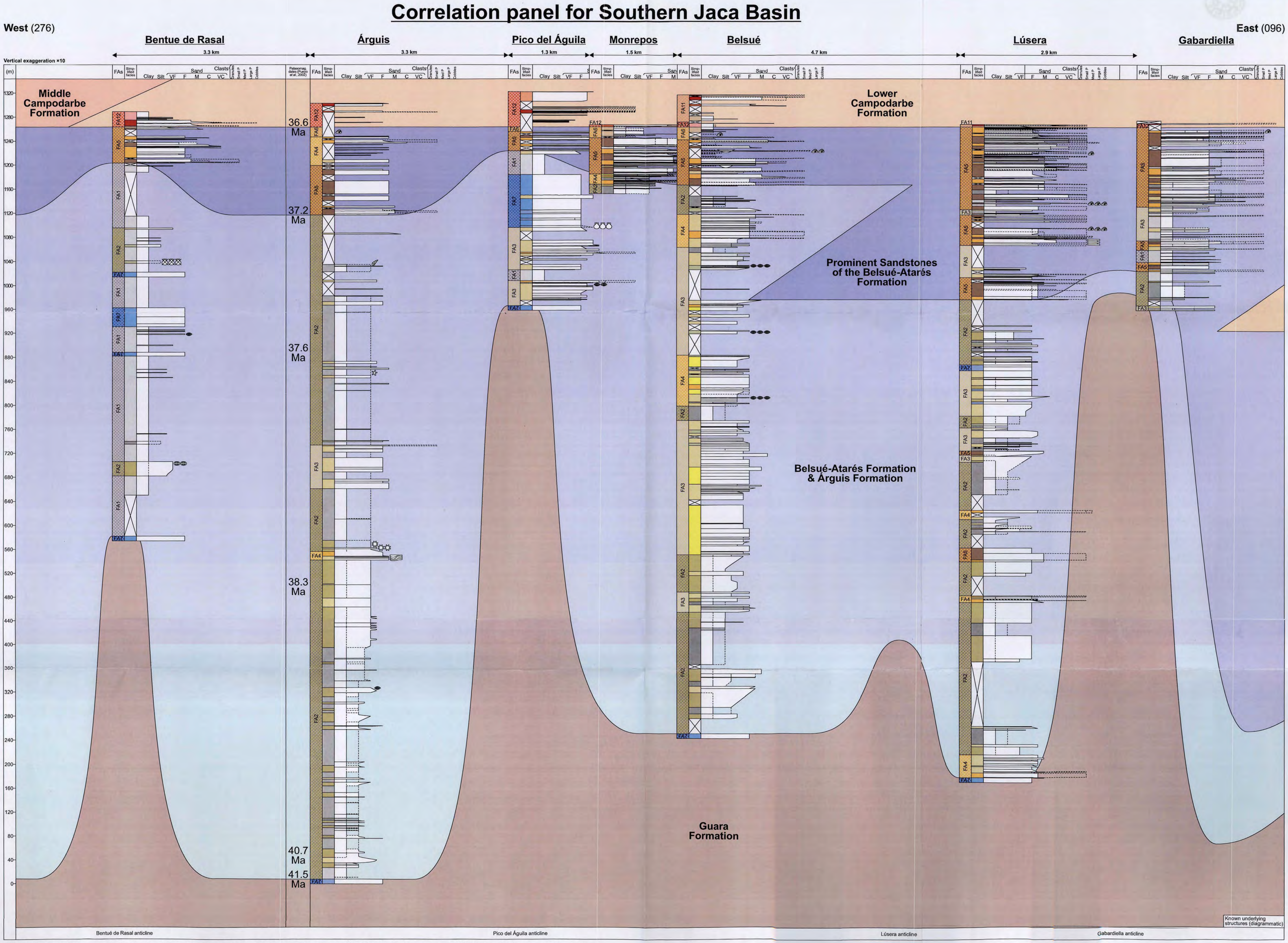

Fig. 9.15. Correlation panel for the Southern Jaca Basin sector. Includes palaeomagnetic dates from Pueyo *et al.* (2002). Vertical exaggeration ×10.

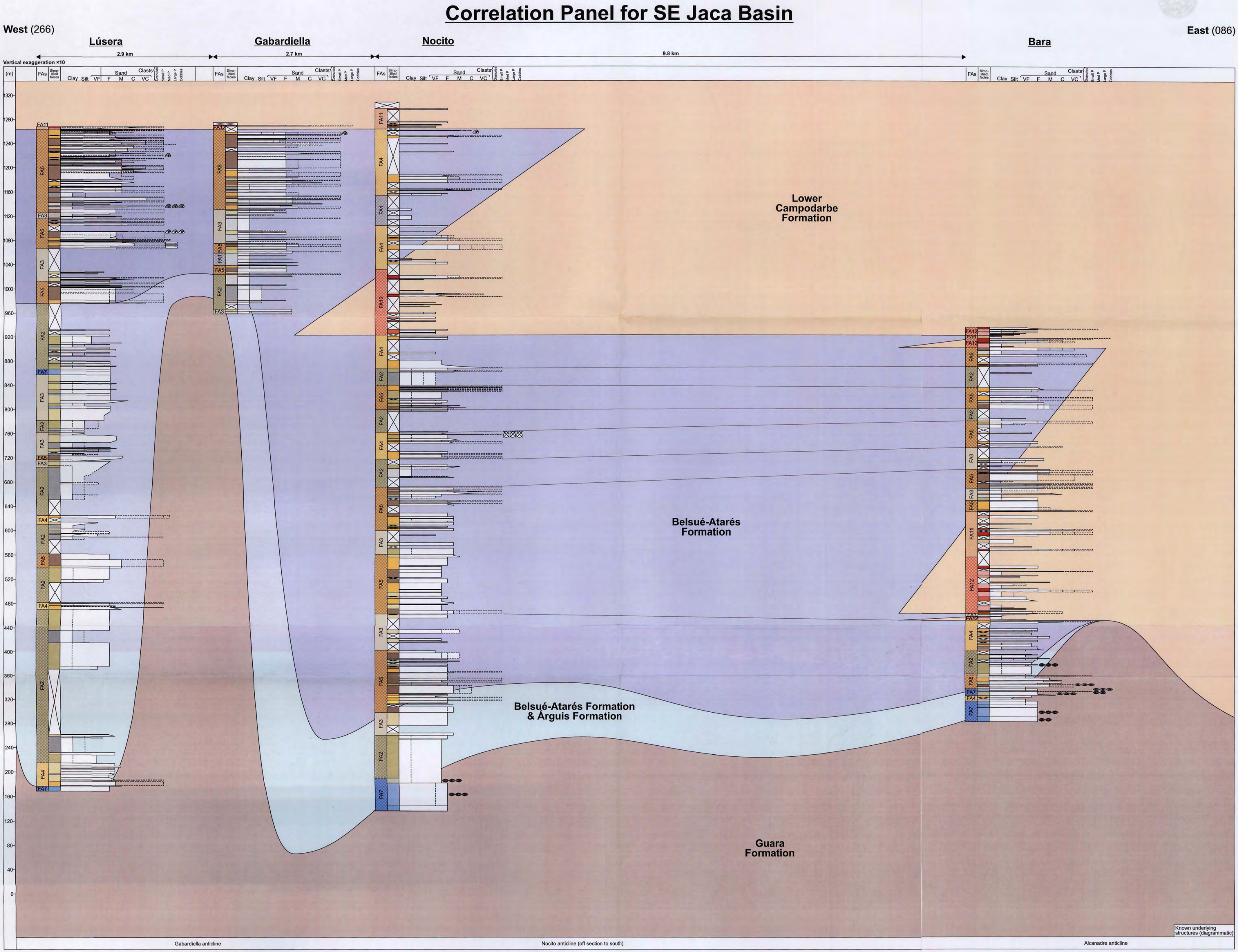

Fig. 8.10. Correlation panel for the SE Jaca Basin sector. Vertical exaggeration ×10.

