The evolution of Permo-Triassic fluvial and alluvial systems in the central Iberian basin, central Spain

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Declaration

I declare that the work contained in this thesis was the result of my independent research except where otherwise stated.

Signed____________________

Philip Edward Hall

December 2005

Abstract

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Philip E. Hall

Previous research on sedimentation in rift basin settings has increasingly examined temporal and spatial controls on deposition and has gone as far as to offer various models for sedimentation in extensional basins. However, few literary accounts have documented the transition from a wholly continental setting to that of marine influence in the rock record or the role long lived sedimentary routing systems, and their associated controls, play in governing axial and transverse sediment drainage to the basin.

The Central Iberian Basin (CIB), central Spain, is a half-graben rift basin that existed during the Permo-Triassic. Modern day exposure of synrift Buntsandstein and Muschelkalk facies in surface outcrop allows us to carefully examine the switch from continental to shallow marine deposits in a rift basin setting. Through detailed facies analysis, palaeocurrent investigation, Fischer plot analysis, tectonic framework history and theoretical modelling of clastic input a scenario is formed. The role allocyclic controls (climate, tectonics and baselevel) play on sedimentation at both the marginal and intrabasinal areas is discussed. Through facies investigation and comparison to juxtaposed, contemporaneous rift basins in the Iberian Ranges, fresh new ideas on ancient rifts are presented and a realistic model is proposed.

Observations suggest that climate dictates the amount and characteristics of flux entering the CIB, whereas tectonics controls the structure of the basin, compartmentalisation, basin floor gradients and the faulted basin margins. It is this structural influence that assists longevity of re-entrant systems to the basin, through sustained relay ramps and cross-cutting transfer faults. The Buntsandstein facies fluvial and alluvial systems reveal clues to the nature of this gradual change of depositional environment and its associated controls.

The findings of this research will help us to further understand dynamic rift settings and will be of interest to academia and petroleum/mining explorations worldwide.

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During my time as a postgraduate I had the fortune to sit on the BSRG committee and would like to show my appreciation to all involved especially John Howell, Mark Wilkinson and Stuart Jones (again!). I've also had the chance to present at national and international conferences, something that I'll always remember fondly as it gave me the opportunity to meet fellow earth scientists and the confidence to talk about my research with them on a grand scale.

The people in my field areas of Alhama de Aragon and Sigüenza, in Spain, made me feel very welcome. They can be sure I will be making my way there again as many time as possible in the future. Special thanks go to Tito and his family for putting up with my stuttering Spanish and my love of their Bistec, and to Ramon at Pub Bar Latino who gave the nights in rural Spain just that little bit more pizzazz. As for the fieldwork in Spain, Alfredo Arche from UCM was always on hand to offer me advice when I was out there. I would like to say a big thank you for all his assistance.

Last, but by no means least, I wholeheartedly dedicate this thesis to my parents who have never stopped believing in me and have supported me both financially and emotionally over, not just my time at Durham, but the whole of my life. Mum, Dad, I knew I had it in me. This thesis is for you.

Phil Hall
December, 2005

"...buy yourself stout shoes, get away to the mountains, search the valleys, the shores of the sea, and the deep recesses of the earth...Lastly, purchase coals, build furnaces, watch and experiment without wearying. In this way, and no other, will you arrive at a knowledge of things and their properties"

(Petrus Severinus: Idea Medecinae Philisophicae, 1951)

Chapter 1

Aims, Objectives and Methodology

1.1 Aims of the study

Extensional basins are important because their sedimentary fills and bounding tectonic structures provide: sinks with high preservation potential for sedimentary and fossil records, of past changes in drainage structure, climate, sediment/water supply, activity growth and decay of bounding rift faults, rifting of continents during cycles of continent break-up. It is the purpose of this study to create a thorough and updated model of the red bed infill and early rift development of the Central Iberian Basin (CIB), central Spain.

Under the title of the thesis study, "*Evolution of Permo-Triassic Fluvial and Alluvial Systems in the Central Iberian Basin, central Spain*" several aims were initially proposed and intentionally addressed throughout this study:

a) To investigate ancient alluvial fan and fluvial systems evolution in once tectonically active half-graben rift basins;

b) To use evidence of the interaction between tectonics and climate to try to gain insight into continental depositional systems development;

c) To understand the structure, sedimentation history and temporal framework in different areas of a half-graben rift basin and compare to established models of rift basin sedimentation in the literature;

d) To investigate allocyclic controls upon the sedimentation of the alluvial facies and relate to improving non-marine sequence stratigraphic concepts.

1.2 Layout of the thesis

Each chapter represents separate areas of the rift basin, acting as a continuum of the research area evolution. The main chapters (2 to 7) are where the overall geological history of the Iberian Ranges is described, three important areas relating to the development of the rift basin depositional systems are presented and interpreted comparisons made to rift basins worldwide, and the findings discussed. In Chapter 2, aims are stated on the title sheet but following chapters state key findings to avoid repetition of the aims for the overall thesis.

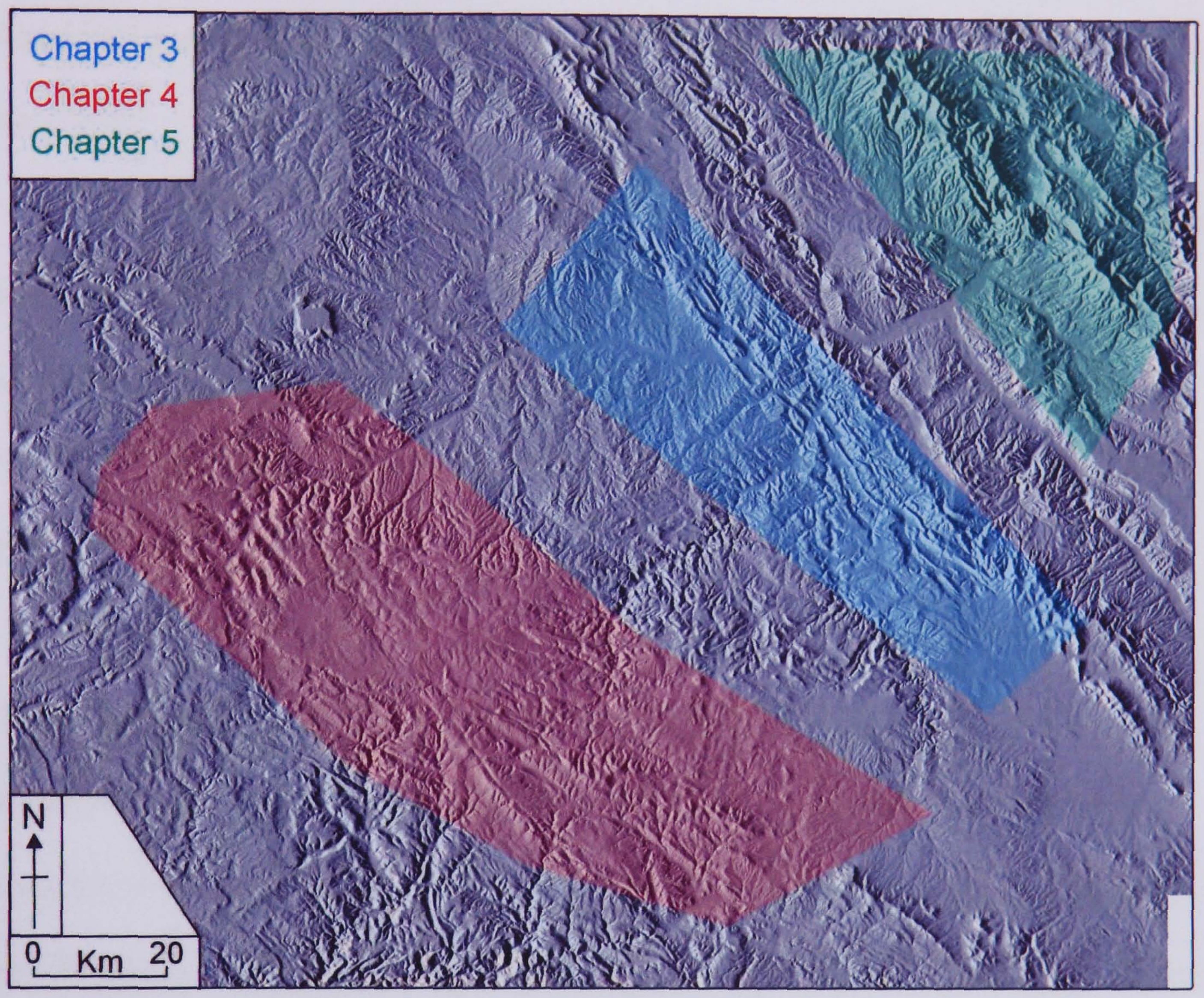


Fig. 1.1: Satellite map showing the location of study areas corresponding to the three faces analysis chapters within the thesis.

Chapter 2 details the evolution of the Iberian Ranges from the Cambrian to the present day and highlights the general stratigraphy and environment of deposition of each of the main epochs. The aim of this chapter is to present a background of the geological history in the CIB to compliment specific geological investigation in following chapters.

Chapters 3 to 5 are concerned with key results from extensive fieldwork - in two areas within the CIB and another in an adjacent basin to the North (Fig. 1.1) - including in-depth facies descriptions and interpretations, and depositional models. The structure of intrabasinal and marginal areas of the basin and the role of climate and tectonics on sedimentation is introduced here, implications of which are elucidated towards.

Following that, in Chapter 6, a comparison is made between the findings on the CIB and literature accounts of the Rio Grande Rift, East African Rift and Red Sea/Gulf of Suez Rift.

In Chapters 7 and 8, all the discussion threads from each chapter are combined and addressed, the latter in a conclusion and summary. Depositional models will be reconstructed and examined, as will sequence stratigraphy across the basin, tectonics, climate and localised accommodation space, giving an overall evolution of the CIB during the Permo-Triassic.

1.3 Introduction

To understand the evolution of synrift fill in the Central Iberian Basin (CIB) it was necessary to engage in extensive fieldwork seasons in Central Spain to record variations in the sedimentary environments. Exposure of the Permo-Triassic sediments in Aragon, central Spain, is excellent allowing a range of measurements to be taken during each field investigation.

Graphic logs were created from the sedimentary deposits and were used in aspects of this study. In addition, the data collection included a thorough account of palaeocurrent directions, provenance analysis, clast size dimension, sedimentary structures and structural data. Further non-quantitative measurements were taken in the form of detailed field sketches, lateral panel sections, rock sample collection and photograph montages.

Analysis of the data was undertaken using the computing and laboratory facilities at The University of Durham. Sketches, graphic logs, photo-montages and geological panels were digitised using CorelDRAW software, which helped visualise the lateral and vertical thickness variation of the deposits along the basin boundary and the nature of the topography they covered. Manipulation of the data led to the calculation of Fischer plots for basin margin sedimentary successions, leading to development of a model of general trends in controls on sedimentation. The chronostratigraphy of the deposits was determined using regional correlation and well constrained age dates from palynoflora (Ramos 1979; Perez-Arluca & Sopeña, 1985; Sopeña et al. 1988; Doubinger et al. 1990; López-Gómez & Arche 1993; Sopeña et al. 1995), were also applied to the regional basin stratigraphy.

1.4 Graphical Logs

The standard method for collecting and recording field data from sedimentary rocks is to construct a graphical log of the succession (*sensu* Tucker, 1996). This technique is favoured among sedimentologists because it gives an immediate visual impression of the section of rocks you are examining and helps with the interpretation of the succession. This visual method helps correlate and compare sections from a number of different areas and additionally, trends in facies, sedimentary cycles and bed thickness are easier to identify. Whilst graphical logs are suitable for representing vertical changes up a succession, one drawback is their failure to fully reveal the changes that occur laterally along section. In order to address this drawback, lateral panels were constructed, made up of several graphic logs in a row.

The characteristics recorded by this method provide an accurate account of the geology up succession, contained within an outcrop. In addition to all information recorded in a field notebook, graphical logs provided the ideal space to document sedimentary structures, fossils, and various lithological characteristics in a simple and clear descriptive manner. Transects that best represented the variety of sedimentology contained within the exposures were chosen at a number of locations throughout the study area. Using a 5 m tape measure, a self-designed information record sheet, and standard field equipment such as compass-clinometer and hand lens, graphic logs at the decimetre scale were constructed. At each location, a decision was made about how many vertical transects to execute, ranging from one at sections where little or no lateral extension of the exposure is present, to several logs forming a correlation panel which best display lateral changes of the bedding across large distances. Spacing of the logs in the latter situation was determined by the amount of sediment exposure offered by the landscape and accessibility of the outcrops.

1.5 Sample Collection

Collecting a representative range of samples was necessary for post-field analysis in the laboratory. Chosen samples were *in situ* deposits with fresh, unweathered surfaces. An appropriate size was pre-determined prior to travelling to the field area, each sample about fist-sized, though sample size increased when the rock type was extremely unconsolidated or promised an advance in understanding of the facies.

Each sample was given a numeric (e.g. sample number 1, 2, 3) and lettered (e.g. M, Monterde; AdA, Alhama de Aragon) identity to assist with cataloguing upon return to the laboratory. Overall, more than 150 samples were collected and analysed in the Department of Earth Sciences laboratory at Durham University. Samples were used for palynological investigation, hand specimen identification, and detailed sedimentological and facies interpretation.

1.6 Photographic montages (photomosaics)

"Photomosaics are useful tools for understanding and communicating geologic features expressed on outcrop faces" (Wizevich, 1991). For this study a series of photographs were taken laterally along each section and pieced together in order to display the transitory facies types or large scale sedimentary structures, to allow detailed analysis of architectural elements, and to provide a complete overview of a logged section (e.g. Fig. 1.2a). The photomosaics taken were also useful for post-fieldwork analysis. Line drawings of large scale features that proved difficult to capture in sketch form at the outcrop were created from the photomosaics (Fig. 1.2b).

In creating a photomosaic, it is necessary to consider a number of factors before recording the outcrop. Wizevich (1991) suggests maximum resolution and minimum geometric distortion of the features is important as is the angle at which the camera is pointed towards the rock face. It is advised that sufficient overlap of each separate photograph is allowed for to produce a useful and well presented composite result.

1.7 Palynological Analysis

Palynological analyses have been undertaken from palynomorphs, spores, pollen and woody debris. The prime importance for this analysis combined with other studies (e.g. Doubinger et al., 1990) is to determine both the environment in which the sediment was laid down and to form a temporal framework for the late-Permian/early-Triassic synrift red beds that form the focus of this research. Palynological analysis of specimens was undertaken by Dr. Geoff Warrington at the British Geological Survey (BGS) using the laboratories at Keyworth, UK.

Continental red beds throughout the geological record are notoriously difficult to extract palynological material as it is often destroyed by post-depositional diagenetic alteration of the beds and oxic conditions, limiting the success of using palynology to date such deposits. However, for this study, it has been important to investigate the basin margin lacustrine systems and attempt to place them within an age-constrained stratigraphic framework. It is important to sample from anoxic or beds with limited oxidation that are typically preserved as a green colour (Fe^{2+}).

Palynological methods are subject to inaccuracies and errors due to contamination or destruction of palynomorphs. Wood et al. (1996) highlight the critical facet of palynological research is the processing method, and explain that careful consideration is applied during the laboratory process. Rock samples collected from the CIB margin underwent a thorough palynomorph extraction process (see Fig. 1.3), first ensuring that the raw sample was unweathered (weathering oxidises and destroys the palynomorphs), was a clean surface sample, and that sample bags were not reused during collection. In addition, laboratory procedures and safeguards were followed to prevent cross contamination by chemicals, other sample specimens and non-distilled water. A consideration of all these will promote accuracy throughout the findings.

1.8 Palaeocurrent Analysis

Palaeocurrent data are those that provide information on the direction of sediment transport in the past (Graham, 1988). Plotted on a palaeocurrent rose diagram (Fig. 1.4), they indicate the direction of sediment movement on a variety of scales from whole basins to individual cross bedding, imbrication and pebble clusters. At these wide-ranging scales, even with small amounts of data, it is possible to determine the direction of palaeoslope, location of source area and any patterns of sediment dispersal that occurred during transportation (Potter & Pettijohn, 1977). In addition, for the purposes of this study, palaeocurrents have been used to help identify sediment conduits and to gauge the level of interaction of transverse and axial depositional systems within the CIB.