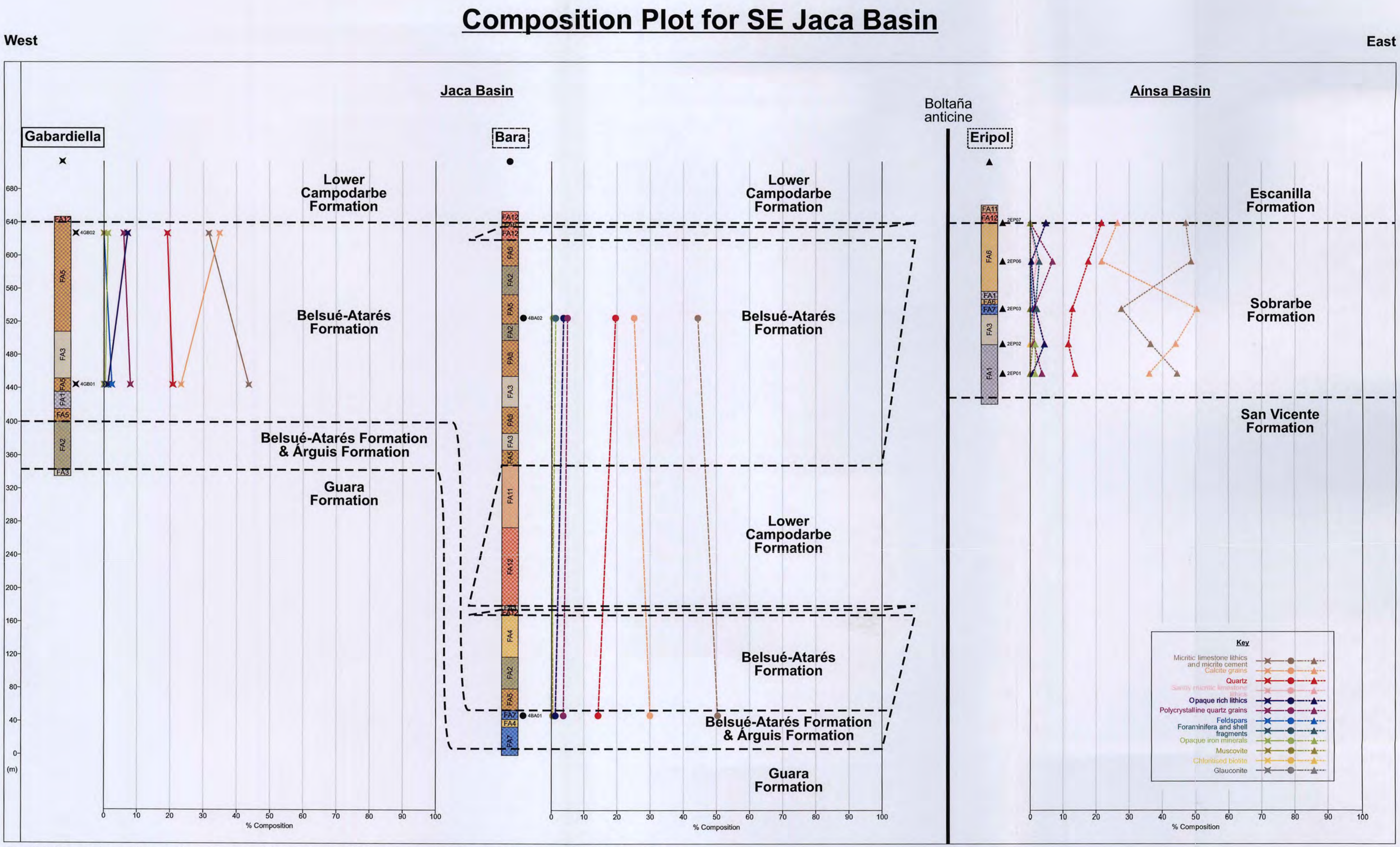

Fig. 8.8. Comparison of the sediment compositions at Gabardiella, Bara (both of the Jaca Basin), and Eripol (Aínsa Basin).

Fig. 7.5. Correlation panel 1 for the Western Jaca Basin sector, covering logs from the northern basin margin. Also included is the Bernués log from the Northern Jaca Basin sector (Chapter 6). Vertical exaggeration ×10.

Fig. 7.6. Correlation panel 2 for the Western Jaca Basin sector, covering logs from the southern basin margin. The logs on this panel are in their correct horizontal positions relative to the logs on correlation panel 1. Includes palaeomagnetic dates from Hogan & Burbank (1996). Vertical exaggeration ×10.

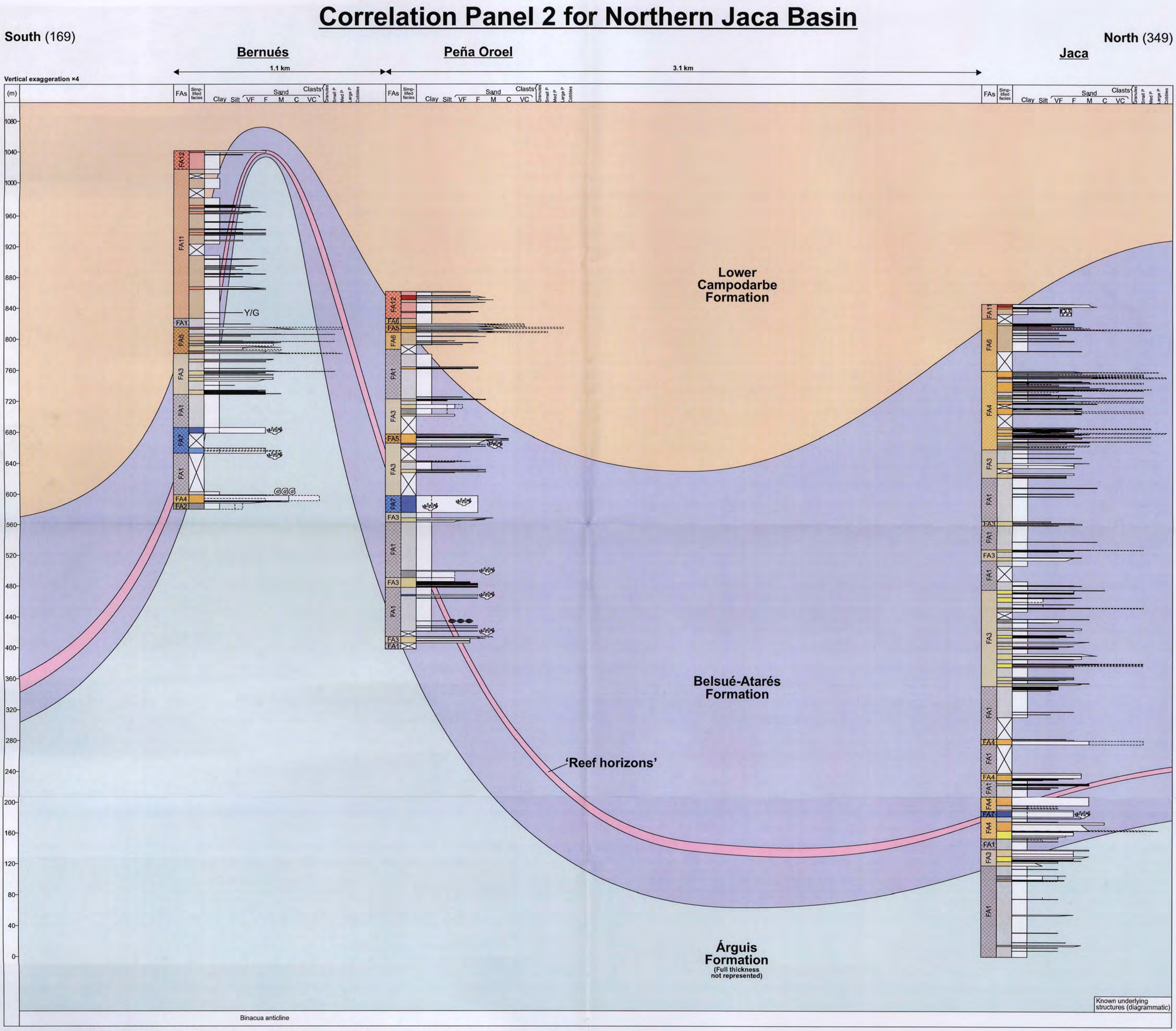

Fig. 6.5. Correlation panel 2 for the Northern Jaca Basin sector. Note the reduced vertical exaggeration of ×4.