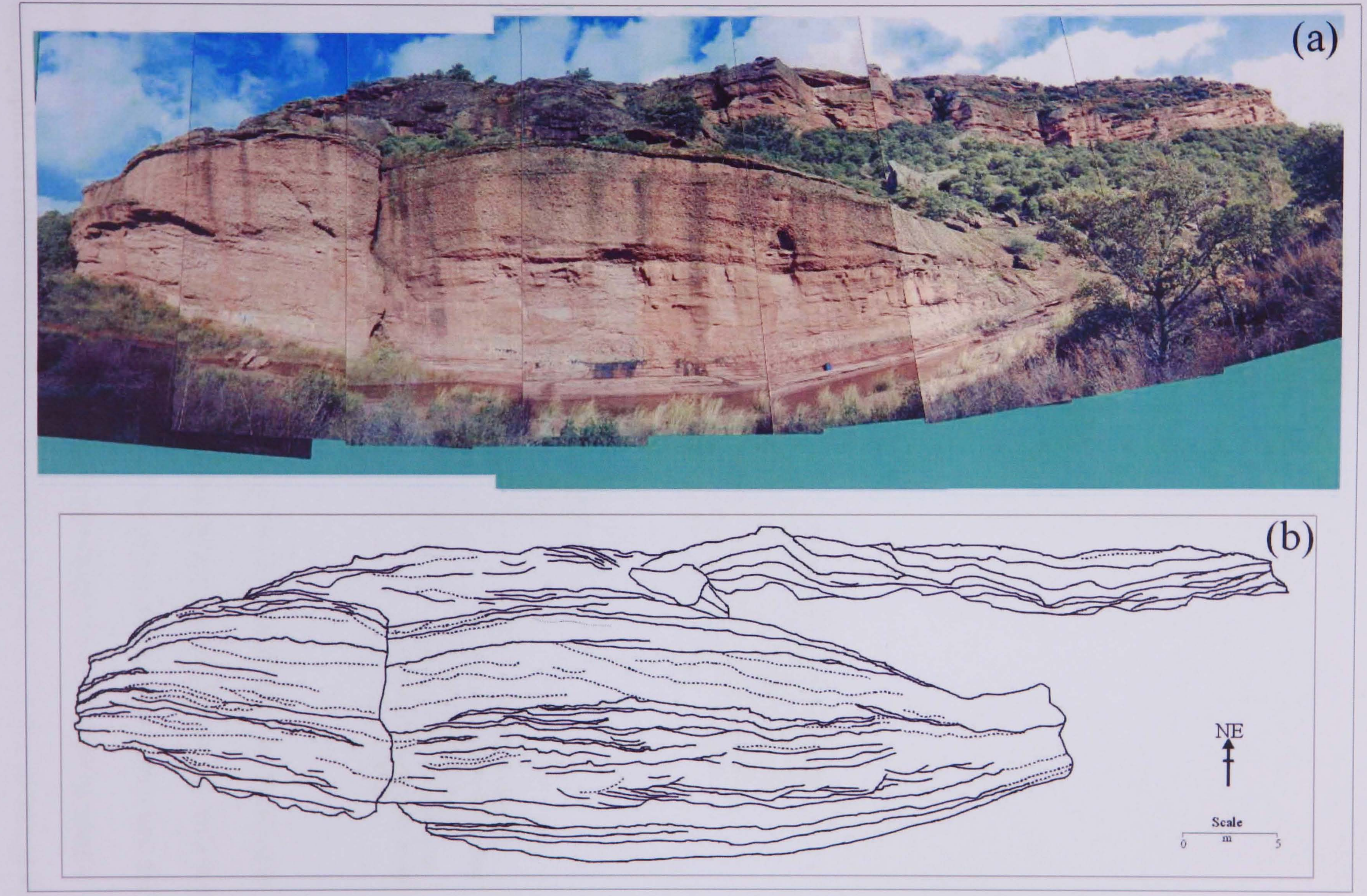


Fig. 1.2: (a) An example of a photo montage of a cliff outcrop, Riba de Santiuste, central Spain; (b) A line drawing of individual bedding within the cliff face created using the photo montage above.

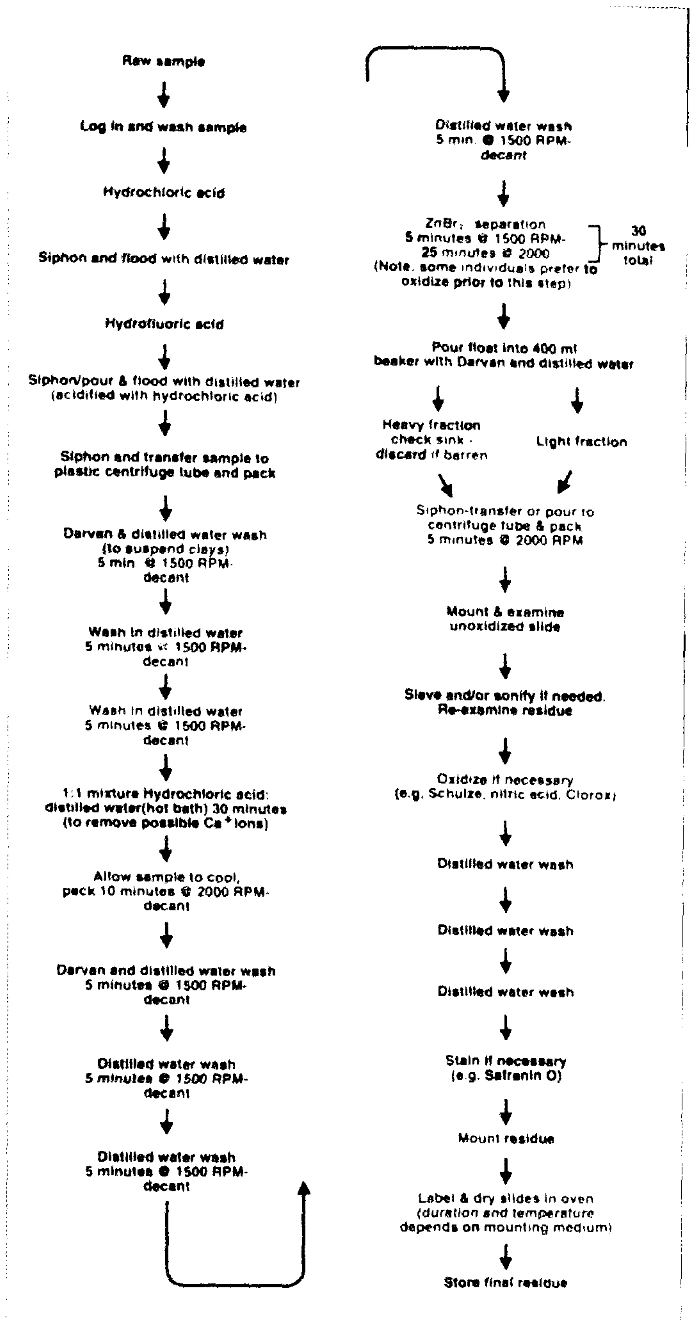


Fig. 1.3: Detailed flow chart presenting the many stages involved in the extraction of palynomorphs from rock samples. With so many vital steps there is a great potential for inaccuracies to occur without procedural safeguards (Wood et al. 1996).

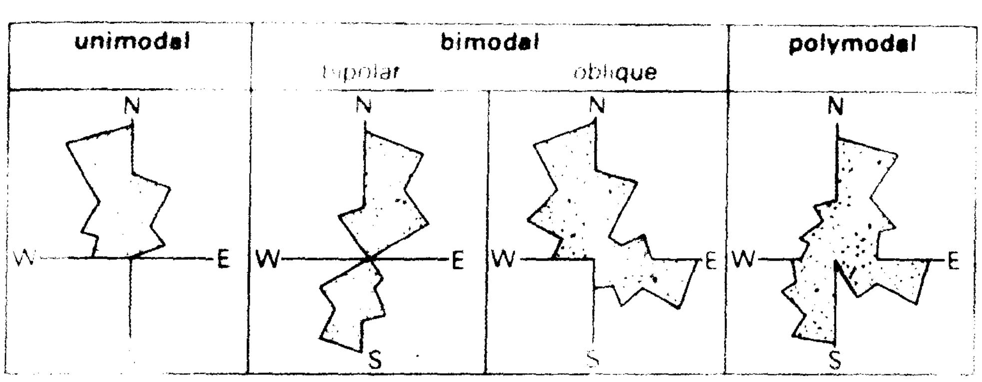


Fig. 1.4: The four types of palaeocurrent rose pattern that can be produced in a rose diagram. Overall direction in these examples would be to the north (Tucker, 1996).

The effects of tectonic tilt were duly considered for all palaeocurrent data collected at each outcrop. In many cases the effects of post-depositional tectonism on the beds in the CIB produces a bedding dip of 30° or less and therefore introduced little error into the measurement. When a steep gradient did occur, the effects were corrected by using a stereographic net (stereonet) to rotate the bedding parallel with the strike of the bed until it reached a horizontal position, as outlined in Graham (1988).

1.9 Fischer Plots Analysis

Fischer (1964) introduced into the literature a graphic way of displaying relative sea-level changes from a sequence of cyclic shallow marine carbonates a method which has been covered and applied to carbonate sequences since (e.g. Read & Goldhammer, 1988; Goldhammer et al. 1993; Sadler et al. 1993; Boss & Rasmussen, 1995). The Fisher plot is a two-dimensional representation of a stratigraphic section where the horizontal axis is plotted as the cycle number and the vertical axis contains subsidence corrected values labelled 'cumulative departure from average cycle thickness' (Sadler et al. 1993; Boss & Rasmussen, 1995) (Fig. 1.5). From this graphical representation, interpretation of hierarchal sea-level fluctuations can be deduced from positive and negative departure from zero. This is an expression of the level of the carbonate platform filling through time and the rate at which subsidence accommodates sedimentation.

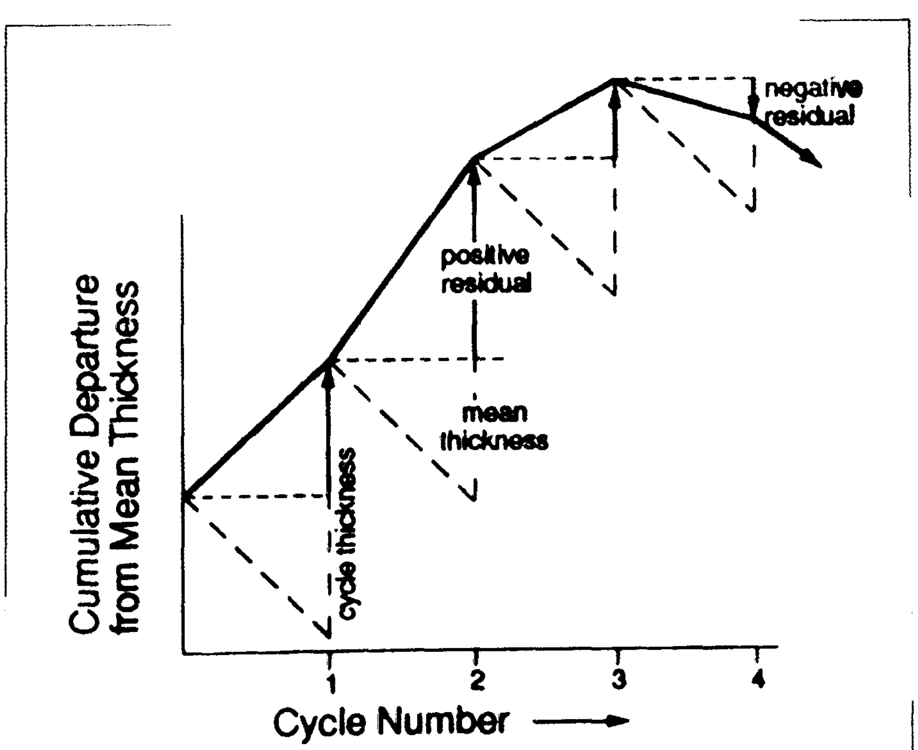


Fig. 1.5: An example of a Fischer plot (cumulative departure from mean cycle thickness as a function of cycle number) (modified from Sadler et al. 1993).

1.9.1 Limitations and assumptions

Interpretation of a Fischer plot requires a number of assumptions, many of which have been highlighted by Boss & Rasmussen (1995). It is presupposed that constant time duration occurred for each cycle and that subsidence was continuous throughout the succession. It is also necessary to assume stratigraphic completeness and that each cycle is tied to a single sea-level event. A further limitation of the method is that plots are recommended to be based on a minimum of fifty cycles to ensure statistical accuracy. Finally, and most importantly, the plots work on the proviso that each decompacted cycle thickness provides a reliable proxy for accommodation space generation. It is this latter point that is essential for the Fischer plot to function as an indication of sea-level fluctuation.

1.9.2 Use with non marine sediments

Fischer plots have commonly been used for tracking the accumulation of shallow-marine carbonate cycles and in turn have been popular in sequence stratigraphy as a guide to sea level history. However, they can be employed on any facies stacking patterns and there is little reason to suggest they cannot be applied to non-marine clastic deposits (Turner, 1999). In this study, Fischer plots were created for each of the graphic logs along the northern margin of the CIB to express the role climate and subsidence played in influencing synrift sedimentation in this continental basin. To investigate, graphic logs were analysed and divided up cycles, the number and vertical position of which were recorded. The results were useful not only for an in-depth insight into the sediment cyclicity of alluvial fan sediments and a proxy for the creation of accommodation space along the CIB margin, but also for an inferred sequence stratigraphic framework. It is hoped this preliminary investigation on non-marine deposits, of which Turner (1999) is a pioneer, will encourage further Fischer plot analysis of non-marine clastic cyclic successions.

1.10 Age Dating

Dating the sediments of the CIB has been a difficult task and not one without pitfalls. Based on the work of several authors, named in the appropriate sections of chapters, the idea was to bring together the current thinking on a timeframe for deposition in the CIB despite glaring absences of dates.

The northern margin is a good example of the difficulty faced when attempting to correlate Buntsandstein sediments across a rift basin. The lack of preservation of spores or pollen leaves little to work on for palynological studies so instead it is necessary to rely on the interpretation of depositional events. Arche (pers. comm.) has provided several pointers as to when beds in the southern CIB were laid down contemporaneously to those deposits at the northern margin of the CIB. Slowly, a correlation panel (observed in Chapters 3, 4, and 5) has been formed of the likely timings of the stratigraphy in the CIB. However, there is room for a great many inaccuracies in this framework and no matter how useful, it should be used and applied to the study as a guide and a way of helping understand the complexities of the synrift sedimentation during the Permo-Triassic on the Iberian Microplate.

Future studies should attempt to address this shortfall in dating knowledge by conducting further searches for palynological evidence or applying other means.

Chapter Two

Geological History

Aims:
- To introduce the geological setting of Central Spain
- To describe and summarise the stratigraphy of the Iberian Ranges
- To identify the important pre-, syn- and post-rift fills of the Central Iberian Basins

2.1 Introduction

It is the purpose of this chapter to present an overview of the geological history of the Iberian Ranges, Central Spain from their earliest origins until Recent times. The Iberian Ranges and associated depositional basins record a stratigraphic evolution of the central Iberian microplate from the Cambrian (c. 1700 Ma) until the Quaternary (c. 13 Ka). The varied stratigraphy and associated structures will be discussed for each of the main events recording the evolution of the area, but a greater emphasis will be placed upon the Permo-Triassic. Early rift phases resulting in the break-up of the Pangaea Supercontinent are well recorded in central Spain along the Iberian Ranges and in the resulting rift basins (e.g. Central Iberian Basin [CIB]).

The research is based upon field exposures within the CIB where a long history of uplift and inversion has exposed well-preserved sections of pre-, syn-, and post-rift stratigraphy. The modern semi-arid climatic setting of the study area and the many cross-cutting modern rivers allow good three-dimensional architecture especially for the Permo-Triassic sediments in strike and dip sections. To provide a complete picture, this chapter will record the full stratigraphic evolution of the central Iberian Ranges.

The accessibility and well-preserved sections is in contrast to many other rift basins where often the synrift is buried beneath thick, postrift deposits or is only identifiable through seismic sections and this resolution imposes major limitations on sedimentological interpretations. The CIB perhaps presents a unique opportunity to study the synrift fill in a late-Palaeozoic/early-Mesozoic rift basin and this will be discussed in further detail in later chapters.

2.2 Geological History of the Iberian Ranges

To fully understand the evolution of the Iberian Ranges and associated rift basins during the Permo-Triassic (synrift phase) it is necessary to present the wider stratigraphic evolution for the Palaeozoic (prerift) to Mesozoic - Recent (postrift).

2.2.1 Lower Palaeozoic History (Cambrian to Devonian)

2.2.1.1 Cambrian

The Iberian Peninsula contains some of the most extensive Cambrian outcrops in Europe including a diverse, continuous record of fossils and facies (Lotze, 1961; Liñán et al., 1993, 2002). Thus it is considered a fundamental source of biostratigraphic information for the Cambrian System and its intercontinental correlations. The Cambrian succession of the Cadenas Ibéricas (Iberian Ranges), in addition to the Iberian Massif, Catalonian coastal ranges and the Pyrenees provide suitable locations for outcrops to be studied (Fig. 2.1).