Correlation Panel 1 for Northern Jaca Basin

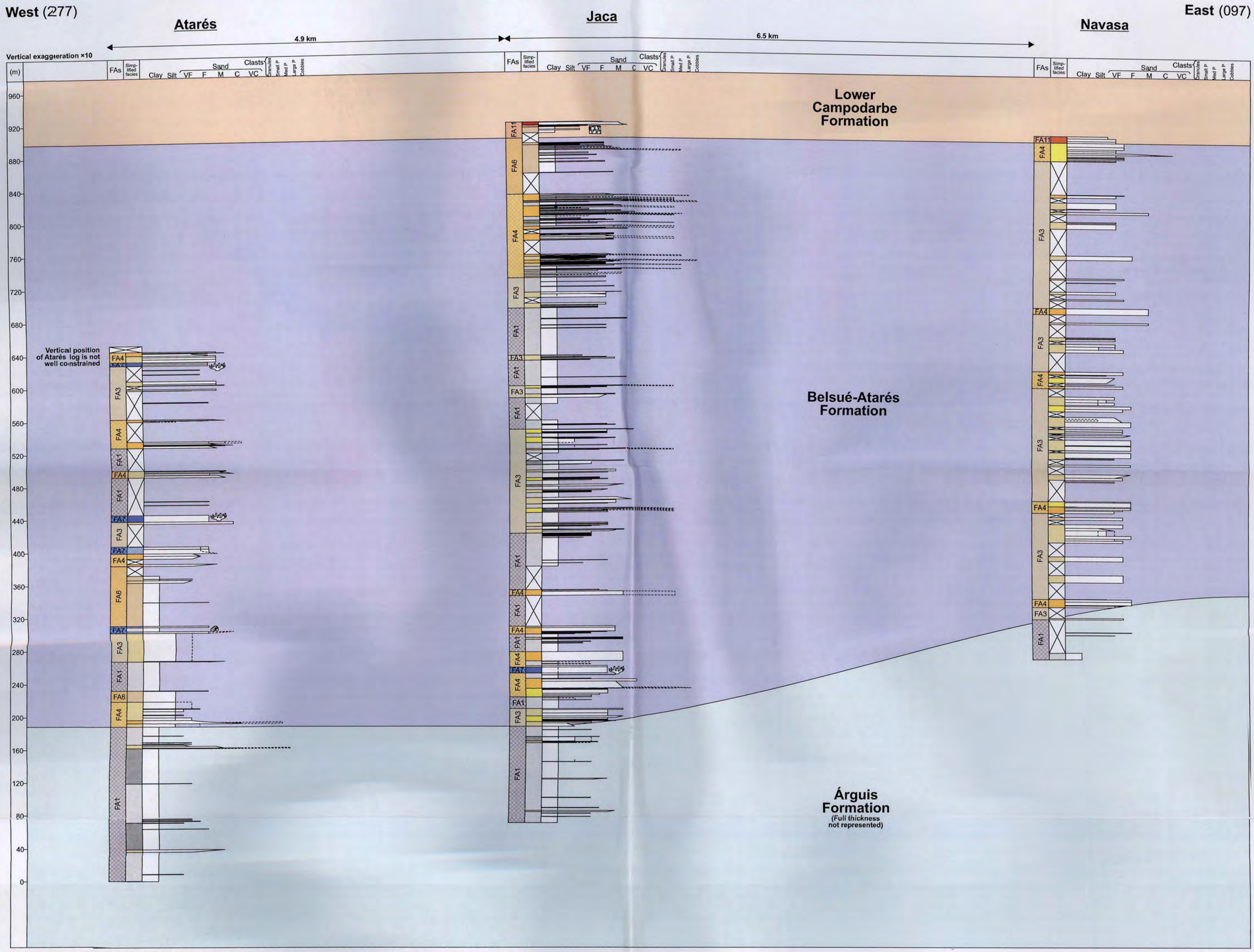

Fig. 6.4. Correlation panel 1 for the Northern Jaca Basin sector. Vertical exaggeration ×10.

Composition Plot for Northern Jaca Basin

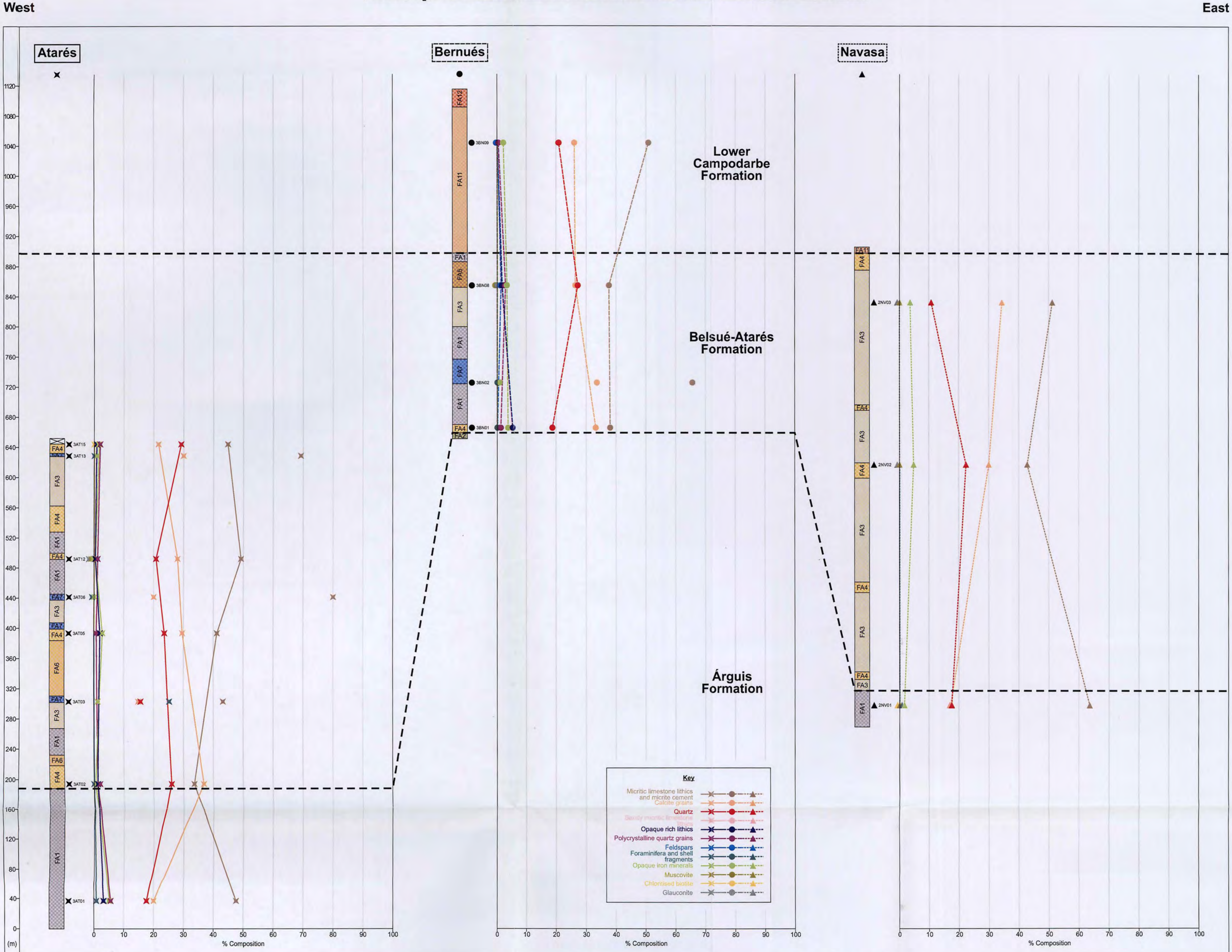

Fig. 6.3. Comparison of the sediment compositions at Atarés and Navasa, which lie to the north of the Binacua anticline, and Bernués, which lies to the south. Data from some limestone beds has also been plotted.

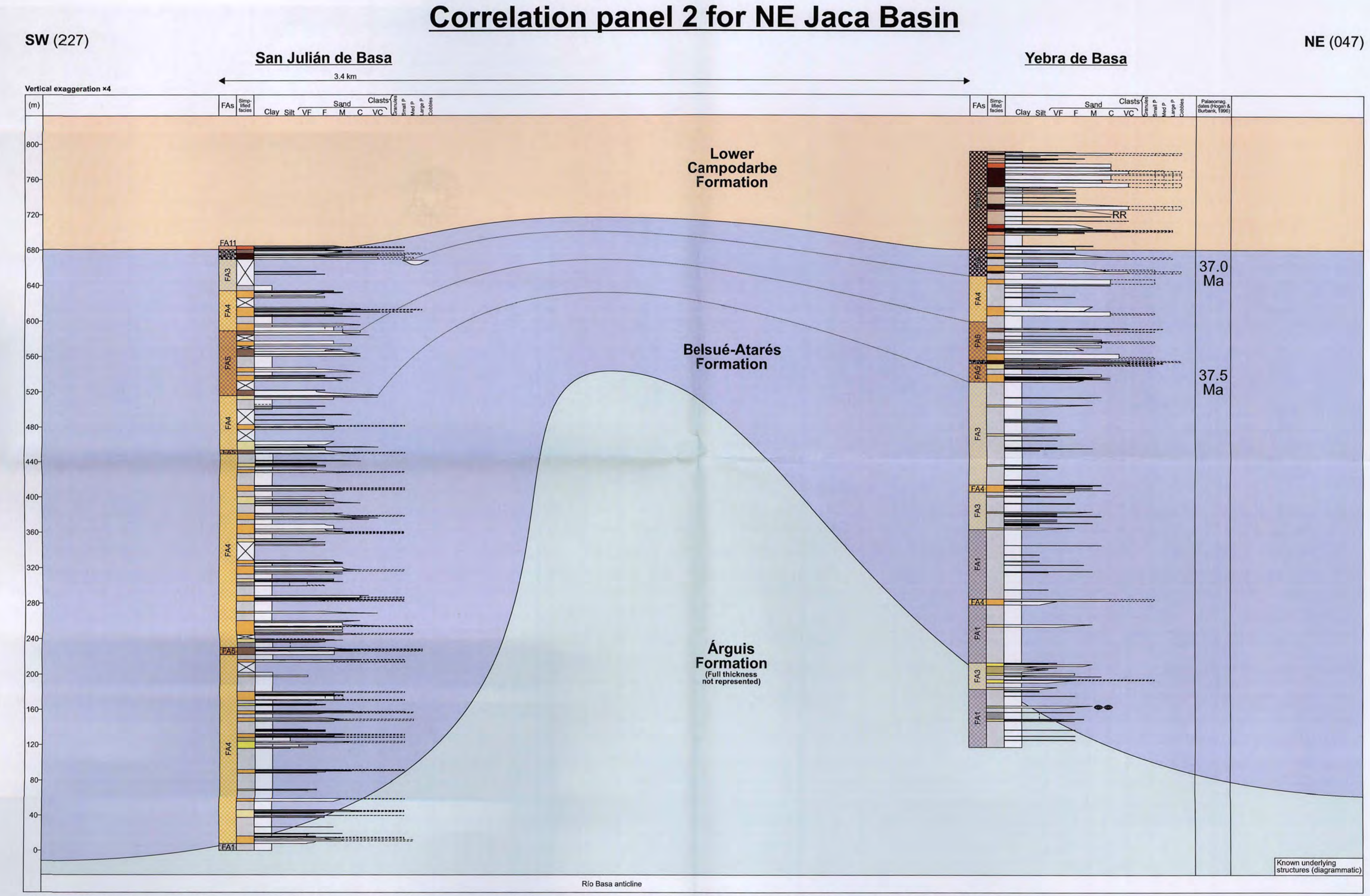

Fig. 5.9. Correlation panel 2 for the NE Jaca Basin sector. Includes palaeomagnetic dates from Hogan & Burbank (1996). Note the reduced vertical exaggeration of ×4.

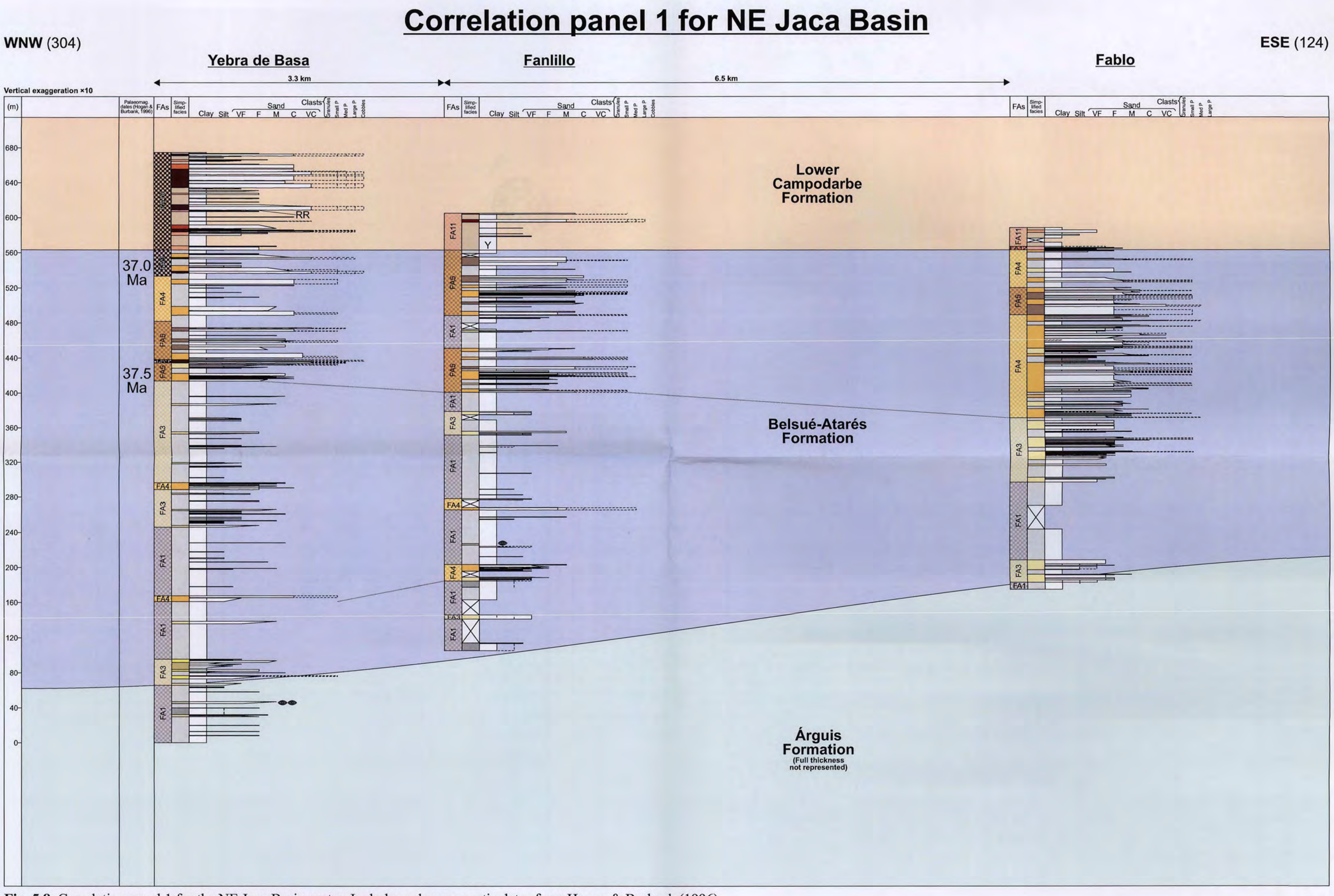

Fig. 5.8. Correlation panel 1 for the NE Jaca Basin sector. Includes palaeomagnetic dates from Hogan & Burbank (1996).

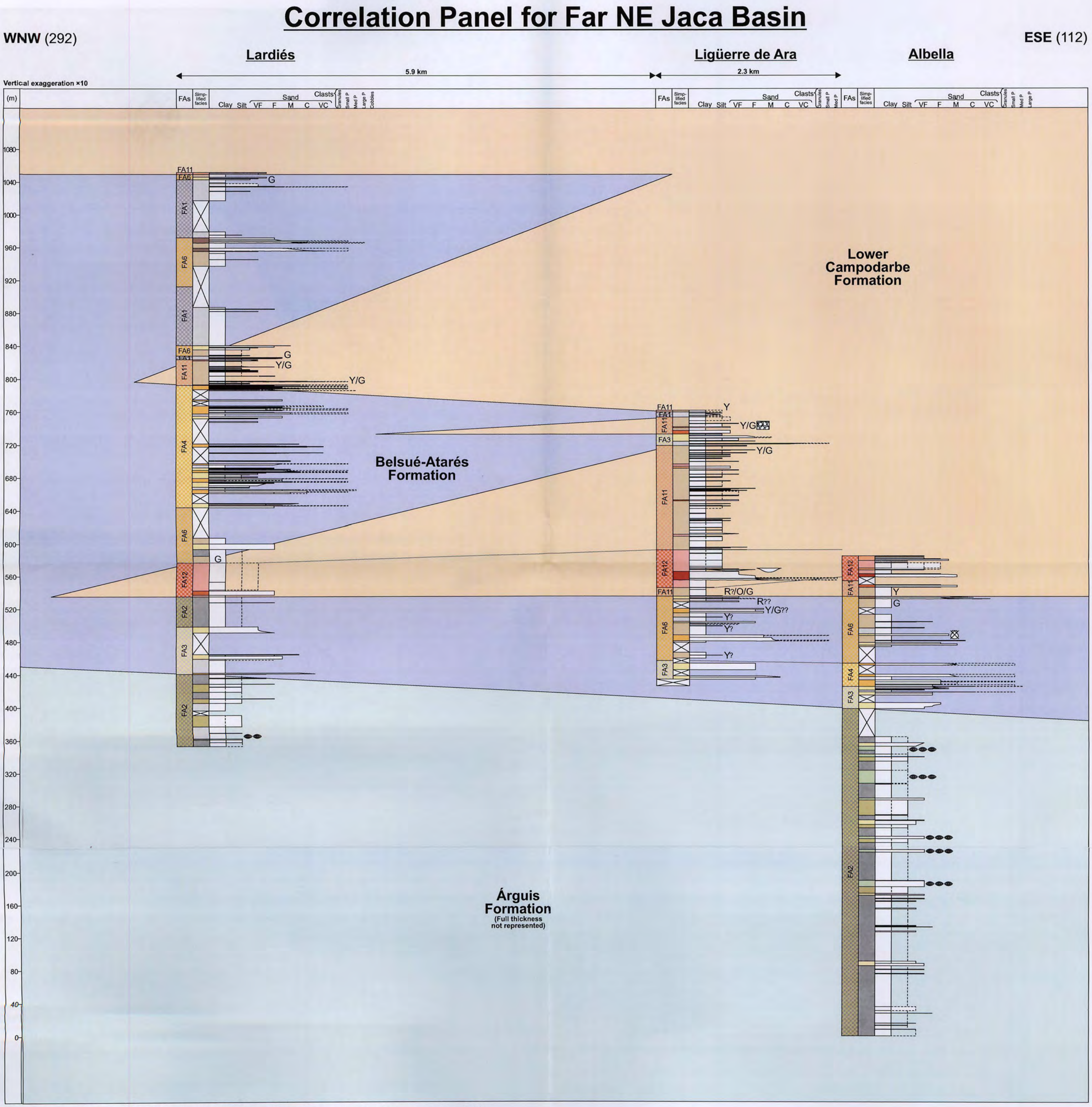

Fig. 4.4. Correlation panel for the Far NE Jaca Basin sector. Vertical exaggeration ×10.