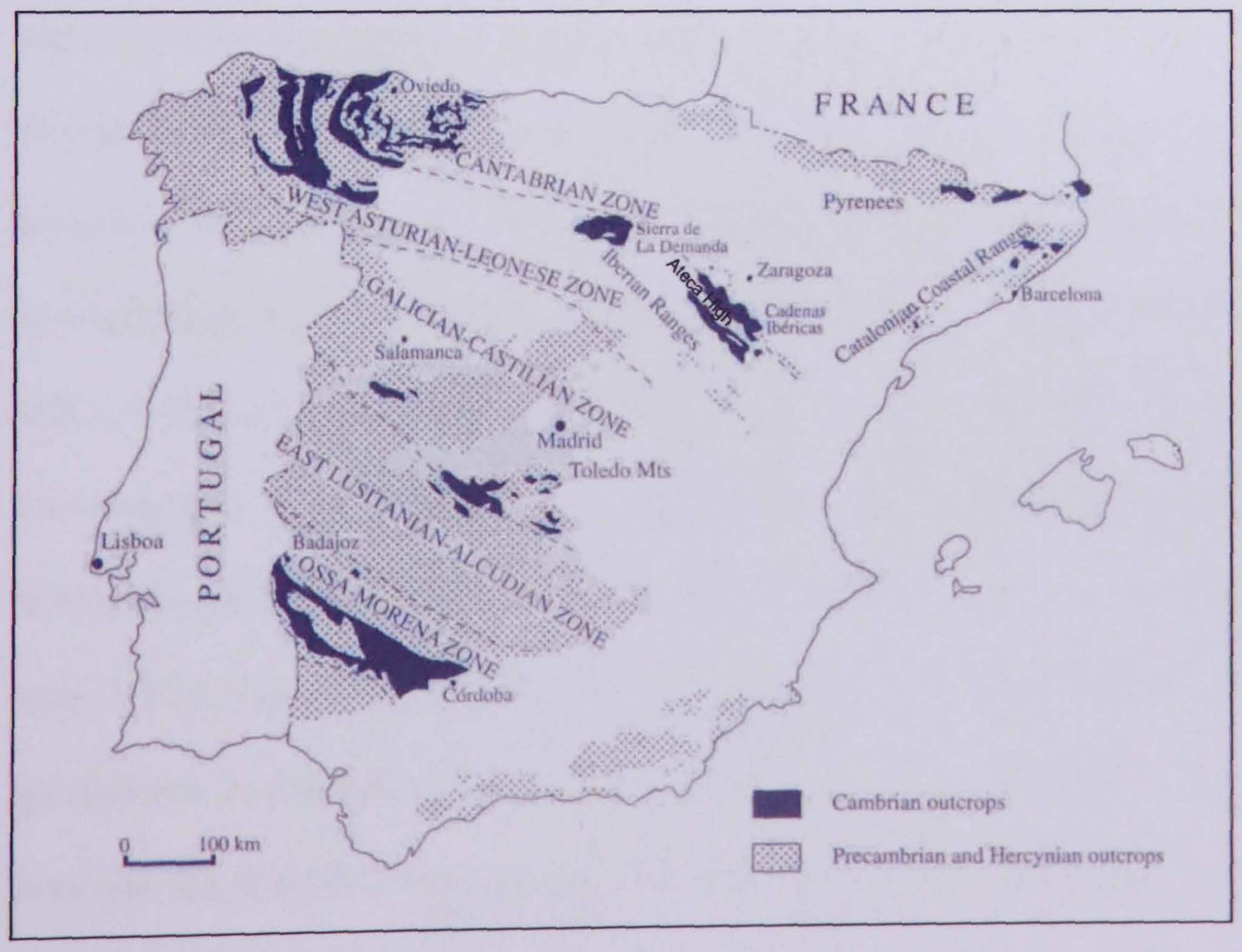


Fig. 2.1: Pre-Mesozoic geological map of the Iberian Peninsula showing location of main Cambrian outcrops and the Ateca High (NE of Madrid) (adapted from Liñán et al. 2002).

The sedimentology and ichnofacies of the Iberian Ranges, and the Cadenas Ibéricas region in particular, has been well documented initially by Lotze (1929, 1961) and more recently by Schmitz (1971) and Gozalo (1995). Lotze's records of deposits in the NW Iberian Ranges (i.e. the focus area of this thesis study), range from quartzarenites and conglomerates of the lower most Cambrian, through shallow marine turbiditic shales and sandstones deposited in a shelf setting, into dolostone and shale deposits of an oscillatory littoral environment. Upper Cambrian sequences around the Ateca region (Fig. 1.1), as well as displaying an extensive range of trilobite, brachiopod, echinoderm and acritarch faunas, are composed of further marine sandstone, shale and conglomeratic successions representing the final depositional episodes of this period.

2.2.1.2 Ordovician

During the Ordovician, the northern areas of Gondwanaland remained as marine shelf environments. Palaeogeographical reconstructions proposed for the Iberian Peninsula indicate this region is a continental margin influenced by tectonic extension that resulted in the formation of fault-controlled, rapidly subsiding troughs in which accumulations of thick synrift sediments collected (Hammann et al., 1976, 1982, 1992; Liñán et al., 1996; Gutiérrez-Marco et al., 2002). Lower Ordovician rocks conformably overlie a thick Cambrian succession and are comprised mainly of siltstones, sandstones, shales and quartzites. Mid to Upper Ordovician sequences vary in thickness, a factor attributed to erosional episodes linked to Late Ordovician glaciations. The sequence has yielded abundant and various shelly faunas of brachiopods, trilobites, molluscs and rare graptolites. Their occurrences within hundreds of metres of shales, sandstones, and limestones fill have been used as comprehensive biostratigraphic markers. Above these Lower-mid Ordovician age sediments sit 50-120 m of glaciomarine diamictites resulting from the Gondwanan glaciations.

2.2.1.3 Silurian

The Iberian Peninsula continued to remain a part of the northern Gondwanan Province during the Silurian (Fig. 2.2a). Estimates of palaeolatitude are somewhere between the colder latitudes of the latest Ordovician times (c. 50°S) to the warm temperate, and sub tropical climate (c. 35°S) of the Lower Devonian. The Iberian Ranges (and specifically the Iberian Cordillera) can be subdivided into two branches: the Aragonese, or eastern branch, and the Castillian or western branch (Fig. 2.3).

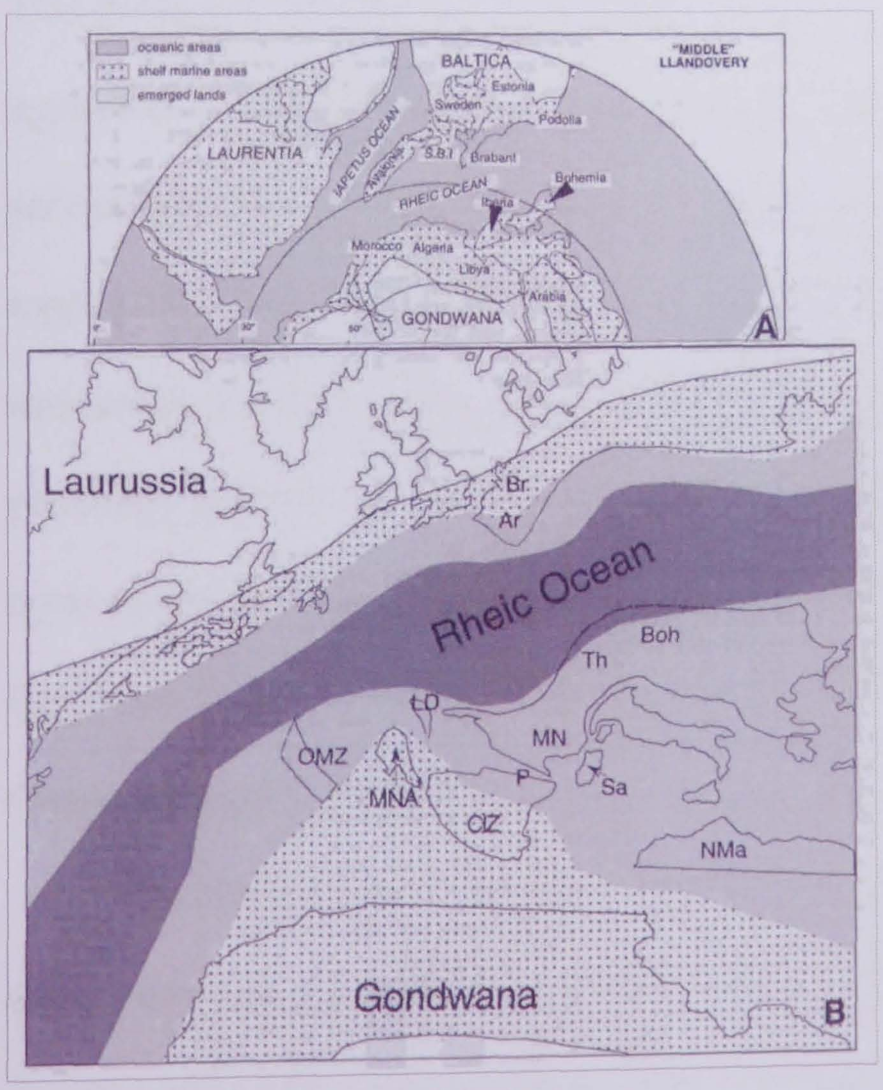


Fig.2.2: (a) Global Silurian Palaeogeography (b) North-Gondwanan Palaeogeographic reconstruction during the Silurian. Colour Key: White = land areas; light grey = inner shelf; medium grey = shelf; dark grey = oceanic areas. Relevant Location Key: Ar, Ardenne; Boh, Bohemia; Br, Brabant; CIZ, Central Iberian Zone; LD, Ligerian Domain of the Amorican Massif; MN, Montagne Noire; MNA, Middle North Amorican Domain; NMa, northern Maghreb; OMZ, Ossa Morena Zone; P, Pyrenees; Sa, Sardinia; Th, Thuringa (all after Robardet & Gutiérrez-Marco, 2002).

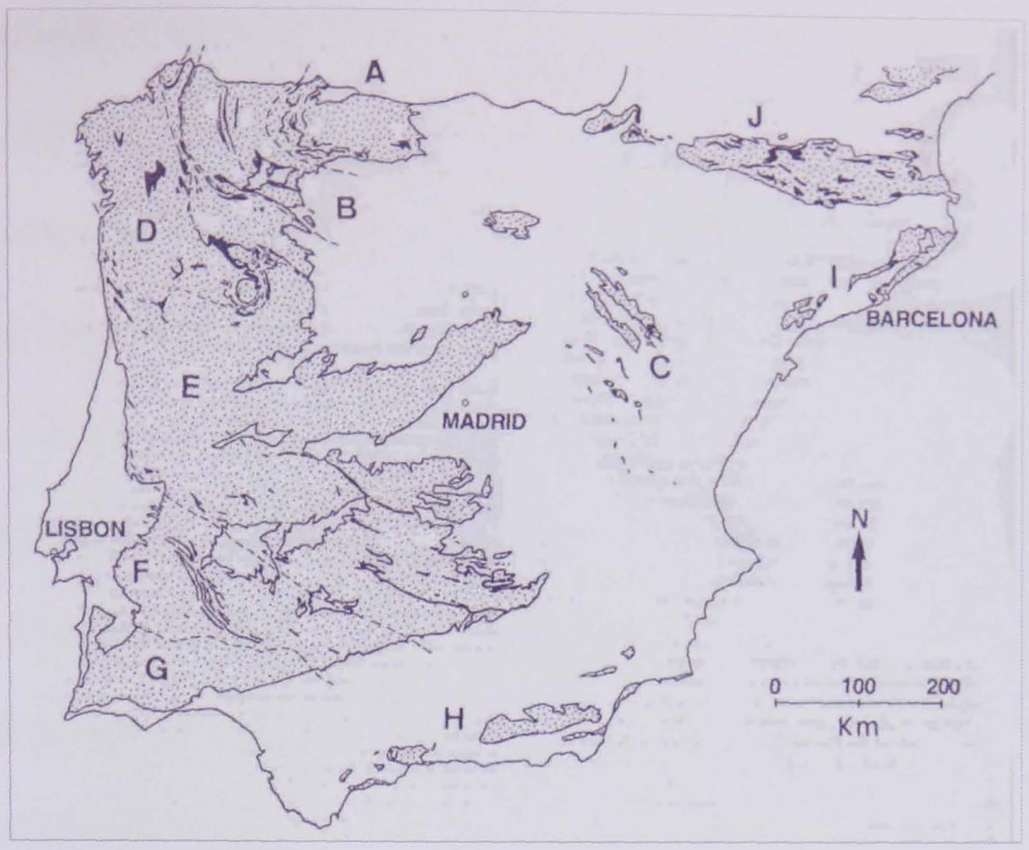


Fig. 2.3: Geological map of the Silurian outcrops (black) in the Iberian Peninsula with reference to Pre-Cambrian and early Palaeozoic outcrops (stippled). Key: A, Cantabrian Zone; B, West-Asturian-Leonese Zone; C, Iberian Cordillera; D, Galicia-Trás-os-Montes Zone; E, Central Iberian Zone; F, Ossa Morena Zone; G, South Portuguese Zone; H, Betic Corilleras; I, Catalonian Coastal Ranges; J, Pyrenees (after Robardet & Gutiérrez-Marco, 2002).

This division exists in documentation of Mesozoic-Cenozoic outcrops, but is also applied to the Mid-Palaeozoic of the Iberian Cordillera. As well as graptolitic shale successions, both branches contain 300-1400 m of deep marine black shales and are topped off by distinctive shallow water sandstones. The presence of intercalated sandstones and black shale in this region suggests that the environment was in close proximity to the North Gondwanan shelf, a short distance from terrestrial source areas providing clastic input (Paris & Robardet, 1990; Gutiérrez-Marco et al. 1998; Gutiérrez-Marco & Storch, 1998; Storch & Gutiérrez-Marco, 1998; Robardet & Gutiérrez-Marco, 2002).

Overall, within the palaeogeographical distribution of northern Gondwanaland, a complicated picture is painted in the literature especially when considered in terms of Pre-Variscan topographical arrangements. Robardet & Gutiérrez-Marco (2002) state that emergent land areas separated by a North-South deep marine divide existed, taking the form of a shallow water inner-shelf environment of the Central Iberian Zone towards more distal and outer-shelf conditions in the northernmost central Iberian zones (Fig. 2.2b). However, it is acknowledged from studies on Moroccan and northern Pyrenean/Cantabrian deposits (Carls, 1975, 1977, 1983; Robardet & Gutiérrez-Marco, 2002) that the palaeotopography of the whole North Gondwanan Shelf may have been complicated by raised land surfaces 'superimposed' on the established larger scale North-South trending shelf landmass. Palaeozoic modifications present difficulties in interpreting the original palaeogeography.