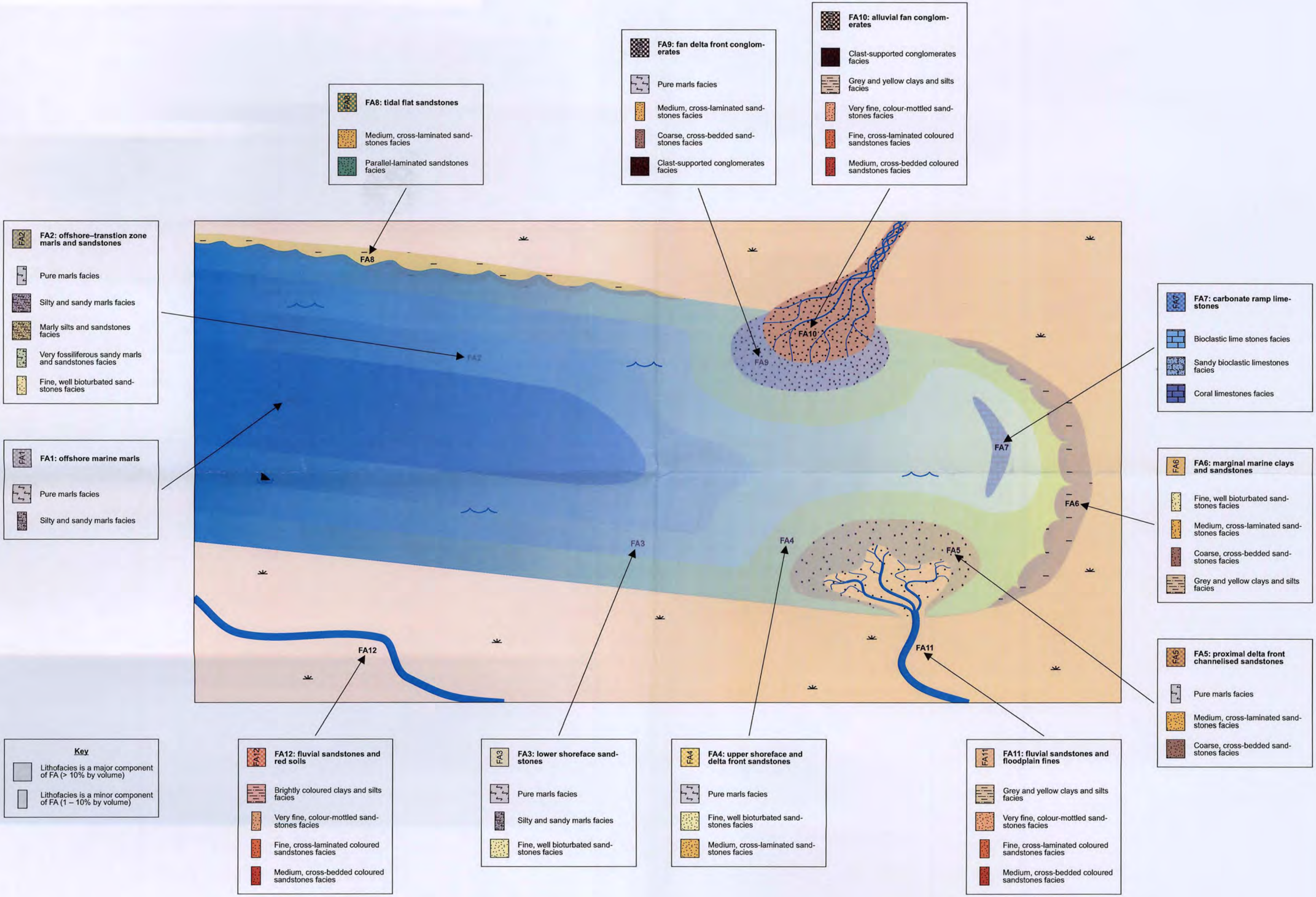

Fig. 3.3. Cartoon of the depositional environments represented by the twelve facies associations defined in the Jaca Basin, and the lithofacies that make up each one.

Lithofacies name	Formation most commonly found in	Common range of bed thicknesses	Common range of package thicknesses	Morphology of beds	Bed contacts	General architecture of beds	Common grainsize range	Most common grainsize	Grainsize distribution within beds	Sorting	Depositional structures	Clasts	Bioturbation	Identified ichnofacies	Fossil content	Usual weathered colour	Depositional processes	Depositional environment(s)
Pure marls facies	Árguis Fm.	< 0.2 – 100 m	< 0.2 – 100 m	Planar, very laterally extensive (> 1000 m)	Commonly gradational	Massive	Clay	Clay		Very well sorted	Very rare parallel lamination					Greys to slightly bluish	Suspension settling	Marine. Lower offshore zone
Silty and sandy marls facies	Árguis Fm.	1 – 100 m	1 – 100 m	Planar, very laterally extensive (> 1000 m)	Commonly gradational	Some internal bedding	Clay – fine sand	Clay	Silt / sand content gradational	Very well sorted	Rare parallel lamination, symmetrical ripples and tabular cross-lamination		Very rare 'sparse bioturbation'		Very rare shell fragments, larger foraminifera and plant debris	Creamy greys	Predominantly suspension settling, but with some weak currents	Marine. Upper offshore zone
Marly silts and sandstones facies	Árguis Fm.	1 – 80 m	1 – 80 m	Planar, very laterally extensive (> 1000 m)	Commonly gradational	Some internal bedding	Clay – fine sand	Very fine sand	Silt / sand content gradational	Very well sorted	Occasional parallel lamination and symmetrical ripples		Very common 'moderate bioturbation'	*Zoophycos*, *Spriophyton* (?), *Ophiomorpha*, *Thalassinoides*	Occasional plant debris, fairly rare shell fragments, *Nummulites*, bivalves, echinoids, bryozoans and oysters	Yellowy	Unidirectional currents and oscillatory flow, plus some suspension settling	Marine. Upper offshore zone
Very fossiliferous sandy marls and sandstones facies	Belsué-Atarés Fm.	0.2 – 4 m	0.2 – 4 m	Planar, laterally extensive (> 100 m)	Sharp	Massive	Clay – medium sand	Very fine sand		Well sorted	Very rare symmetrical ripples		Common 'moderate bioturbation'	*Thalassinoides*	Almost ubiquitous *Nummulites* and shell fragments, common *Chlamys*-type bivalves and other foraminifera, fairly common oysters, fairly rare gastropods and bryozoa, rare bivalves	Grey to yellowy	Fossil concentration by currents	Marine. Warm, shallow sea. Various depths from offshore–transition zone and shallower
Fine, well bioturbated sandstones facies	Belsué-Atarés Fm.	< 0.2 – 3 m	< 0.2 – 10 m	Planar, laterally extensive (> 100 m)	Sharp	Single beds at base of B-A Fm., to packages of 2 – 4 beds higher up	Silt – medium sand	Fine sand	Fairly rare fining upwards	Moderately sorted	Occasional symmetrical ripples and parallel lamination		Almost ubiquitous 'moderate bioturbation' to 'high bioturbation'	*Thalassinoides*, *Planolites*, *Diplocraterion* (?)	Common shell fragments, fairly common plant debris, occasional *Nummulites*, other foraminifera, *Chlamys*-type bivalves and oysters	Yellowy-greys to browns	Oscillatory flow. Bioclast transport	Marine. Variable water depths, but some around normal wave base
Intensively symmetrically rippled sandstones facies	Belsué-Atarés Fm.	< 0.2 – 3 m	< 0.2 – 3 m	Planar, laterally extensive (> 100 m)	Sharp	Usually single beds. Very rarely amalgamated into packages	Very fine – fine sand	Fine sand	Rare coarsening upwards	Moderately sorted	Ubiquitous symmetrical ripples, occasional flaser bedding		Very common 'moderate bioturbation'		Common shell fragments, fairly common *Nummulites*, occasional plant debris	Yellowy-greys to browns	Oscillatory flow	Marine. Above normal wave base
Medium, cross-laminated sandstones facies	Belsué-Atarés Fm.	1 – 5 m	1 – 10 m	Planar and laterally extensive (> 100 m) to occasional channelisation	Occasional erosive bases	Commonly amalgamated into packages of 3 – 5 beds	Very fine – coarse sand	Medium sand	Occasional fining upwards	Moderately to very poorly sorted	Almost ubiquitous tabular cross-lamination, fairly common trough cross-lamination, fairly rare symmetrical ripples	Common small marl rip-ups (4 – 10 mm). Fairly common small pebbles (4 – 10 mm) - fairly well rounded, extrabasinal origin	Common 'moderate bioturbation' to rare 'high bioturbation'	*Palaeophycus* (?)	Very common shell fragments, plant debris and oysters, fairly common *Nummulites*, occasional *Chlamys*-type bivalves, rare other bivalves	Orangey-brown	Unidirectional currents, and some lesser oscillatory flow. Supply of extrabasinal pebbles. Marine reworking	Marine. Upper shoreface or delta front
Coarse, cross-bedded sandstones facies	Belsué-Atarés Fm.	1 – 5 m	1 – 10 m	Laterally extensive (> 100 m), but variable, to channelised (< 20 m)	Common erosive bases	Commonly amalgamated into packages of 2 – 4 beds	Fine to very coarse sand	Coarse sand	Common fining upwards	Poorly to very poorly sorted	Almost ubiquitous tabular cross-bedding, very common tabular cross-lamination, fairly common trough cross-lamination and -bedding	Very common small, medium and large marl rip-ups (4 – 64 mm). Occasional small pebbles (4 – 10 mm) - well rounded, extrabasinal origin	Rare 'moderate bioturbation'. Commonly concentrated towards tops of beds	*Ophiomorpha*	Very common shell fragments, common plant debris and oysters, rare *Nummulites*	Orangey-brown	Unidirectional currents, causing erosion and dune migration. Some channelisation. Little or no marine reworking	Marine. Proximal delta front. Subaqueous channels and mouth bars
Bioclastic limestones facies	Belsué-Atarés Fm.	0.4 – 5 m		Planar, laterally extensive (> 100 m)	Sharp, though may grade into sandy bioclastic limestones facies	Single beds	Carbonate mud	Carbonate mud		Very well sorted			Occasional 'low bioturbation'		Almost ubiquitous shell fragments, very common *Nummulites*, fairly common other large foraminifera, occasional *Chlamys*-type bivalves, fairly rare bryozoa	Light grey	Carbonate mud deposition	Marine. Below wave base, but in photic zone. No siliciclastics
Sandy bioclastic limestones facies	Belsué-Atarés Fm.	0.4 – 5 m		Planar, laterally extensive (> 100 m)	Sharp, though may grade into bioclastic limestones facies	Single beds	Carbonate mud, with lesser amounts of silt – fine sand	Carbonate mud	Sand grainsize varies gradationally	Well sorted			Occasional 'low bioturbation'		Almost ubiquitous shell fragments, very common *Nummulites*, occasional other types of large foraminifera (including *Alveolina*) and *Chlamys*-type bivalves	Light grey to yellowy	Carbonate mud deposition. Supply of siliciclastics by weak currents	Marine. Above wave base. Close to clastic supply
Coral limestones facies	Belsué-Atarés Fm.	0.4 – 20 m		Planar, laterally extensive (> 100 m)	Sharp	Single beds	Carbonate mud, with lesser amounts of silt – fine sand	Carbonate mud		Well sorted					Ubiquitous colonial corals (very diverse - about 15 kinds, whole or fragmented), common shell fragments, rare foraminifera (but no *Nummulites*)	Light grey to creamy-yellow	Coral growth and reef formation	Marine. Warm, normal salinity sea. Around wave base, and in photic zone. High sedimentation rates
Parallel-laminated sandstones facies	Yeste-Arrés Fm.	1 – 8 m	1 – 20 m	Planar, laterally extensive (> 100 m)	Sharp	Very commonly amalgamated into packages of up to 10 beds	Very fine – medium sand	Fine sand		Moderately sorted	Ubiquitous parallel lamination to internal bedding (5 mm – 10 cm), common symmetrical ripples, fairly common asymmetrical ripples, fairly rare tabular and trough cross-lamination and desiccation cracks	Rare, small marl or clay rip-ups (4 – 10 mm)	Common 'moderate bioturbation'		Very rare plant debris	Greys and yellows	Unidirectional currents and oscillatory flow. Cycles in environmental energy / sediment supply. Drying out of sediments	Marginal marine. Inter-tidal to supra-tidal flat
Matrix-supported conglomerates facies	Belsué-Atarés Fm. (also in Lower / Middle Campodarbe Fm.)	0.2 – 3 m		Lenticular (< 10 m lateral extent)	Sharp or erosively based	Single beds	Medium sand – large pebbles (30 – 64 mm)	Coarse sand	Rare fining and coarsening upwards	Poorly to very poorly sorted	Occasional tabular cross-lamination and cross-bedding in matrix. No clast alignment fabric	Small, medium and large pebbles (4 – 64 mm) - sub-angular to well-rounded, most are limestone with a few sandstone, extrabasinal. Fairly common small and medium marl or clay rip-ups (4 – 30 mm)			In B-A Fm.: fairly common shell fragments, occasional oysters and *Nummulites*	Greys and browns	Strong unidirectional currents carrying pebbly, poorly sorted sediments as bedload	Marine or terrestrial. River channels, deltaic distributary channels, submarine delta front channels, or delta front channel mouth bars
Clast-supported conglomerates facies	Lower / Middle Campodarbe Fm. (also in Belsué-Atarés Fm.)	0.4 – 5 m. 2 – 3 times thicker in LC Fm. than B-A Fm.		Planar, laterally extensive (> 100 m), but often variable along lateral extent	Very common erosive bases	Single beds. May contain crude lenticular bedding. Occasional coarse sandstone lenses	Coarse sand – cobbles (> 64 mm)	Large pebbles (30 – 64 mm)	Largest clasts sometimes confined to lenses	Very poorly sorted	Occasional tabular cross-lamination in sandstone lenses. No clast alignment fabric	Small, medium and large pebbles (4 – 64 mm), and cobbles (> 64 mm) - sub-angular to well-rounded, most are limestone or sandstone, extrabasinal. Plus rare, small igneous and metamorphic pebbles (4 – 10 mm) - extrabasinal	Single instance of mollusc (*Gastrochaenolites*?) borings into a calcareous sandstone pebble		In B-A Fm.: very rare shell fragments and oysters	Greys and browns	In B-A Fm.: unconfined gravity-driven grain flows. In LC Fm.: sheet floods. No channelisation in either case	Marine or terrestrial. In B-A Fm.: steep fan delta front. In LC Fm.: alluvial fan
Grey and yellow clays and silts facies	Lower / Middle Campodarbe Fm. (also in Belsué-Atarés Fm.)	0.4 – 40 m	0.4 – 40 m	Planar, laterally extensive (> 100 m)	Gradational, or occasionally sharp	Clays: massive. Silts: single beds	Clay – silt	Clay		Very well sorted	In silts: common parallel lamination		In silts: common 'moderate bioturbation'		In B-A Fm.: single occurrences of gastropods, bryozoa, *Chlamys*-type bivalves and plant debris	Grey to yellow - often grading vertically. Occasional beds of yellow-grey colour mottling (associated with bioturbation). Grey beds confined to B-A Fm.	Suspension settling of clays and silts, with varying iron mineral content	Marine or terrestrial. Wide- ranging low energy environments
Brightly coloured clays and silts facies	Lower / Middle Campodarbe Fm.	1 – 10 m	1 – 25 m	Planar, laterally extensive (> 100 m)	Gradational, or occasionally sharp	Clays: massive. Silts: single beds	Clay – silt	Clay		Very well sorted	In silts: occasional parallel lamination		In silts: very common 'moderate bioturbation', and occasional 'high bioturbation'		Very rare plant debris	Deep yellows, oranges, pinks and reds, rarely almost magenta and, very rarely, green. Beds may be a mixture of any of the above, sometimes with vertical gradations. Occasional colour mottling in silts	Suspension settling of clays and silts. Haematisation. Immature palaeosol development	Terrestrial. Floodplain, with regular floods. Semi-arid climate most likely
Very fine, colour-mottled sandstones facies	Lower / Middle Campodarbe Fm.	0.4 – 2 m	0.4 – 4 m	Planar and laterally extensive (> 100 m) to wedge-shaped and inextensive (< 10 m)	Sharp	Usually single beds, but occasional packages of 2 – 4 beds	Silt – fine sand	Very fine sand	Rare fining upwards	Well sorted	Occasional parallel lamination, rare and poorly developed tabular and trough cross-lamination, and desiccation cracks		Very common 'moderate bioturbation', and occasional 'high bioturbation'		Very rare plant debris	Yellows, oranges and reds. Colour mottling is very common. Occasional green root traces in red rock	Deposition of sands and silts by weak unidirectional currents and from suspension settling. Haematisation. Drying out, bioturbation and root penetration	Terrestrial. Floodplain, fed by crevasse splays and overbank floods
Symmetrically rippled, coloured sandstones facies	Lower / Middle Campodarbe Fm.	1 – 4 m	1 – 6 m	Planar, lateral extent not determined	Sharp	Usually single beds, but occasional packages of 2 – 3 beds	Clay – fine sand	Very fine sand		Well sorted	Ubiquitous symmetrical ripples, occasional flaser bedding, rare tabular cross-lamination		Very common 'moderate bioturbation'. Occasional 'high bioturbation' towards tops of beds			Yellows, pinks and reds	Oscillatory flow in a body of water. Some haematisation	Terrestrial. Lake, playa lake and/or floodplain
Fine, cross-laminated coloured sandstones facies	Lower / Middle Campodarbe Fm.	0.4 – 3 m	0.4 – 5 m	Planar to wedge shaped. Not very laterally extensive (< 20 m)	Rare erosive bases	Almost always single beds	Very fine – medium sand, and small pebbles (4 – 10 mm)	Fine sand	Occasional fining upwards	Well sorted	Very common tabular cross-lamination, fairly common trough cross-lamination, occasional parallel lamination	Occasional small clay rip-ups and rare quartz pebbles (4 – 10 mm) - commonly concentrated toward base of each bed	Very common 'low bioturbation' to 'moderate bioturbation'. Occasional 'high bioturbation' towards tops of beds		Very rare plant debris	Yellows, with occasional pinks and rare reds. Occasional colour-mottling, usually yellow-grey, but also with rare reds, and very rare greens	Unidirectional currents, sometimes waning. Relatively rapid deposition. Some haematisation	Terrestrial. Fluvial system: crevasse-splay lobe or minor channel
Medium, cross-bedded coloured sandstones facies	Lower / Middle Campodarbe Fm.	1 – 5 m	1 – 10 m	Planar and laterally extensive (> 100 m), but variable, to laterally inextensive (< 20 m) or channelised	Common erosive bases	Almost always single beds	Fine to very coarse sand, and small pebbles (4 – 10 mm)	Medium sand	Very common fining upwards	Moderately sorted, except coarsest beds which may be poorly sorted	Very common tabular cross-bedding, fairly common trough cross-bedding and tabular cross-lamination, rare trough cross-lamination	Common small, medium and large clay rip-ups clasts (4 – 64 mm). Fairly common small pebbles (4 – 10 mm) - well-rounded limestone pebbles, or rare sub-angular to sub-rounded quartz. Clasts are commonly concentrated at bases of beds, and especially so in beds with erosive bases	Very common 'low bioturbation' to 'moderate bioturbation'. Occasional 'high bioturbation' towards tops of beds	*Beaconites* (?)		Greys and pale yellows, occasionally pinks or reds. Fairly rare red-yellow colour mottling	Strong unidirectional currents, causing dune and bar migration. Flow migration or waning. Erosion of fine sediments. Relatively rapid deposition. Some haematisation	Terrestrial. Channels of a laterally migrating fluvial system, partly sourced from outside Jaca Basin