2.2.1.4 Devonian

During the Devonian in Spain deposition in marine conditions prevailed, though the type of marine environment varies from supratidal to subtidal settings. Pre-Hercynian reorganisation of plate boundaries during the Early Devonian led to a narrowing of oceanic basins separating Laurussia and Gondwanaland, and the northwards convergence of the Iberian Peninsula (Ziegler, 1989). Up to 4000 m of Devonian shales, fine-grained sandstones and quartzites, plus some shelly limestones and marls, were laid down in the region of the Iberian Ranges (Celtiberia) (Gozalo & Liñán, 1988; Carls, 1988; García-Alcalde et al., 2002) though can only be found in isolated locations (Fig. 2.4). Early Palaeozoic basement played host to these patchy outcrops of Devonian rocks which are most likely to caused by varying amounts of subsidence, water depth and sediment supply. Siliciclastic sediments dominate much of what exposure there is, however, significant calcareous reef development have also been observed throughout areas north of the Iberian Ranges such as the Pyrenees and Catalonian coastal ranges. Phosphate nodule horizons discovered within the

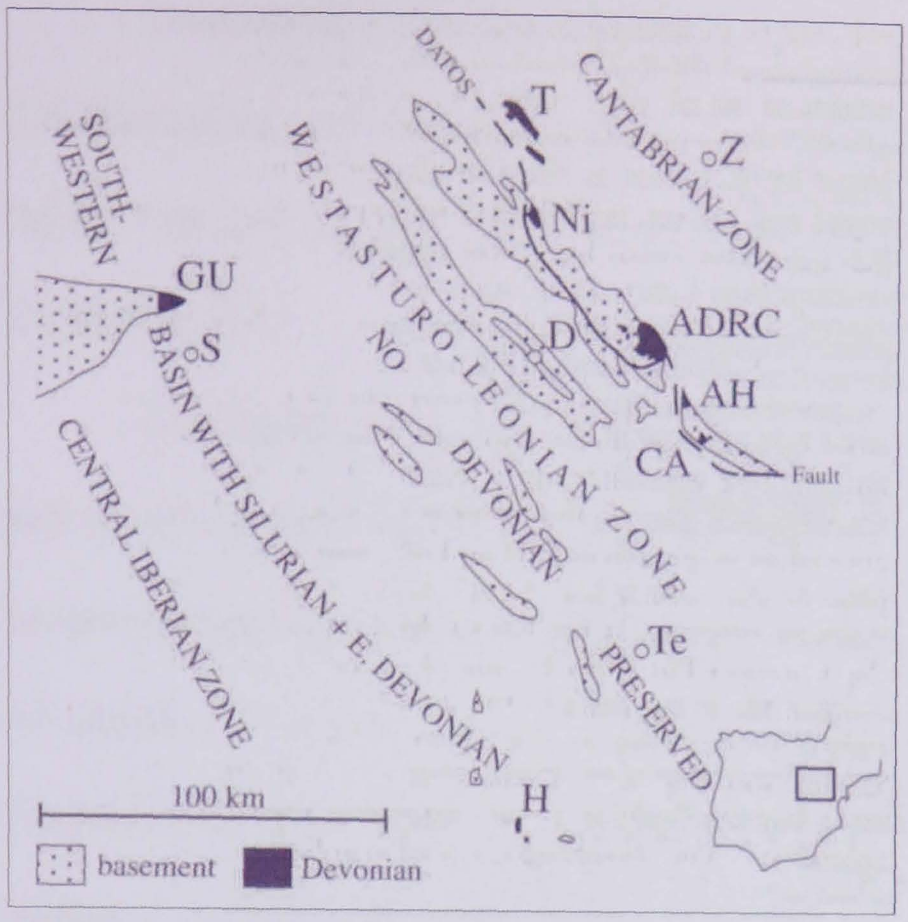


Fig. 2.4: Geological map of the Celtiberia Devonian outcrops. Key to localities: D, Daroca; S, Sigüenza; Te, Teruel; Z, Zaragoza (after García-Alcalde et al. 2002).

siliciclastic successions and a lack of reef and algal growth points towards an upwelling of cooler water from the Palaeotethys to the east (García-Alcalde et al. 2002). However, interpreting the, frequently incomplete, deposits is hampered in some cases by overprinting and faulting by Variscan and Alpine tectonics.

2.2.2 Upper Palaeozoic History (Carboniferous to Early-Permian)

2.2.2.1 Carboniferous

During the Early Carboniferous, a great deal of plate readjustment had started. Western realms of the Proto-Tethys Ocean were beginning to close and the northern margin of the landmass of Gondwana was subducting (Ziegler, 1989). Laurussia and Gondwanaland continued to rotate towards each other during the Visean (~335 Ma) and increasingly important continental ice sheets in Gondwana caused major glacio-eustatic sea-level changes.

Towards the mid-stages of the Early Carboniferous (Early Visean), northern Gondwanaland, and much of Europe (including the Iberian Peninsula) was affected by the Variscan Orogeny, which formed part of the global Hercynian Orogeny Mega-Cycle (Fig. 2.5).

Lasting into the Late Carboniferous, the Hercynian Orogeny had a massive effect on Palaeozoic strata of Spain, causing deformation, displacement, metamorphism and erosion. It significantly altered the palaeogeography of Laurussia (European Plate) and Gondwana, acting as a precursor to the formation of the mega-landmass, Pangaea. The European Variscan belt (Fig. 2.6) is the result of oblique collision and interplay of these Palaeozoic mega continents and a number of intra-Palaeozoic continental microplates. Ribeiero et al. (1990), Shelley & Bossière (2000), and Áblaos et al. (2002) suggested disruption and convergence of these microcontinents resulted in the formation of major fold belts along the northern margins of the Proto-Atlantic and the Proto-Tethys. The arcuate configuration of the

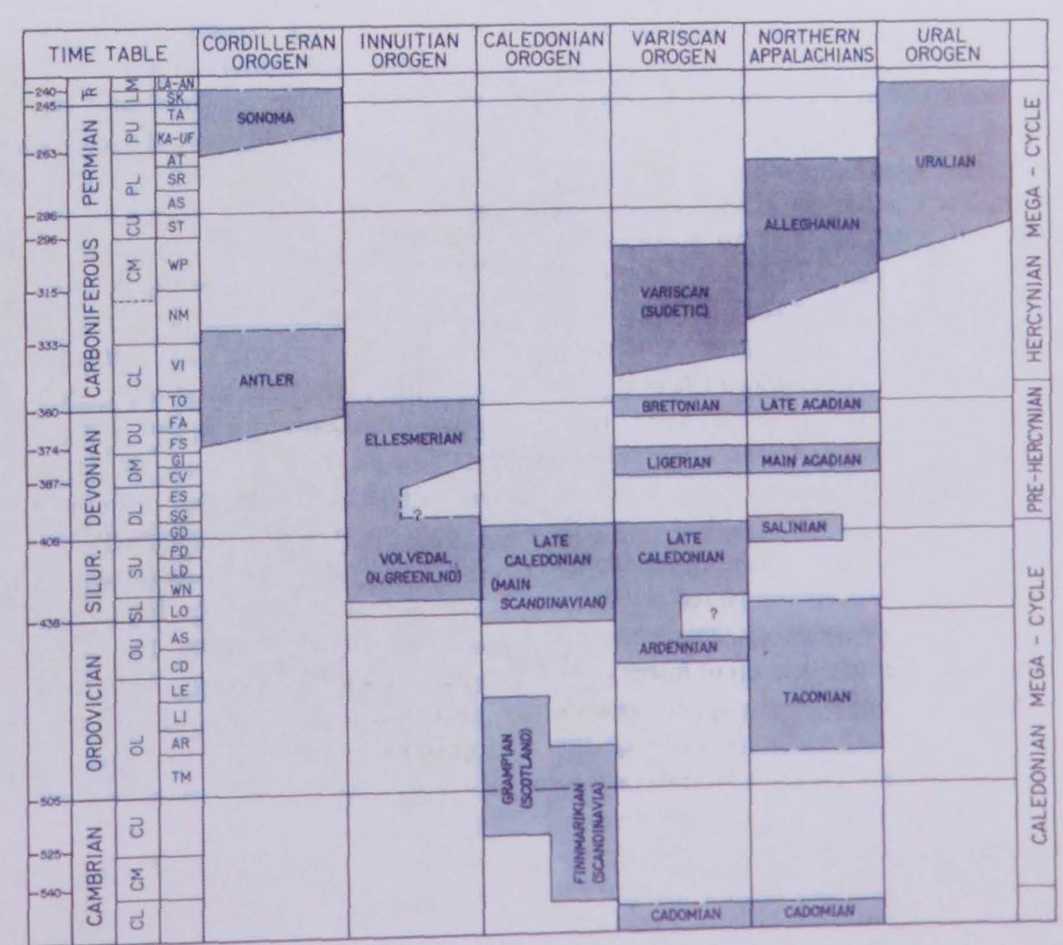


Fig. 2.5: Timing of the Variscan (Subdetic) Orogeny and correlation to other Palaeozoic orogenic cycles (after Ziegler, 1989).

fold belt, that involved major deformation of nappes and wrench faulting, resulted from the geometric influence of a number of microcratons created within Gondwanan back-arc rifts (Zielger, 1989). The strong tectonic control on the Iberian microplate resulted in mobile, unstable NW/SE trending basins under a compressive structural regime that contained sedimentary successions showing rapid temporal and spatial changes in lithofacies and thickness (Villena & Pardo, 1983; Colmenero et al., 2002). Unconformably overlying Devonian strata, Carboniferous sediments up to 1000 m thick, found around Teruel in the SE of the Iberian Ranges, are made up of sequences of wave-dominated shelf sandstones, shales from distal submarine fans and completed by sandstones and breccias of slope and prograding shelf facies. In general, sedimentation was coeval with the Variscan Orogeny, in contrast to the rift to passive margin depositional settings of the Palaeozoic, was dominated by siliciclastic rocks varying from deep marine turbidites, through to shallow marine and coal bearing strata with occasional complete continental successions.

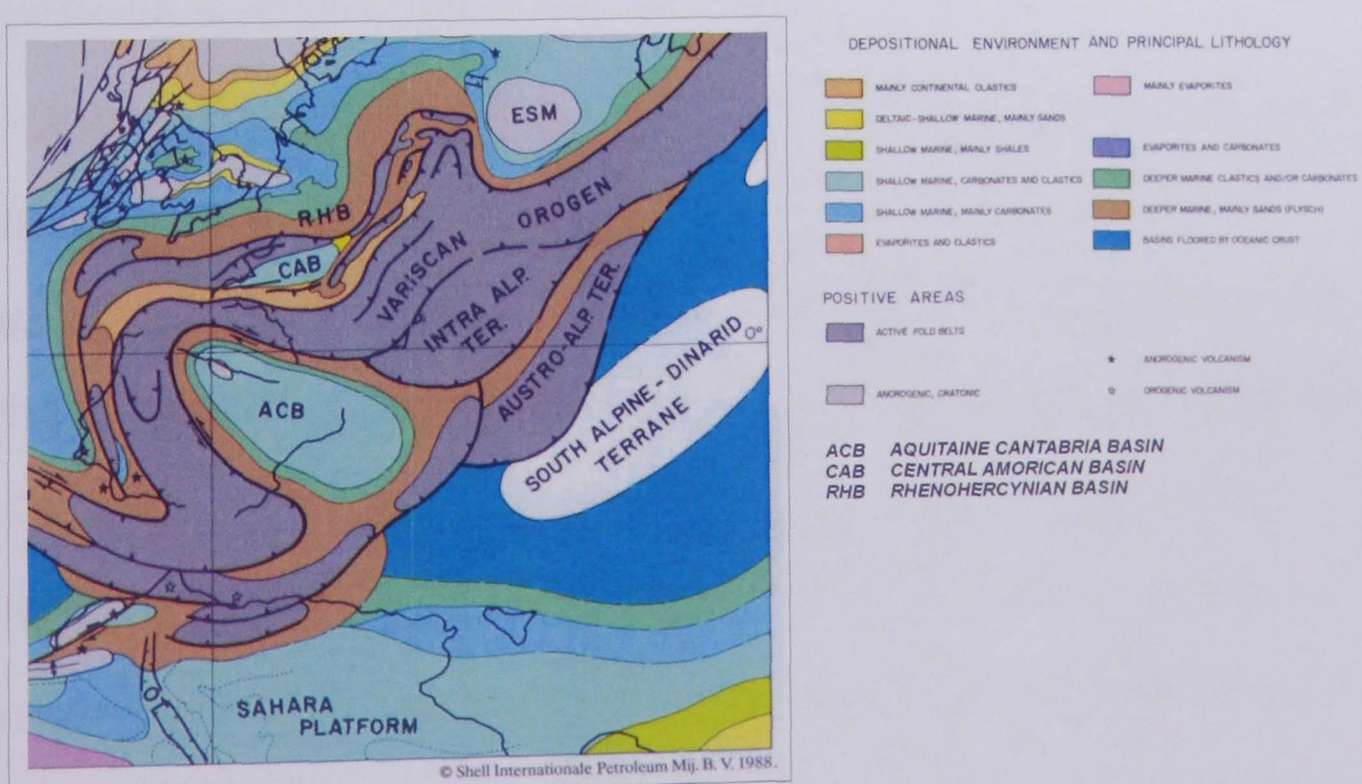


Fig. 2.6: Palaeogeographic reconstruction of the European Variscan Belt during the Early Carboniferous. Key: ACB, NE-E Iberian Peninsula; CAB, Central Amorican Basin (Adapted from Ziegler, 1989).

The Variscan Orogeny and the early Atlantic rifting during the Late Carboniferous (Stephanian) to Lower Permian (Autunian) continued to strongly influence the internal structure of all the micro continents, including the Iberian microplate. The development of a mega shear zone along the belt separating Europe from Africa culminated in the creation of two influential dextral strike-slip faults: the Bay of Biscay Fault Zone (BBFZ) and the Gibraltar Fault Zone (GFZ) (Fig. 2.7). The movement along these faults caused rotation of the Iberian Microplate, crustal extension and reactivation of previous Hercynian structures. The extension created NW/SE trending, intra-continental sedimentary basins controlled by reactivated, normal dip-slip faults (Ziegler, 1989; Cassinis et al., 1995; Sánchez-Moya et al., 1996; Castro et al., 2003; López-Gómez et al., 2003). The basin development and extension regime would lead to the creation of coeval fault-bounded rift basins on the Iberian Peninsula.

2.2.2.2 Permian

At the beginning of the Permian, widespread post-orogenic volcanism and associated magmatic events accompanied movement on the massive suture zone in the palaeogeography of Pangea (Sopeña et al., 1988; Arche et al., 1999; Castro et al., 2002; Lago et al., 2004). Stephanian (Late Carboniferous) to Permian calcalkalne volcanic rocks are widely represented across the Iberian Ranges (Fig. 2.8). Exposures are predominantly volcaniclastic, mainly agglomerates and tuffs (containing lithics and crystal lapilli), and are andesitic in nature, displaying a NW/SE linear geometry controlled by pre-existing Variscan structures (Castro et al. 2002). The thickness of these deposits ranges between 20 m and 150 m (Lago et al. 2004) at Rillo de Gallo (near Molina de Aragon) hosting a thick succession of tuffs and shale deposits. They are found unconformably overlying deformed Lower Palaeozoic basement and are overlain by Late Permian (Thüringian) Buntsandstein facies red beds. The volcaniclastic deposits are interbedded within sedimentary horizons of 'Saxonian' facies red beds and can be seen as grey-green and black fine-grained ash-tuff layers, deposited as ash-fall in a calcalkaline shallow lacustrine setting similar to that seen in the lakes of the East African Rift Basin (e.g. Lake Baringo: Frostick & Read, 1990; Frostick, 1997).

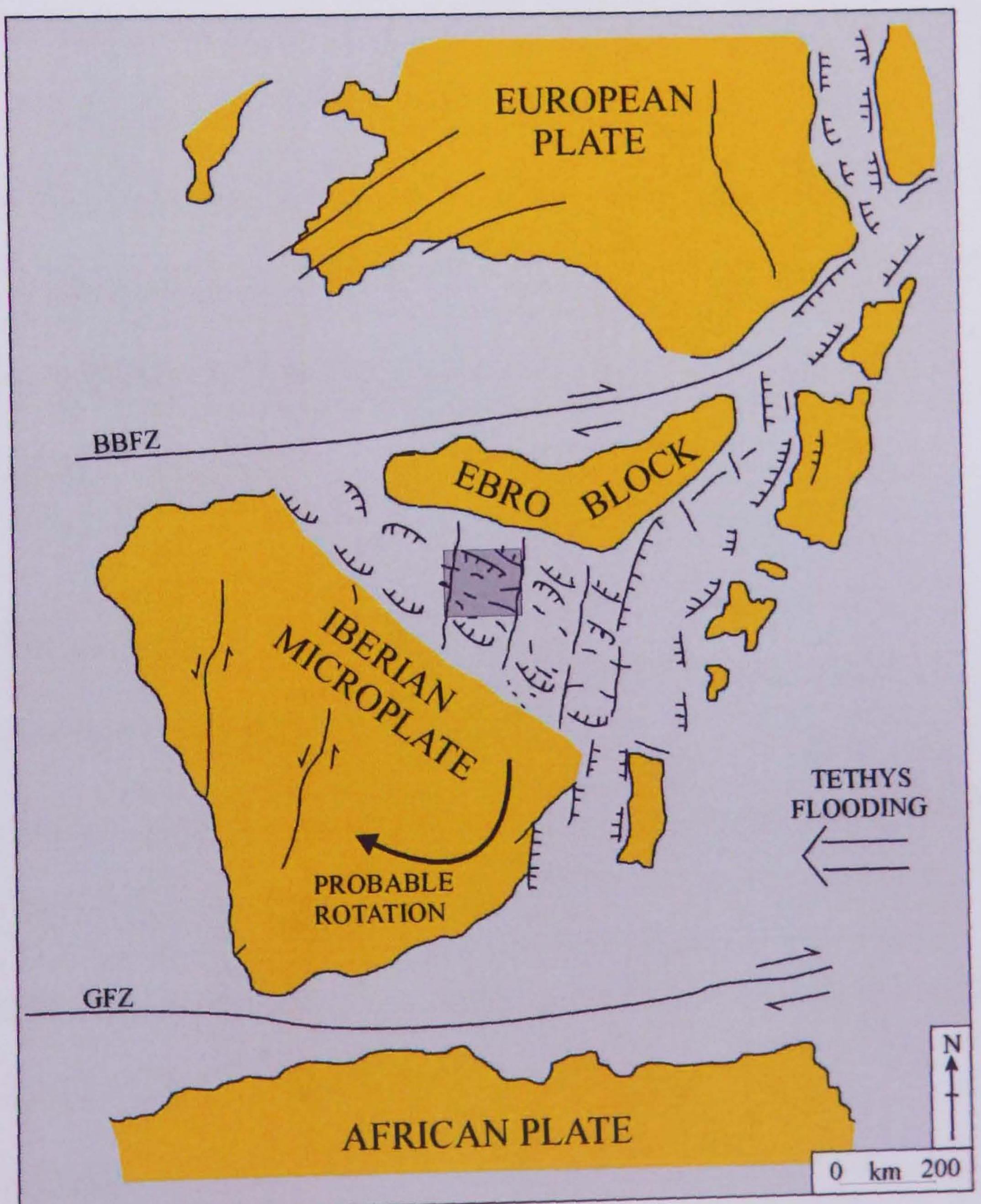


Fig. 2.7 Palaeogeographic map of the Late Carboniferous showing rotational movement of the Iberian Microplate along Bay of Biscay Fault Zone (BBFZ) and the Gibraltar Fault Zone (GFZ). Dark grey boxed area indicates the thesis study area within the Iberian Ranges (Adapted from López-Gómez & Arche, 1997).

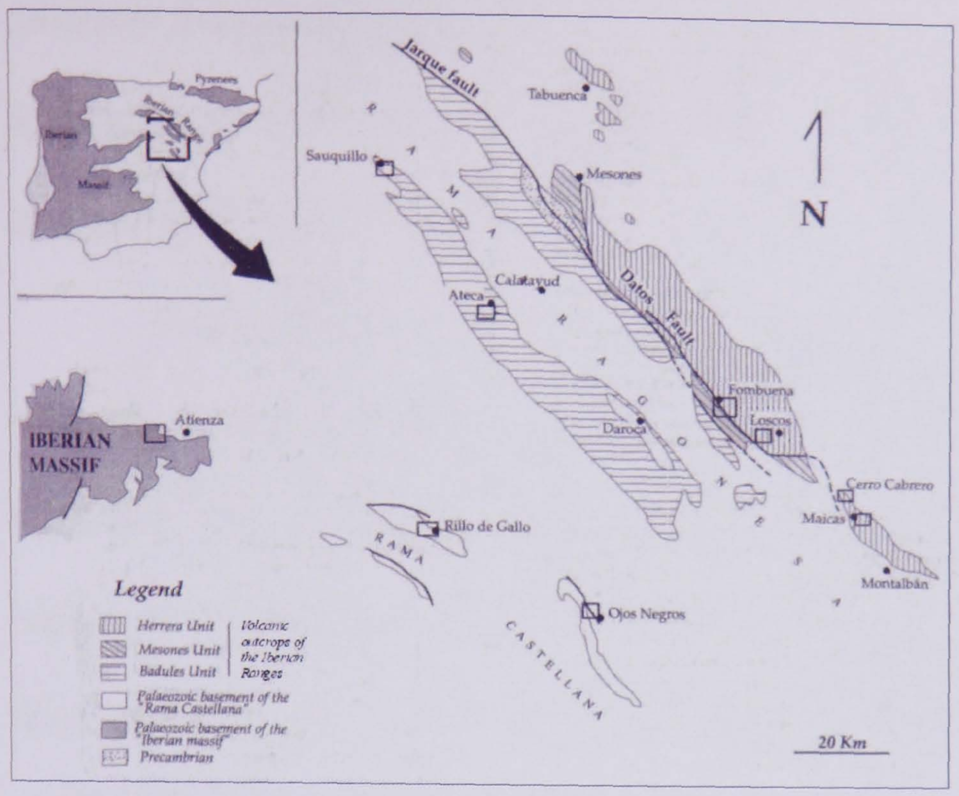


Fig. 2.8: Geological map of the Iberian Ranges showing the main Late Carboniferous-Lower Permian outcrops (adapted from Castro et al. 2002 and Lago et al. 2004).

The depositional succession contains abundant fossil flora and pollen assemblages supporting an Autunian age (~289 Ma) (Sopeña et al. 1988; Castro et al. 2002; Lago et al. 2004). This volcanism is related to the development of sedimentary basins across the Iberian Ranges, in particular the Central Iberian Basin (CIB) and the Iberian Basin controlled by reactivation of late-Variscan normal and strike-slip fault structures (Castro et al. 2002).

2.2.3 Upper Palaeozoic to Lower Mesozoic

2.2.3.1 Upper Permian to Middle Triassic

Crustal extension, caused by late-Variscan movement along the megashear zone bounded by the BBFZ and GFZ, produced a number of intraplate rift basins within the Iberian Microplate. Sopeña et al. (1988) acknowledged that the presence of earlier Hercynian structural influences was an important control on the Mesozoic evolution of Iberia.

The complex graben systems that evolved in the Permian occurred along the margins of the Iberian Ranges, the NW/SE trending, intracratonic, linear alpine structure located in central and eastern Spain. The rift basin systems were bounded by parallel NW-SE orientated normal faults developed during widespread extensional periods (Fig. 2.9).

These elongated structurally controlled depocentres, 1-2 km in length, were subjected to strain, in the Late Permian, resulting in along-strike propagation of faults and linkage of adjacent basins. However, extension rates varied and whilst higher levels of extension produced substantial basins, such as the Iberian Basin and the CIB, lower rates had the effect of creating relative uplifted areas or narrow corridors (Arche & López-Gómez, 1996; López-Gómez et al. 2002).

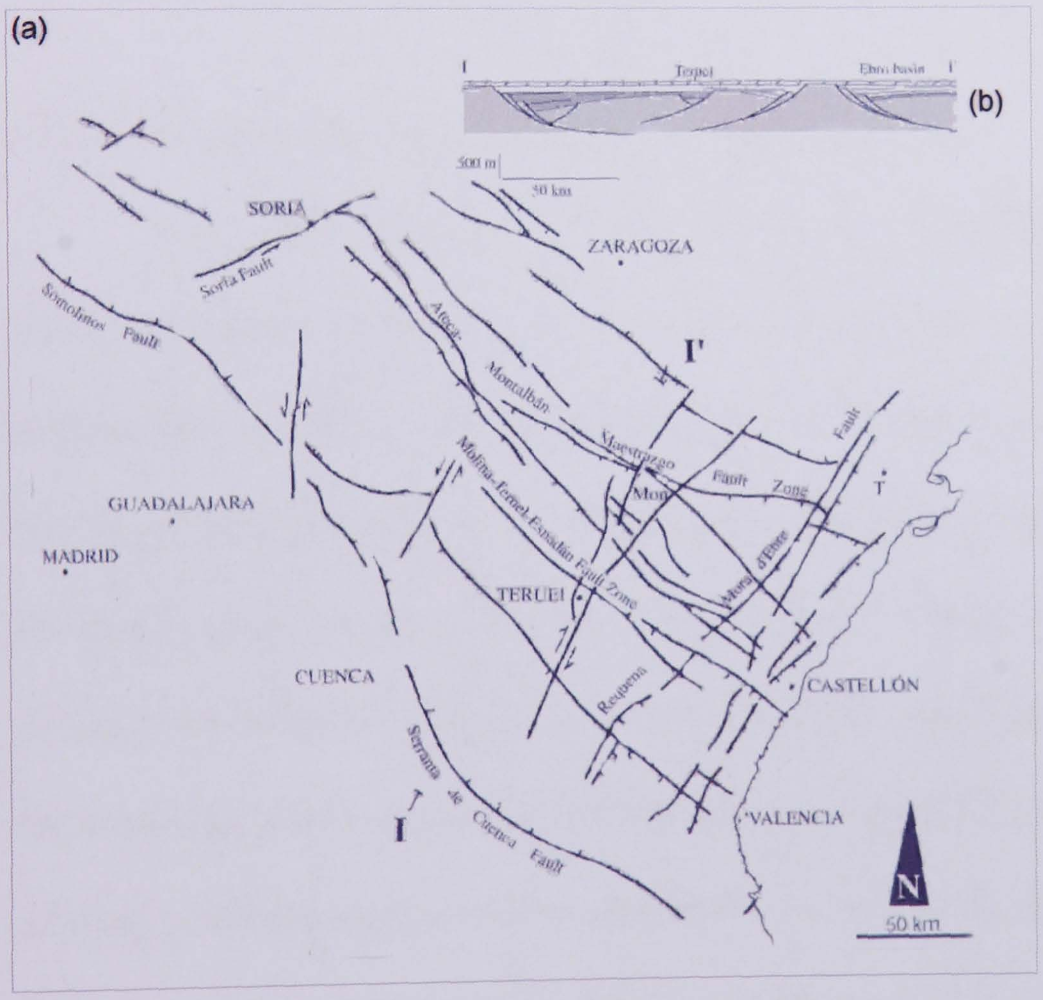


Fig. 2.9: (a) Active faulting during the Permo-Triassic rifting and extension of the Iberian Ranges region; (b) Cross-section of the Late Permian-Early Triassic graben geometry of the rifting across the Iberian Basin (taken from López-Gómez et al. 2002).

Initially called the Iberian Trough (Sánchez-Moya et al., 1996), the Iberian Basin existed in the SE Iberian Ranges and is related to coeval basins such as the Ebro, Pyrenean and Catalan (Arche & López-Gómez, 1996). According to Van Wees et al. (1998) forward modelling and backstripping analysis of sediments has determined that the tectonic subsidence history in the Iberian Basin is characterised by pulsating periods of stretching punctuated with relative periods of tectonic quiescence and thermal subsidence. The stretching events have been closely linked with the opening of the Atlantic Ocean and Tethys Sea.

A separate half graben rift basin, the CIB, began to evolve to the NW of the Iberian Basin during the Late Permian. It too formed as a result of continued extension across the Iberian Ranges during the Late-Carboniferous-Permian, and was bounded by reactivated normal fault segments orientated NW/SE. The basin was smaller than its sister basin (the Iberian Basin) to the SE, and at its widest point spanned 50 km and stretched 100 km in length (Fig. 2.10).

2.2.3.2 Permo-Triassic depositional history in the CIB

During latest Thüringian-Autnian (Late Permian-Early Triassic) times, the eastern region of the Iberian Microplate underwent further reorganisation of sedimentary basins and palaeoenvironments resulting in moderate to low subsidence and the pronounced geometry and structure of the CIB in the NW Iberian Ranges. Sediment exposures located in NW/SE orientated outcrops over the Iberian Ranges sit unconformably on a Hercynian basement of deformed Palaeozoic (Cambrian to Silurian) metasediments (mainly slates and quartzites) (Fig 2.11). Sedimentary infilling of Buntsandstein facies was similar in both the Iberian basin and the CIB with alluvial fan conglomerates, lacustrine systems and fluvial deposits common. However, despite these facies being contemporaneous, there is no evidence for their interaction across the whole basin. The deposits of the Iberian Basin have previously been divided up into six major sequences (Arche & López-Gómez, 1999), however the same 'alloformations' are not seen in the CIB, instead the CIB first experienced synrift sedimentary deposition towards the end of the Upper Permian. In the CIB,

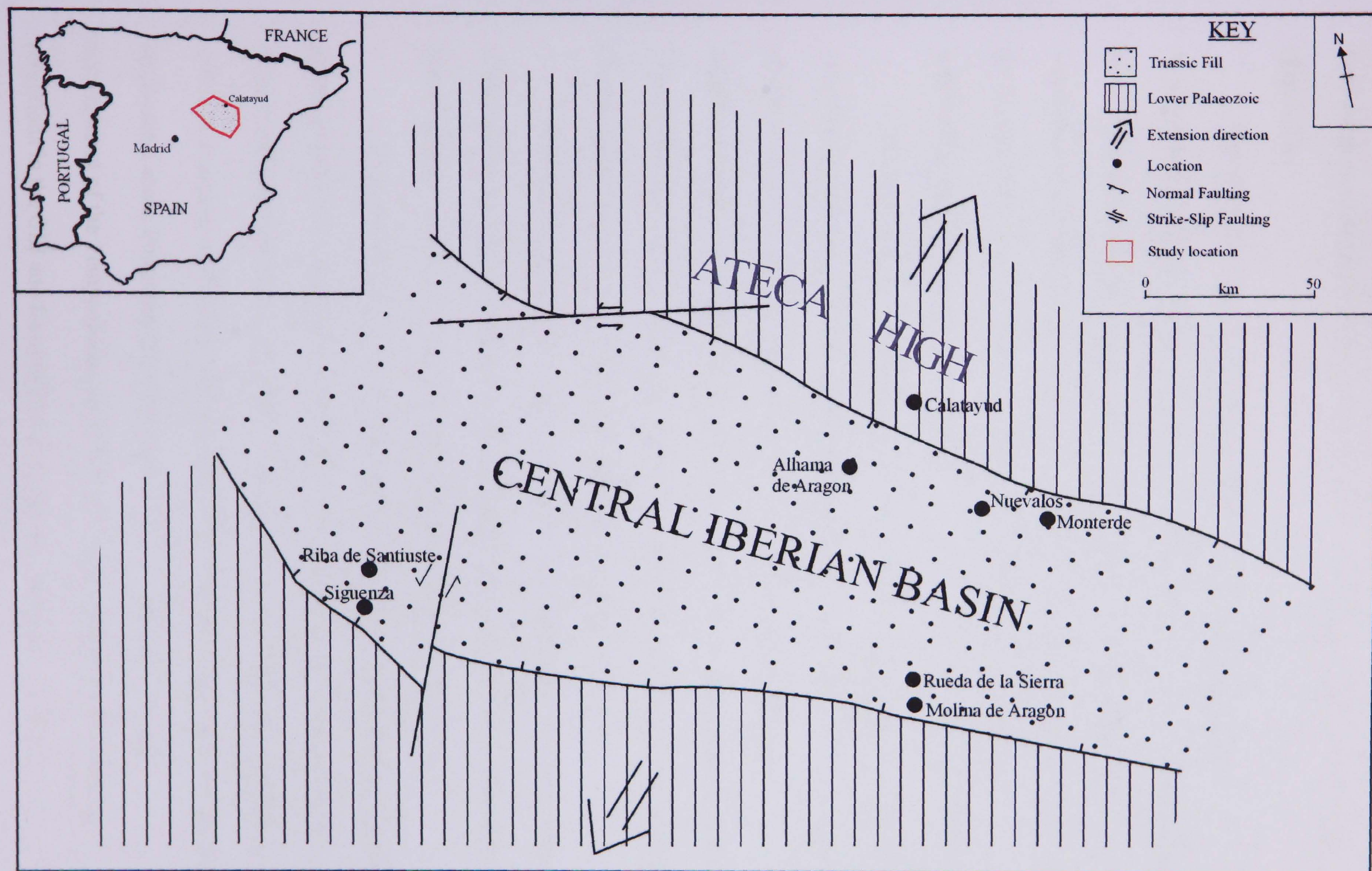


Fig. 2.10: Sketch map of the overall plan view structure of the Central Iberian Basin (CIB), central Spain.

Autunian (Upper Permian) deposits are absent, although Thüringian (Latest Permian) beds are present represented by Buntsandstein facies, but not the 'Saxonian' facies (Fig. 2.12).

The deposits of the Buntsandstein facies in the CIB include classic continental red bed alluvial fan and playa lake sediments at the northern margin and alluvial fan and fluvial deposits at the southern margin and intrabasinal areas. Deposition of alluvial and fluvial red beds continues through the Permo-Triassic until the Middle Triassic where sedimentation in the CIB changes to deltaic facies, superseding their continental predecessors.

An important characteristic of the Permo-Triassic basin infill is the lack of volcanic deposits found in other rift basin settings and expected due to the amount of crustal extension in the CIB (López-Gómez et al. 2002). A clear absence of magmatic material in the outcrops available for study indicates some early to middle Triassic volcanic synrift activity, although some monogranitic dykes are found in the Central Range of the Iberian Peninsula (López-Gómez et al. 2002).

The subsidence pattern and low subsidence rate developed over the duration of the infilling of the CIB during the Middle to Upper Triassic, mirroring that of the Iberian Basin to the SE (Fig. 2.13) (López-Gómez et al. 1993, 1998, 2002).

A final, short-lived rifting episode during the Middle Triassic caused a major graben polarity inversion in the Iberian Basin and is likely to have had an influence on the CIB (López-Gómez et al. 2002). Thick deposits of fluvial conglomerates, up to 600 m in places, in-filled the CIB half-graben adjacent to the southern margin and intrabasinal areas. Following this (during the Ladinian; Middle Triassic), development of the Tethys Ocean initiated a westwards transgression of marine conditions in the CIB and flooded all but the highest topographic areas.