Fig. 3.1. Simplified sedimentological characteristics of each of the twenty lithofacies identified. The final two columns offer an interpretation of the depositional processes that could have formed each lithofacies, and a suggestion of which depositional environments that these processes could have occurred in.

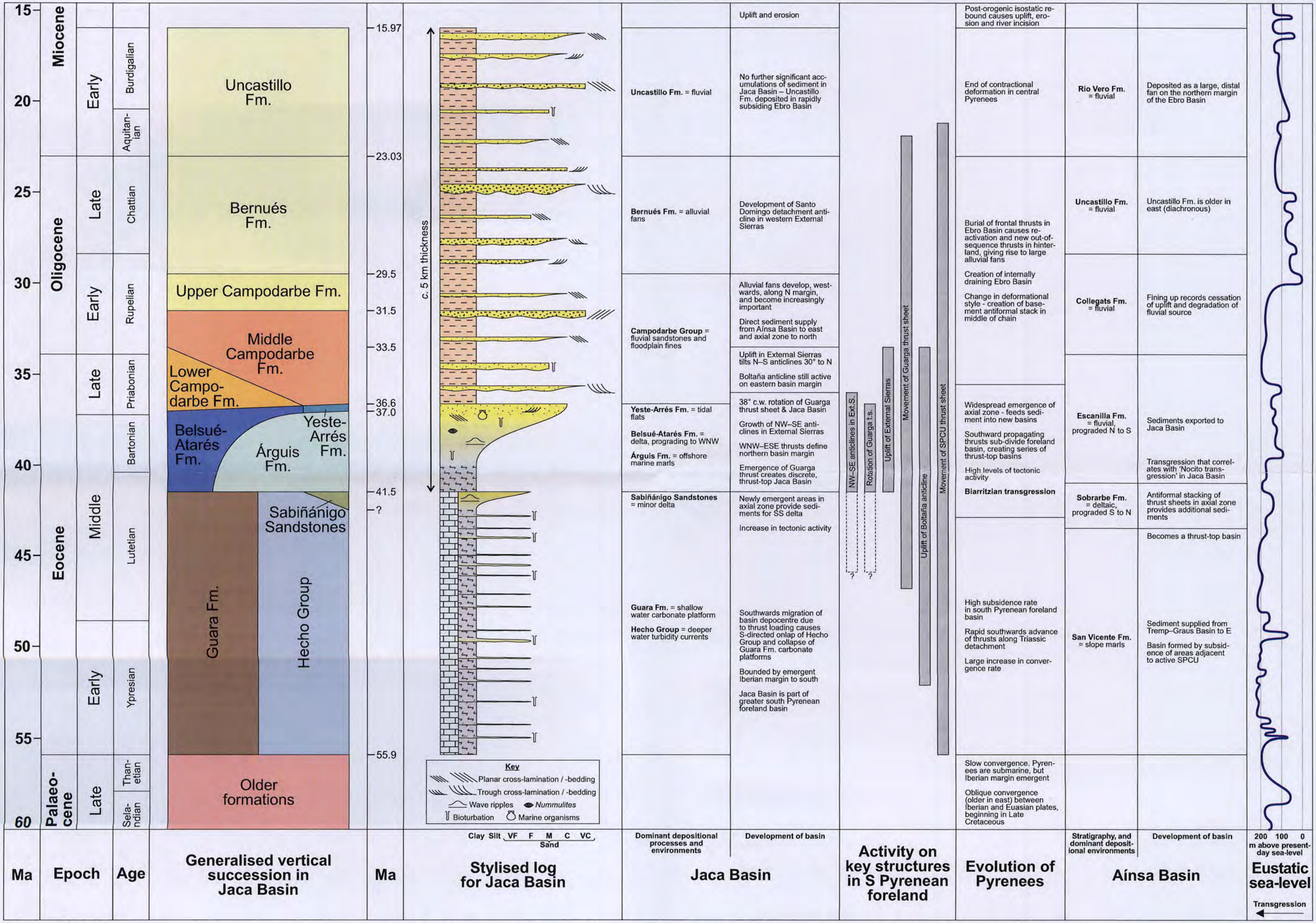

Fig. 2.20. Development and in-fill of the Jaca Basin. Palaeomagnetic dates from Hogan & Burbank (1996) and Pueyo *et al*. (2002). Eustatic sea-level curve from Haq *et al*. (1987). All other references as per text of Chapter 2.

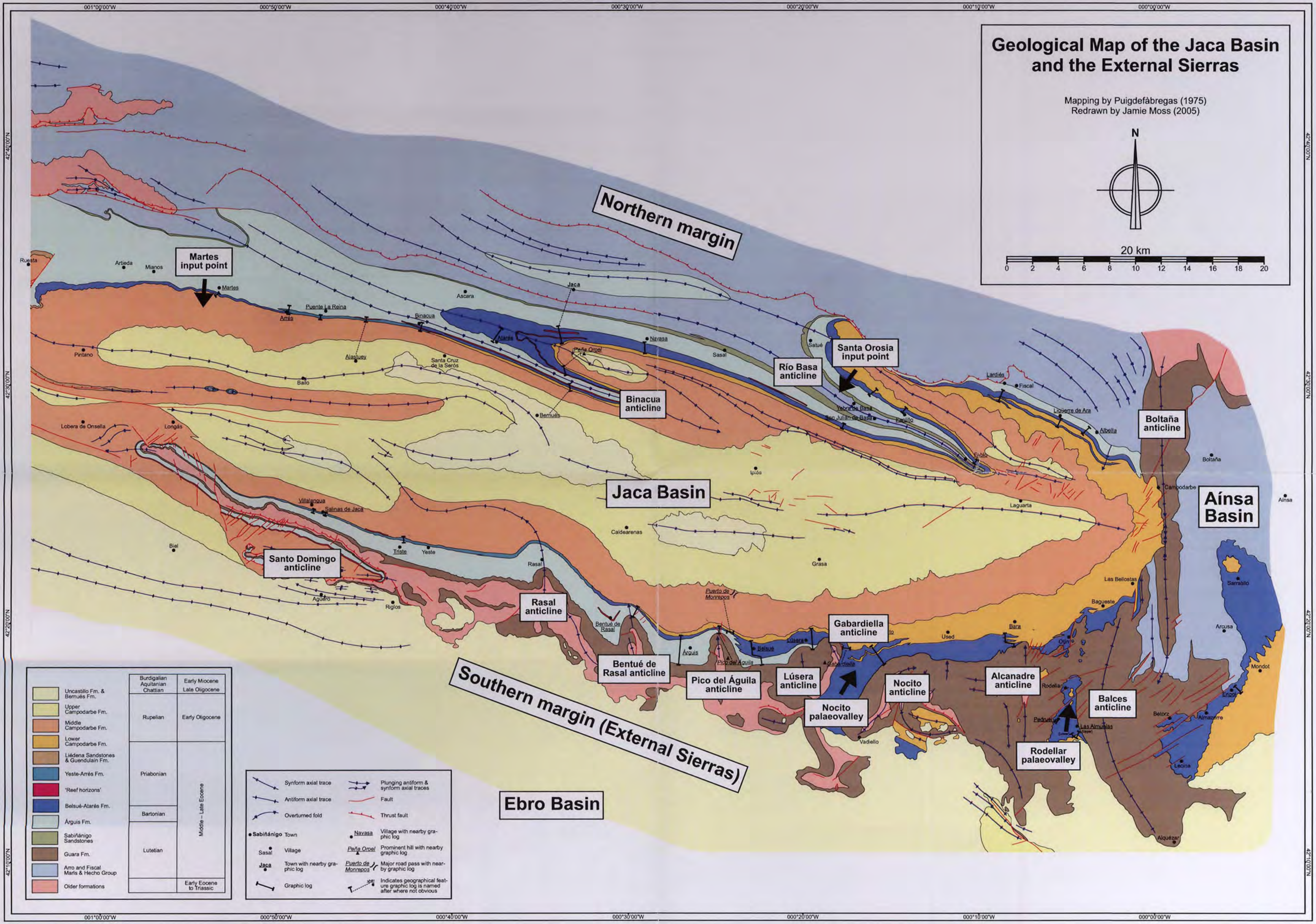

Fig. 1.3. Geological map of the Jaca Basin, External Sierras and the western Aínsa Basin, indicating the names of the key geological structures of the area.