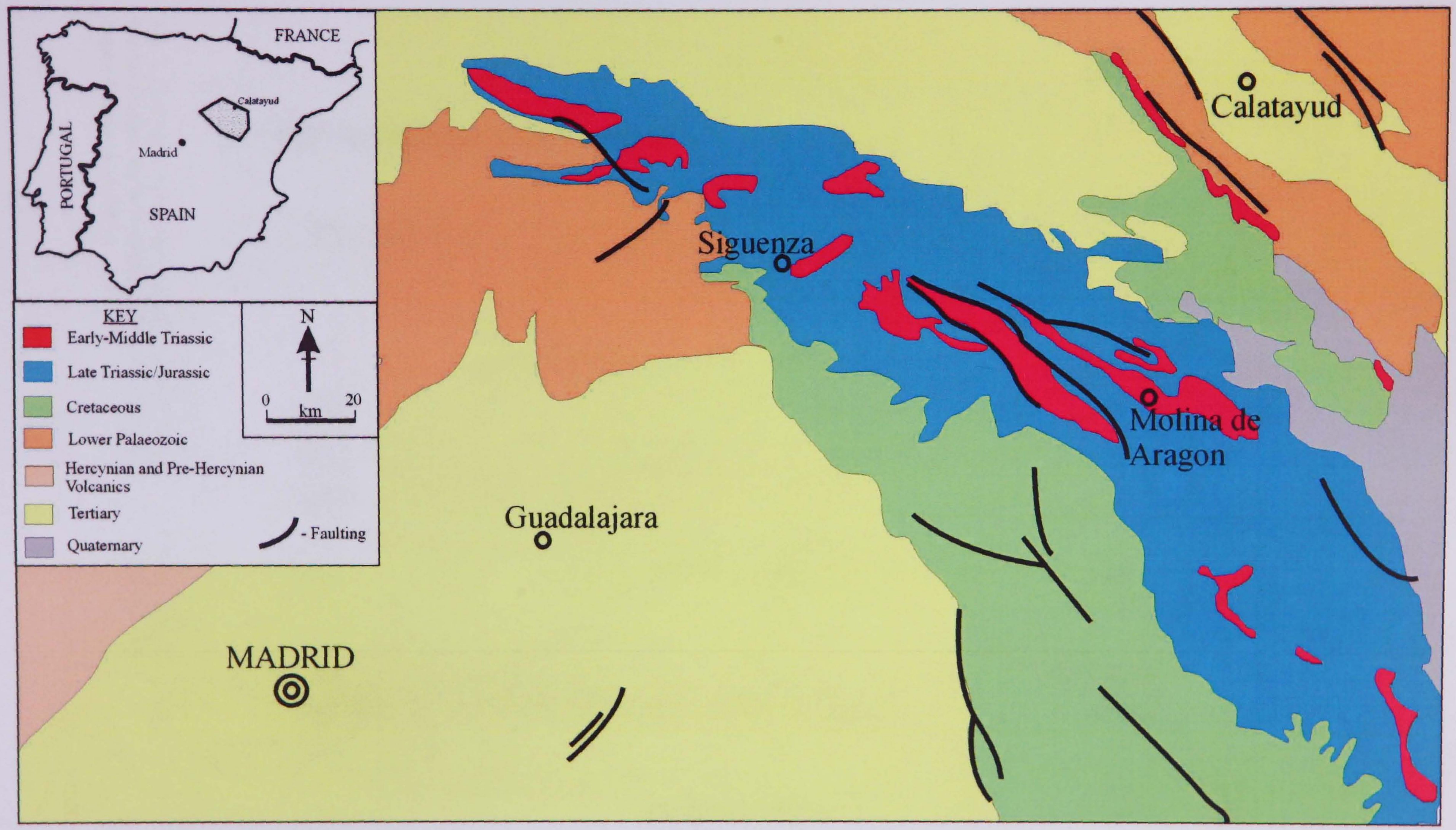


Fig. 2.11: Geological map of the Central Iberian Basin, with Early-Middle Triassic deposits, orientated along a NW-SE lineation, representing deposition at the basin palaeomargin.

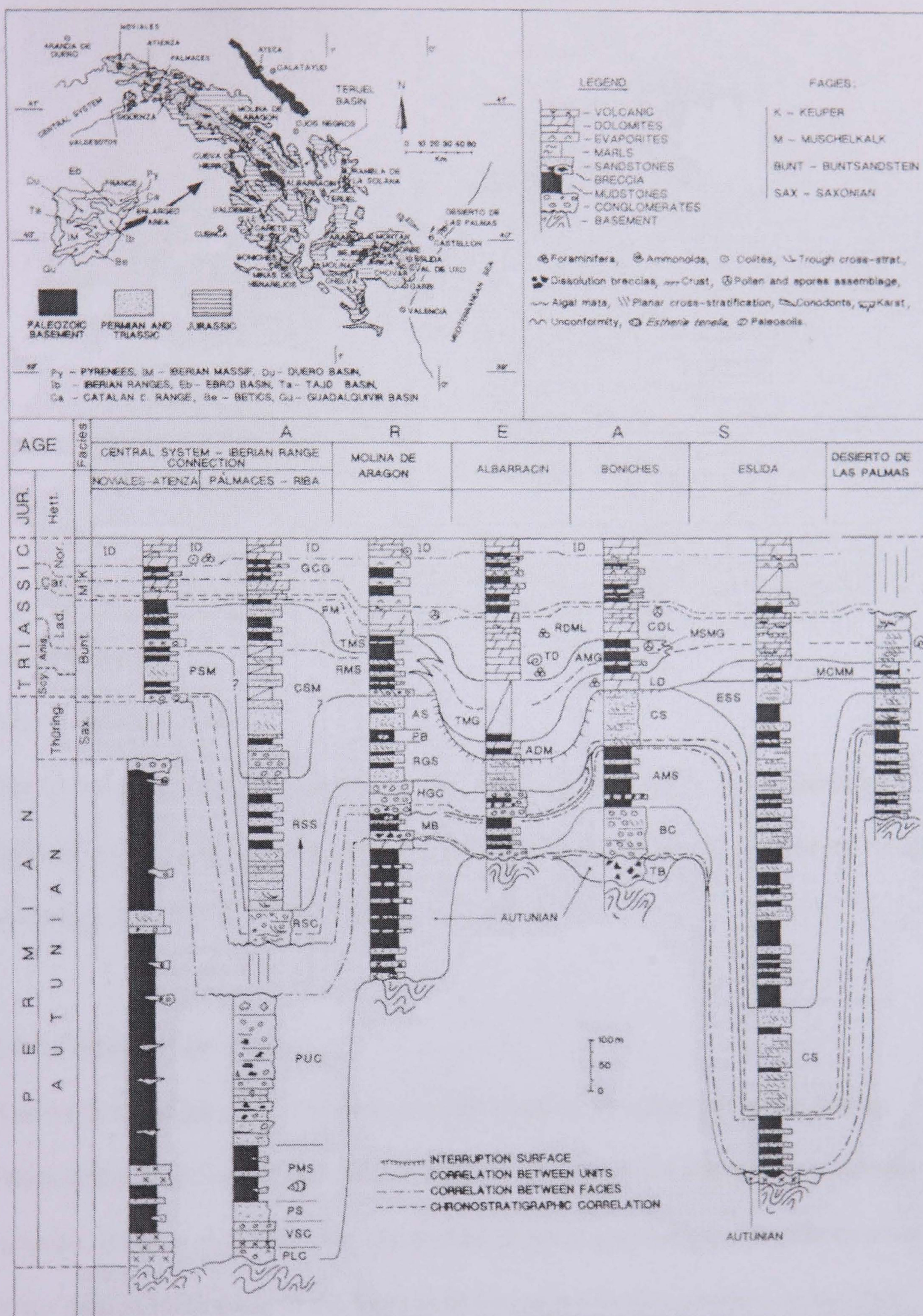


Fig. 2.12: Location map and graphic log panel of the Permo-Triassic deposits of the Iberian Ranges, including Molina de Aragon situated in the CIB (taken from López-Gómez et al. 2002).

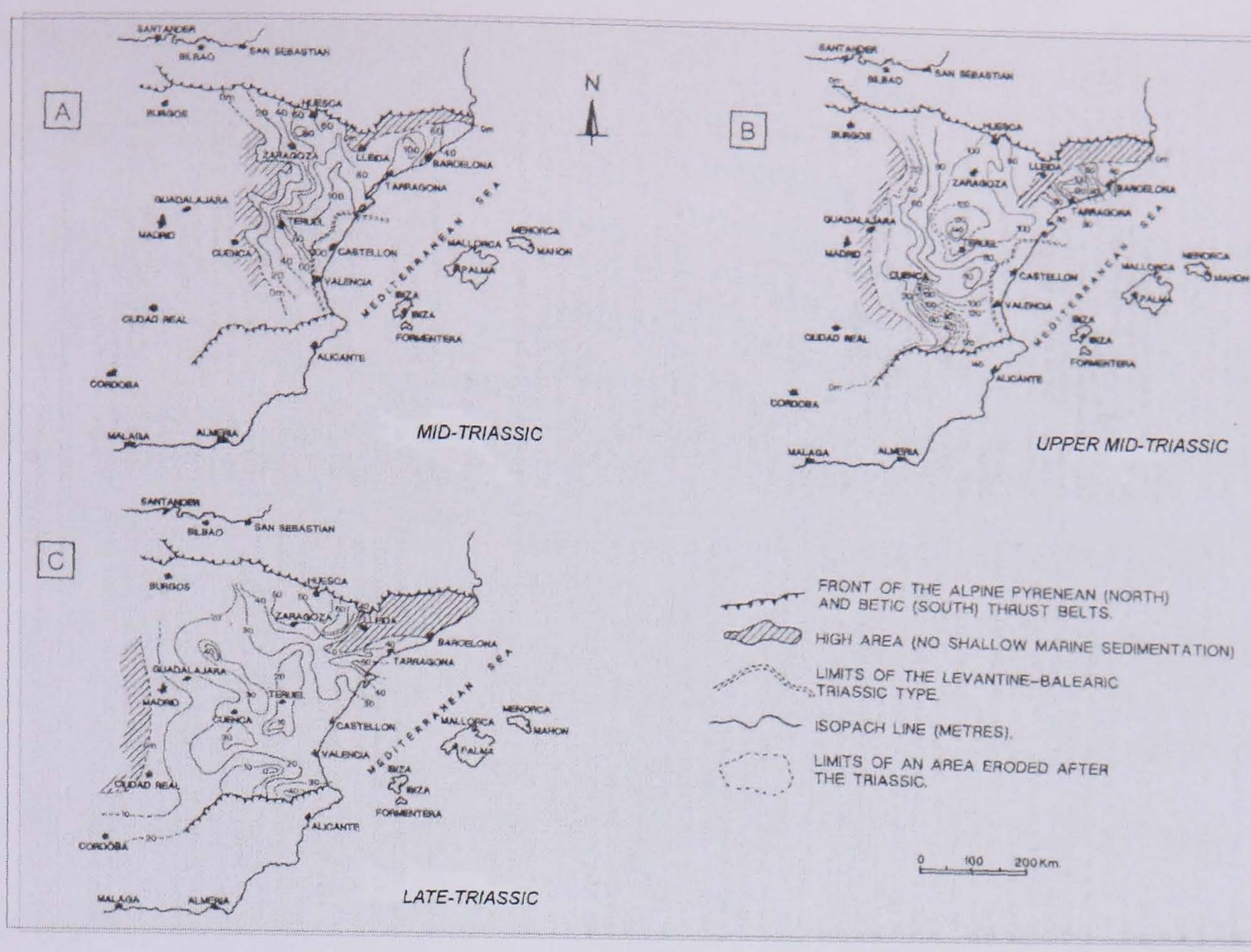


Fig. 2.13: Isopach map of the Triassic evolution of subsidence corresponding to Muschelkalk facies deposition in the Eastern Iberian Peninsula (adapted from López-Gómez et al. 2002).

2.2.4 Mesozoic

2.2.4.1 Early Triassic

Due to the nature of the sedimentation and basin histories, the events of the Early Triassic in the central areas of the Iberian Microplate have been discussed previously in section *2.2.3* and should be referred to therein.

2.2.4.2 Middle-Late Triassic

A subsequent, thermally controlled, postrift phase of development of the Iberian basins began at the end of the Middle Triassic and continued into the Late Jurassic (López-Gómez et al. 2002). The Tethys Sea began to encroach on the eastern areas of the Iberian Microplate in the form of five transgression-regression cycles, each one successively migrating further westwards between late-Anisian and Ladinian (Middle Triassic). Palaeozoic highs, such as the Ateca high that bounded the northern margin of the CIB, were drowned (López-Gómez et al. 1998, 2002) and a single basin was established across all southern areas parallel and adjacent to the Iberian Ranges. Sedimentation was not uniform; shallow marine calcareous and siliciclastic deposits of Muschelkalk facies and evaporitic units of the Keuper facies were deposited across the now amalgamated CIB and Iberian Basin. The latter facies accumulated in areas of high subsidence, producing thick (60-250 m in total, 100 m thick at Molina de Aragon: López-Gómez et al. 2002) evaporitic, gypsum and mudstone units. Tripartite carbonate, siliciclastic sediment and dolomite limestone units of the Muschelkalk, ranging between 40-120 m thick in total, predate and are contemporaneous with deposits of the Keuper facies, as a result of three major transgressive events across Iberia. The deposits of the Muschelkalk and Keuper facies form pronounced and laterally persistent ridges across the present day Iberian Ranges landscapes.

2.2.4.3 Jurassic

Late Triassic and Early Jurassic rifting enhanced the coverage of the Tethyan transgression (Salas & Casas, 1993; Aurell et al., 2002; Gibbons & Moreno, 2002). The Iberian Massif and areas of western Spain remained above sea level but reduced in extent as seas from the north and northeast grew. A Lower Jurassic continental shelf formed on the southern margin of the Iberian Massif and bordered a narrow marine trough that now linked Tethys Ocean with the Atlantic Ocean (Scandone, 1975). This, together with the eastwards extending Iberian Basin, formed the Prebetic shelf system, with the Subbetic basin and Balearic shelf and basin developed further to the South (Fig. 2.14).

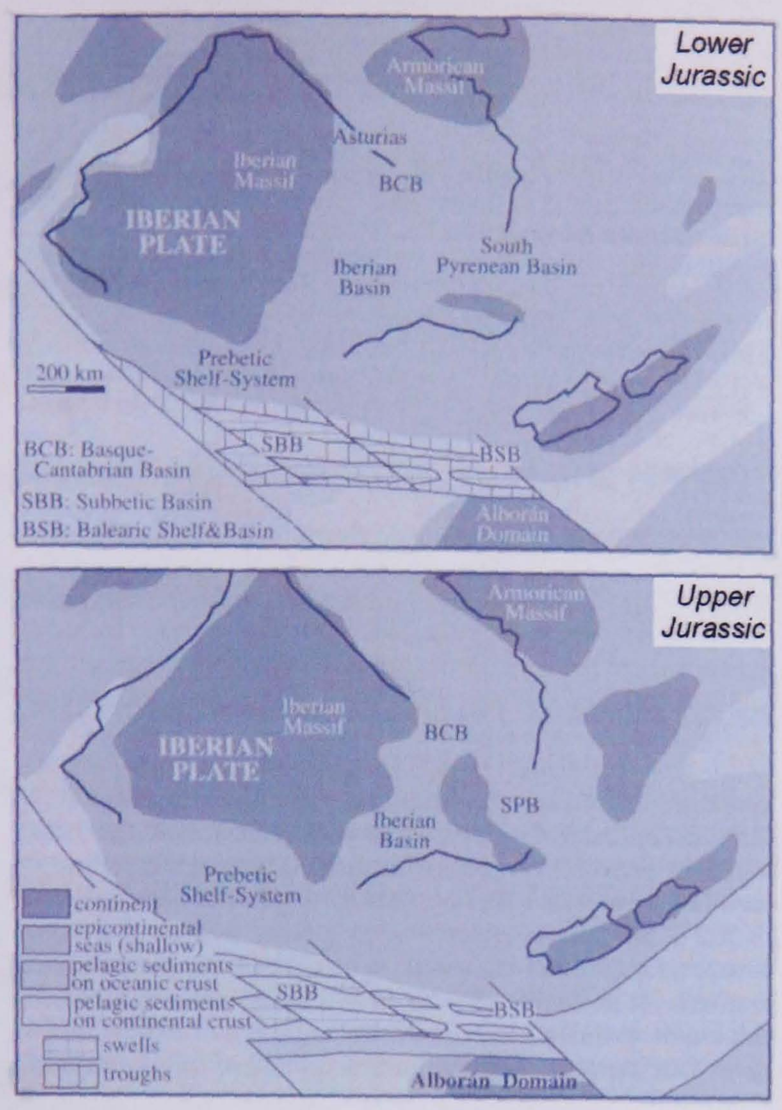


Fig. 2.14: Palaeogeographic reconstructions of the Iberian Microplate during the Lower Jurassic and Upper Jurassic with varying sedimentary domains of south and east Iberia (modified from Aurell et al. 2002).

Across the Iberian Ranges, and particularly in the ancestral CIB and Iberian Basin, normal faults were again reactivated during the Jurassic and Early Cretaceous and fault-related subsidence started to control the basin bathymetry leading to an uneven, complex history of sedimentation. Jurassic sediments of the Iberian Ranges and southern Catalonian Coastal Ranges outcrop extensively across the eastern half of the Iberian Peninsula. Facies and thickness variations occur due to the differential movements over space and time. A basal Jurassic unconformity is present and is overlain by dolomitic-evaporitic-breccia units due to a progressive deepening of the marine conditions is recorded (Aurell et al., 2002). This deepening, when examined in detail, is actually comprised of a series of deepening to shallowing depositional sequences that only reached the Iberian Basin later in their evolution. Each is recognisable by the distinctive ramp facies depositional sequences that are found throughout the basin (Tucker et al. 1993; Calvet & Tucker, 1995).

The base of the Middle Jurassic coincides with the break-up of the carbonate platforms of the eastern Iberian Peninsula and is marked by a discontinuity. Fragmentation, into sub-basins and platforms, occurred as a result of reactivation of normal faults and was accompanied by volcanic intrusion, in the interior of the Iberian Massif, of a 400 km long dyke emplaced during this stretching period. The upshot of this synsedimentary tectonic activity is a discontinuous and erratic stratigraphic record for this time period. In the central part of the Iberian Basin, there existed two platform areas: the Aragonese and the Castillian platforms. The platforms are composed of facies associated with a mid- to outer-carbonate ramp environment (oolitic-dolomite facies) and a relatively deep marine facies of biomicrite association. Again, discontinuities are identified across the Iberian Basin related to a series of major deepening-shallowing upward cycles (Salas & Casas, 1993; Aurell et al. 2002).

Palaeogeographic reorganisation during the Late Jurassic led to the formation of a wide, homogeneous carbonate ramp with reduced relief and dipping gently towards the east. Further fault reactivation induced facies change and increased sedimentary thickness in bathymetrically lower areas. Elsewhere, Upper Jurassic (Oxfordian) deposits are poorly represented or absent on higher levels, whilst Kimmeridgian facies reflect a shallow, inner platform environment with carbonate deposition common (Fig. 2.15) (Aurell & Meléndez, 1993; Aurell et al., 1998).

2.2.4.4 Cretaceous

The Cretaceous rocks of Spain outcrop in three Alpine orogenic belts: the Betic Cordillera, the Pyrenees, and the Iberian Ranges (Martín-Chivelet et al., 2002). They represent Cretaceous deposition of sediment in four basins covering the Iberian Peninsula (Figs. 2.15, 2.16). The literature suggests that inversion (Sópeña et al., 1988; Salas et al., 2001) and a reaction to the beginnings of the Alpine cycle during the Late Jurassic and Early Cretaceous ensured the basins provided a variety of environments - alluvial fans to pelagic seas - in which sedimentation could occur.

An Early Cretaceous continental rifting phase produced four sub-basins within the Iberian Basin and allowed thick successions of continental to shallow marine carbonates and clastics to form. In particular, exceptional vertebrate and plant remains have been found in what appears were exceptional preservation settings. The Late Cretaceous was a post-rift interval when the Iberian Basin formed a narrow seaway linking the north and south Iberian continental margins. At this time, there was once again a marine transgression westwards resulting in the deposition of shallow marine limestone intercalated with sandy carbonates and marls, accumulated under the influence of global eustacy and regional tectonics. Up to 800 m sediment collected in the basin as shallow seas covered the majority of the eastern portion of Iberia – a consequence of thermally induced subsidence and sea level rise (Salas et al. 2001; Capote et al. 2002; Martín-Chivelet et al. 2002).

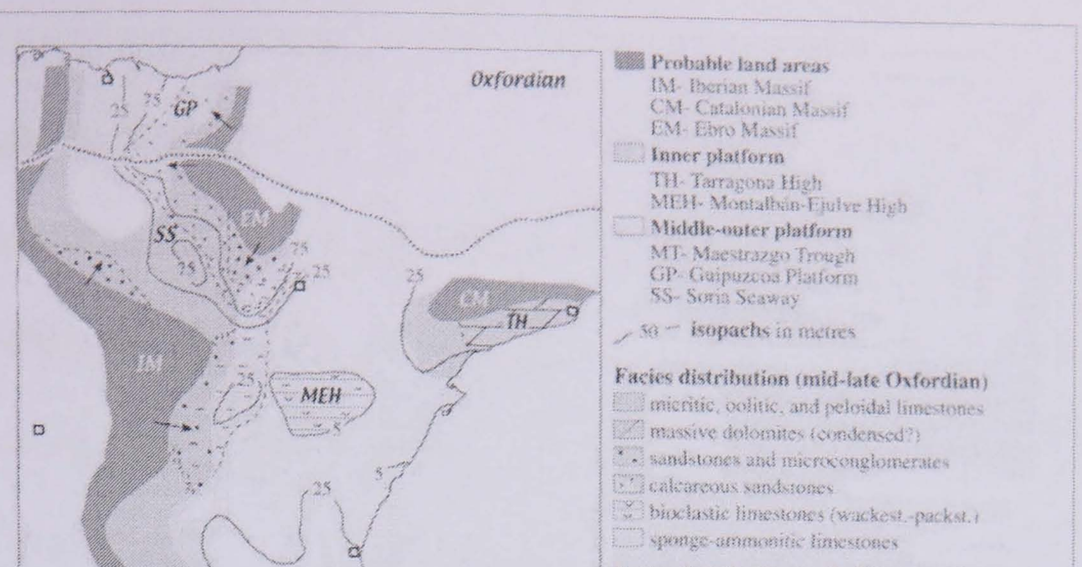


Fig. 2.15: Facies distribution maps of the Upper Jurassic (Oxfordian-Berriasian) in eastern Spain (taken from Aurell et al. 2002).

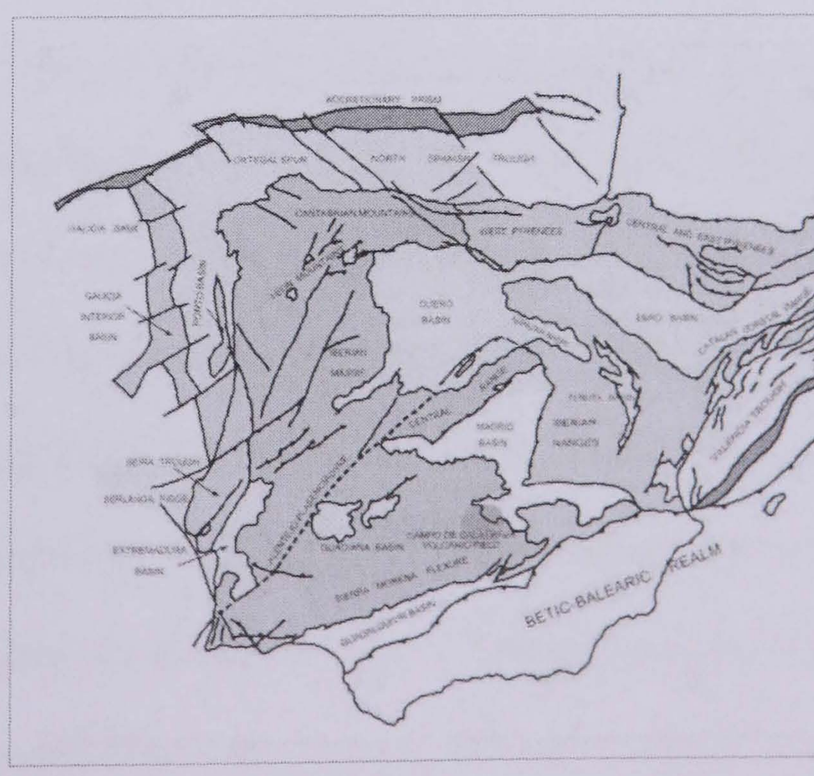


Fig. 2.16: Cretaceous and Cenozoic Basins of Iberia (taken from Capote et al. 2002).

2.2.5 Tertiary to Recent

From the latest Cretaceous into the Miocene the geology of Iberia was affected by the Alpine Orogeny (Fig. 2.17) (Alonso-Zarza et al., 2002; Capote et al., 2002). The Iberian Plate was being obliquely subducted beneath the Eurasian Plate resulting in continental collision.

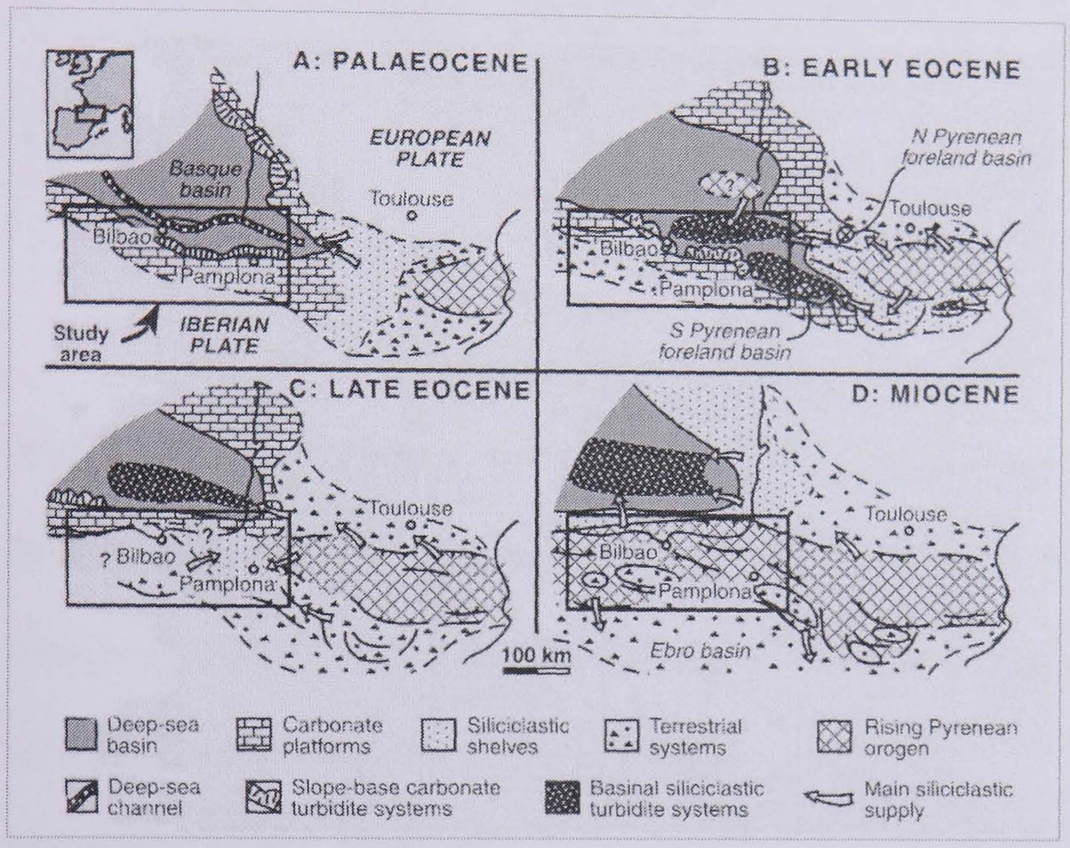


Fig. 2.17: Progressive collision of the Iberian Microplate and European Plate during the tertiary (taken from Alonso-Zarza et al. 2002).

Rapid subsidence of marine troughs and synsedimentary tectonic thrusting occurred as turbiditic sediments filled up the voids. The inversion of this Mesozoic passive to transtensional plate margin helped to form the mountainous region of the Pyrenees and major northwards and southwards thrusting related to persistent convergence (of the Iberian Microplate and the rest of Europe) maintained the structure of the Ebro foreland basin and influenced the sediment supply and facies distribution (Fig. 2.18).

Across the Iberian Ranges, the onset of the Alpine orogenic events produced newly emergent highs separated by increasingly isolated depocentres (Alonso-Zarza et al. 2002; Gibbons & Moreno, 2002). Normal faults that once bordered the rift basins of eastern Iberia were now reactivated as thrust faults, causing inversion of the basin and uplift of a topographic high that today is known as the Iberian Ranges.

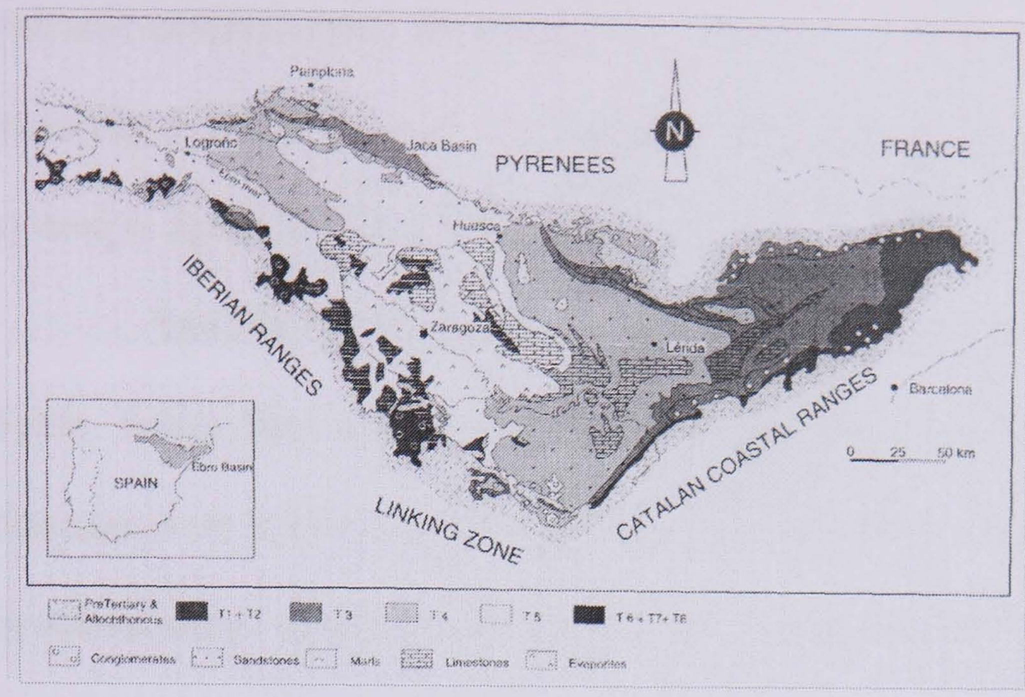


Fig. 2.18: Geological map of the Tertiary deposits of the Ebro Basin. T1 (oldest) to T8 (youngest) represent tectono-sedimentary units (taken from Alonso-Zarza et al., 2002).

The basin, now amalgamated into the larger (10,000 km²) Madrid Basin (Fig. 2.19), was filled with up to 2000 km of Tertiary terrestrial deposits, identified by deep boreholes and seismic profiles. These deposits record the development of a mosaic of continental environments (Calvo et al., 1989, 1990). Evaporitic units, as well as lacustrine deposits and alluvial fan facies grace the exposures now found in this area of Spain (Alonso-Zarza et al., 2002). Tertiary sedimentary rocks in Spain were thus deposited during and after Alpine orogenic compression in the Iberian domain.