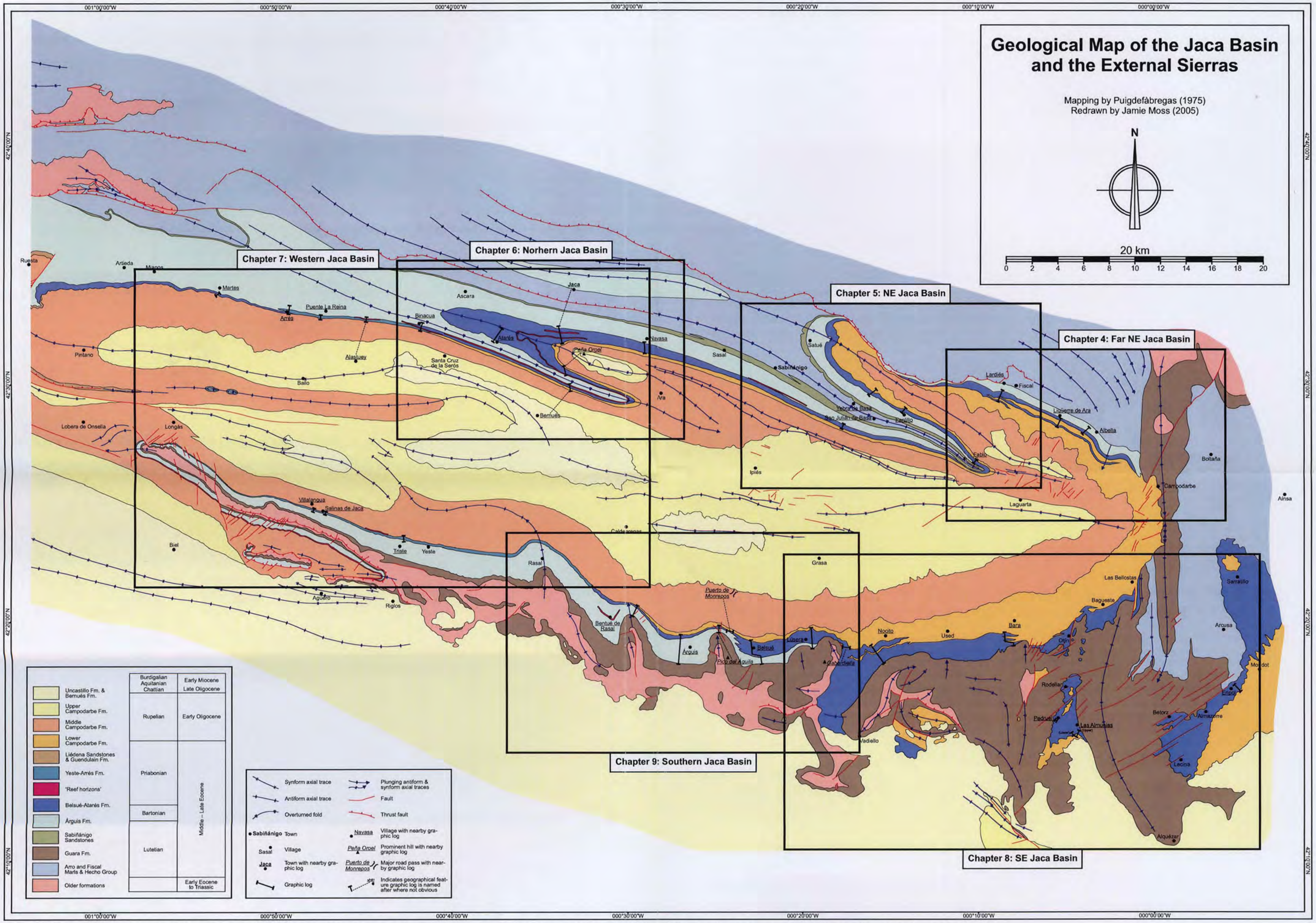

Fig. 1.2. Geological map of the Jaca Basin, External Sierras and the western Aínsa Basin, indicating each of the basin sectors upon which chapters 4 – 9 focus.

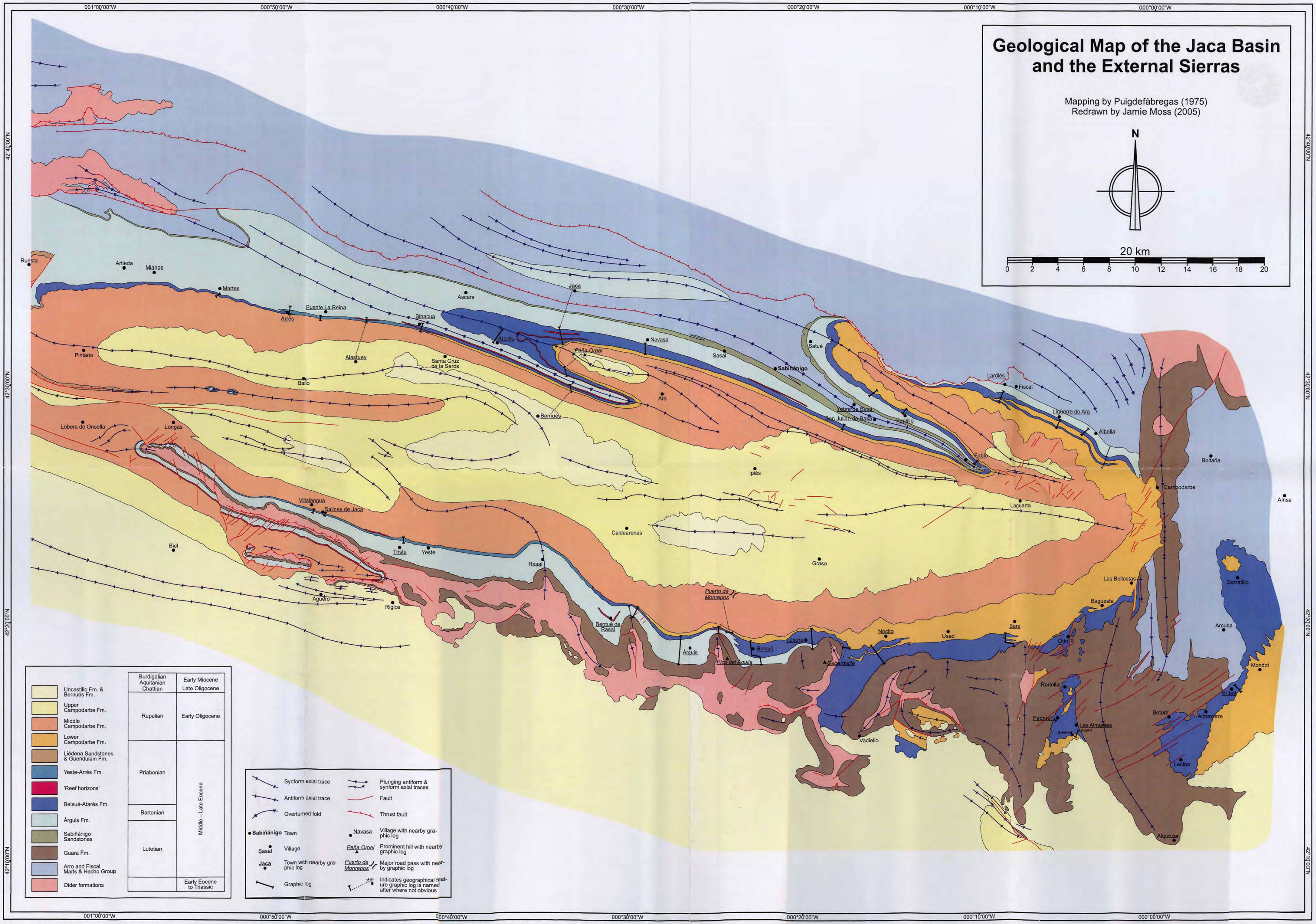

Fig. 1.1. Geological map of the Jaca Basin, External Sierras and the western Aínsa Basin, indicating the positions of the graphic logs undertaken during the course of this work. Based on the original mapping of Puigdefàbregas (1975).

Fig. 10.1. A vertical cross-section depicting the dominant facies associations (depositional environments) of the northern (top) and southern (bottom) basin margin areas of the Jaca Basin. The correlation is diagrammatic, and the boundaries depicted only represent changes in depositional environment, so are not necessarily key surfaces or isochrons. Includes palaeomagnetic dates from Hogan & Burbank (1996) and Pueyo *et al.* (2002), and additional constraints from the mapping of Puigdefàbregas (1975). Vertical exaggeration ×10.