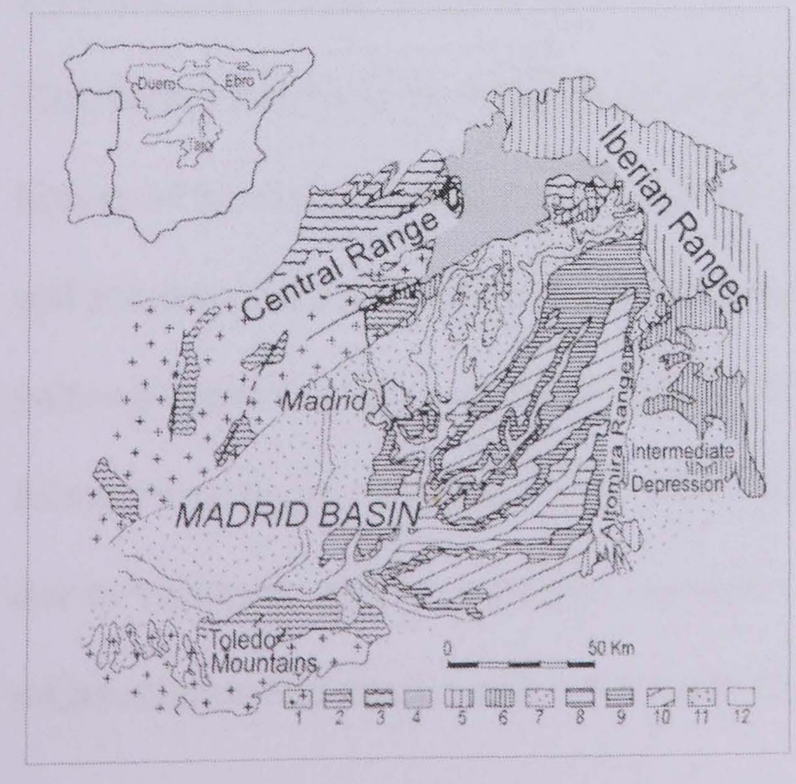


Fig. 2.19: Geological map of the Tertiary Madrid (Tajo) Basin. Lithology key: 1, plutonic rocks; 2, shales, marbles, quartzites and gneisses; 3, shales and metagreywackes; 4, shales, quartzites, and metavolcanic rocks; 5, Mesozoic basement (mainly carbonates); 6, Palaeogene (terrigenous and carbonates); 7, lower to upper Miocene terrigenous sediments; 8, lower Miocene unit; 9, intermediate Miocene unit; 10, upper Miocene unit; 11, Pliocene; 12, Quaternary (taken from Alonso-Zarza et al. 2002).

In contrast to the Tertiary rocks of Iberia, those of the Quaternary record a host of facies including glacial, alluvial, fluvial, lacustrine, aeolian, coastal and volcanic environments. These indictors to the history of the modern environment, including evidence for the initiation of the Ebro Basin, allowed the largest fluvial system in Spain to find and develop a drainage route into the Mediterranean Sea.

The Iberian Ranges played their part in the Quaternary development of Spain. Today, they form an important fluvial divide, separating Atlantic fluvial drainage from Mediterranean drainage (Gutiérrez-Elorza et al., 2002). The present geomorphology of the Iberian Ranges was created by late Tertiary tectonism, which is responsible for high grounds and associated depressions seen on the current landscape. The pulse of structural influence forced a palaeoenvironmental change from calcareous sedimentation to alluvial plains and the generation of wide mantled pediments. At present, the pulses of tectonism still continue, although have reduced effect on sedimentation (Gutiérrez-Elorza et al., 2002). A palaeohistory that has left a signature in the rich variety of deposits found in exposures across the Iberian Ranges.

2.3 Summary of the main events

The Iberian Peninsula provides an excellent record of not only the lithostratigraphic history of Southern Europe, but also offers a good account of the palaeogeography and palaeoenvironment of rift basin development along the Iberian Ranges. It is palaeogeographical readjustment of the continents that led to closure of the oceans, formation of mega-landmasses such as Pangaea, and creation of extensional basins due to Variscan orogenic processes throughout the Palaeozoic. Mesozoic sedimentation and continuation of tectonic movement then caused the crust to extend further until the Tethys Sea encroached westwards representing a major marine transgression.

The marine realms of the late Mesozoic played host to numerous episodes of sedimentation controlled by eustatic and regional tectonics until late in the Cretaceous the Alpine Orogeny began to affect the Iberian Microplate. The result was a convergence of the Iberian and Eurasian plates and eventual subduction of the former. This caused inversion of many eastern Iberian basins and created the Ebro foreland basin as well as the large Madrid Basin, both of which are influential in capturing fluvial systems of the present day.

The structure of the CIB can still be observed today (Fig. 2.20), even though the basin has been subjected to deformation, orogenic inversion and the deposition of thick successions of sedimentary cover from countless geological episodes. The excellent weathering profile and general basin physiography lends the CIB to be studied in detail through outcrop analysis of the synrift sedimentary fill and associated tectonic and climatic events (see Chapters 3, 4 and 5).

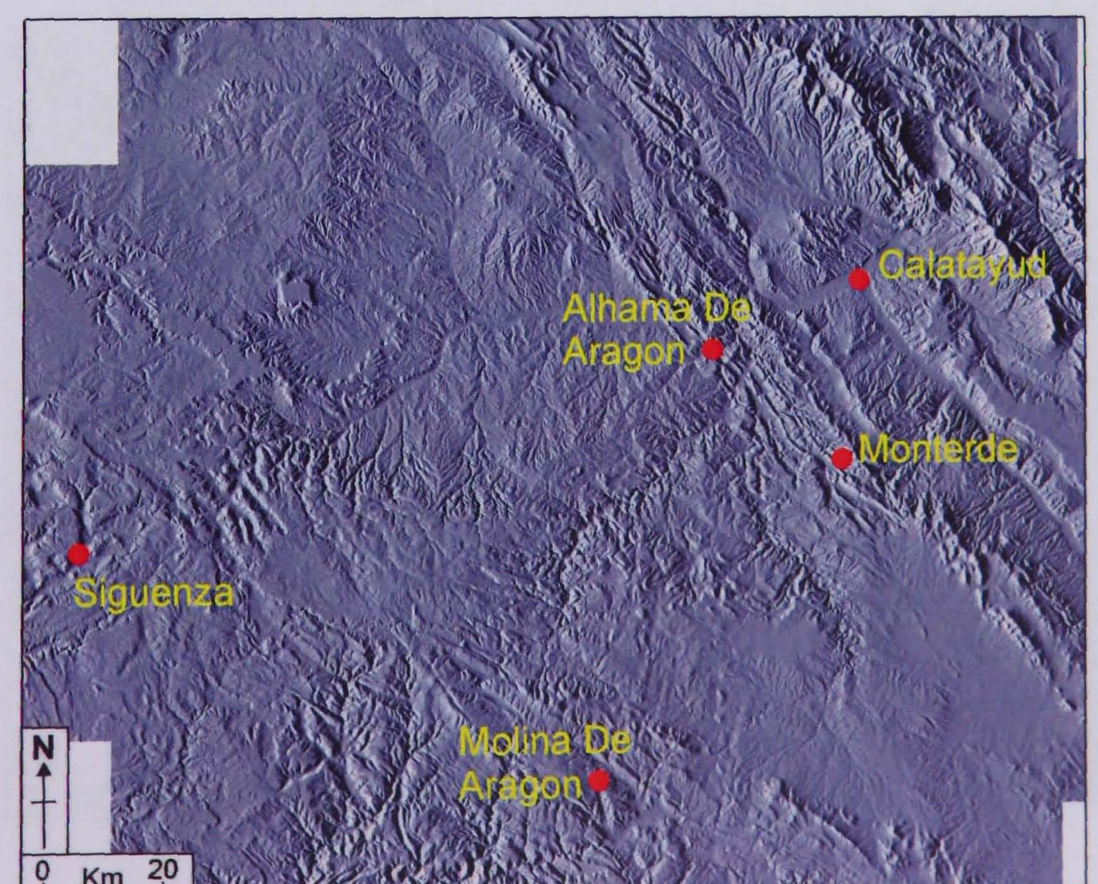


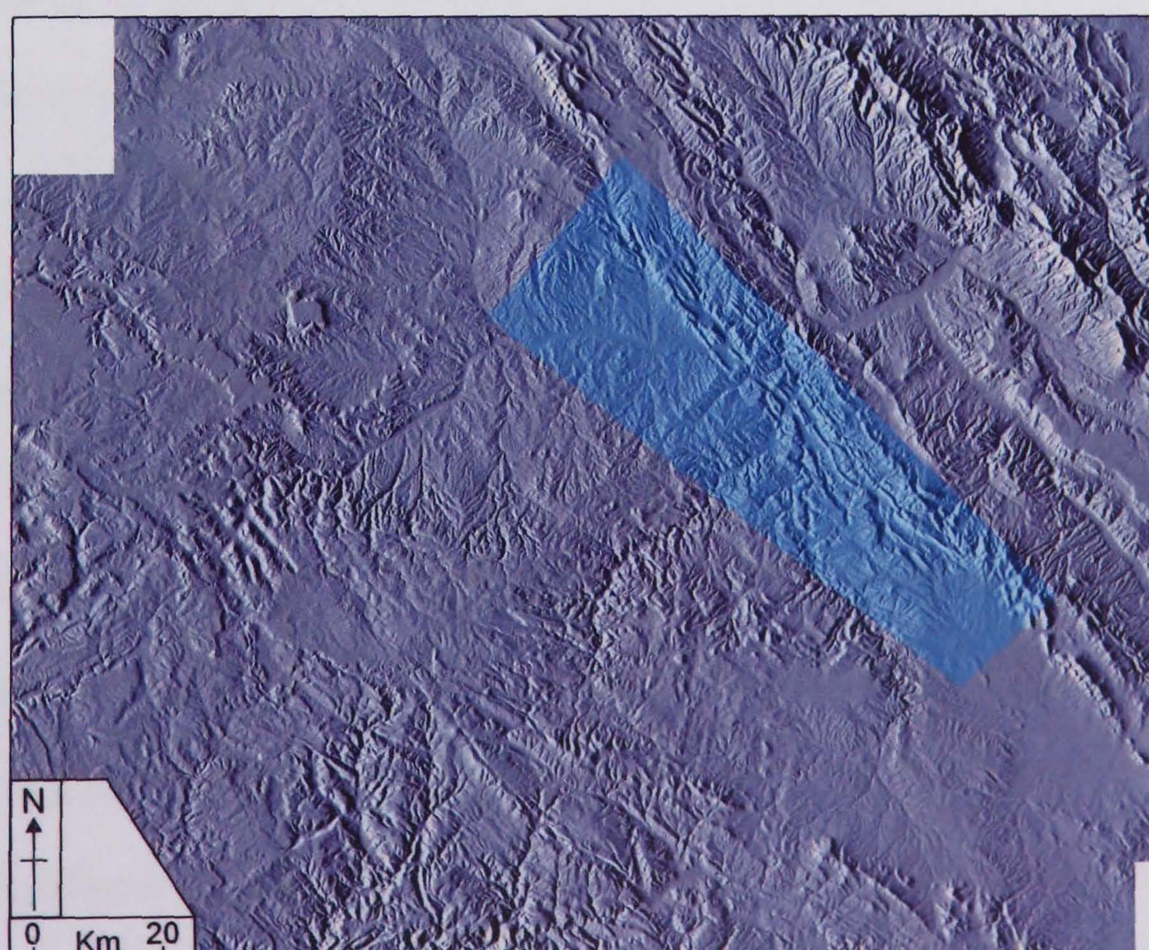
Fig. 2.20: Satellite image of the modern day Iberian Ranges clearly displaying the wedge-shape structural signature of the CIB on the landscape. Refer to Fig. 1.10 and 1.11 for locations.

Chapter 3

Sedimentation at the Northern Margin of the Central Iberian Basin

Key Findings:

- This chapter documents the synrift sedimentary facies and architectural changes along a 40 km strike section of the CIB;
- The basin boundary is dominated by several normal fault segments (<5 km in length) that are joined by relay zones and some transfer faults;
- Regional stratal surfaces within the succession have been used to identify time equivalent units that demonstrate variability in thickness and architecture, related to the tectonic development of basin margin normal faults and;
- Synrift sediment flux entered the basin via irregularly spaced structurally controlled conduits that indicate an existence up until the late stages of basin development and rift evolution, a period of c. 6.5 Myr.



3.1 Introduction to basin margin sedimentation

Sedimentation in rift basins is a topic in earth science that has received increasing discussion in the literature (e.g. Leeder & Gawthorpe, 1987; Alexander & Leeder, 1990; Frostick & Steel, 1993; Gawthorpe & Leeder, 2000). However, our understanding of the nature of deposition at the margins of rift basins remains limited partly due to reliance on subsurface seismic sections. The CIB deposits in central Spain provide an excellent record of synrift sedimentation and allow detailed investigation into synrift sedimentation. The focus in the past has been on the effects of allocyclic controls such as climate and tectonics (e.g. Manspeizer, 1985; Leeder et al., 1998; Gawthorpe & Leeder, 2000) on sediment supply and facies deposition, however their interaction is rarely addressed in the literature (Hall & Jones, *in prep.*).

Sedimentation at the margin of the Central Iberian Basin (CIB) formed in a number of different, yet connected, environments and the deposits now provide a detailed geological record of continental to marine facies (Fig 3.1).

This chapter focuses upon the continental sedimentary evolution along the northwest margin of the CIB during the Late Permian to Early Triassic. At this time a Hercynian basement lineament, the Ateca High, controlled a system of half grabens under an extensional structural regime and produced varying scales of displacement along the basin boundaries. The irregular spacing of fault-controlled topographic conduits along strike influences sediment flux to the CIB. The longevity of these depositional systems characterises sedimentation along the northern margin and is an important new finding amongst the rift basin literature.

The influence of climate at the northern margin of the CIB had a marked effect on the sedimentology and distribution of deposits from source to sink. Climatic

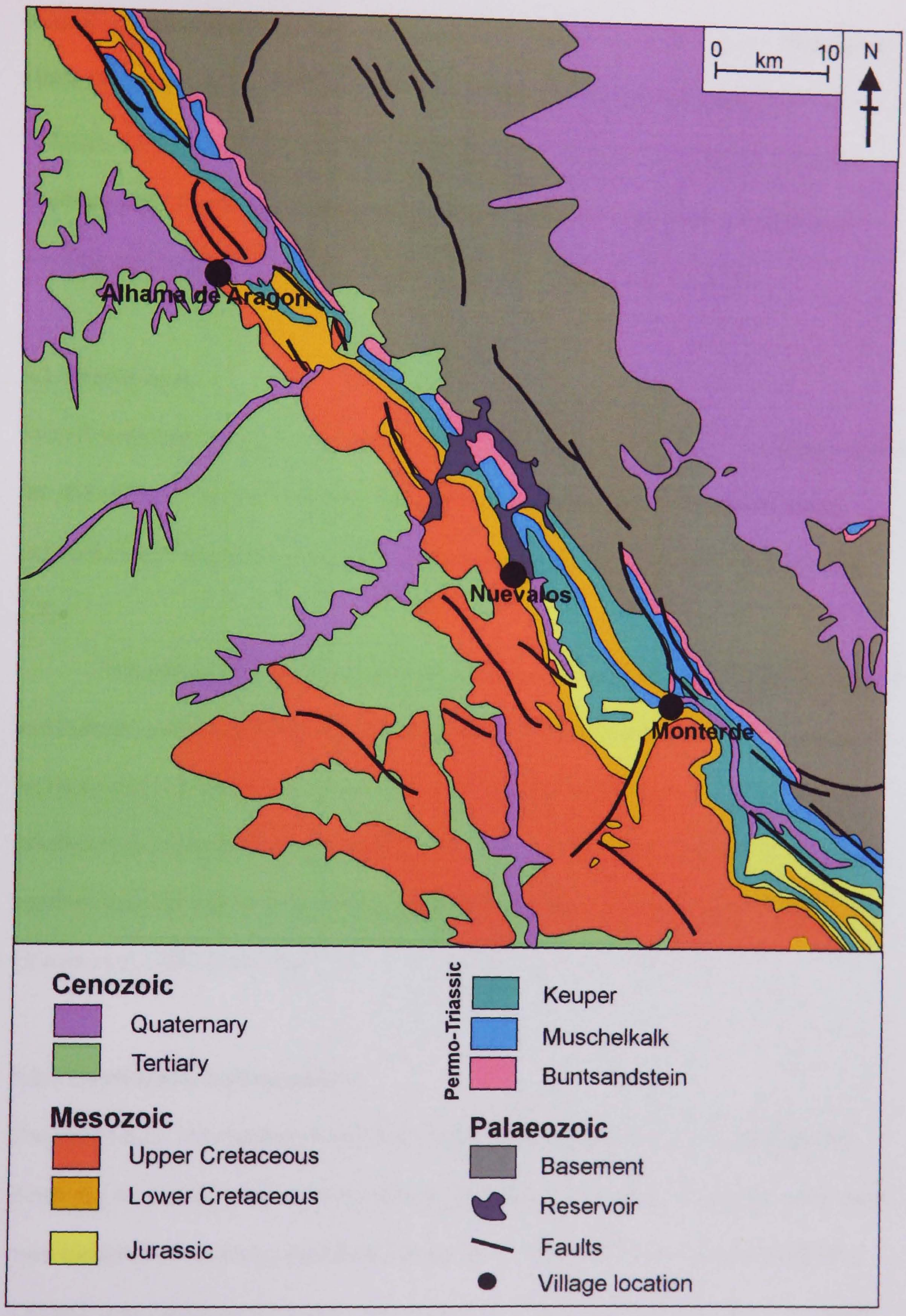


Fig. 3.1: Geological map of the northern margin of the CIB, central Spain.

control on sedimentation is held as an important factor in synrift settings (Manspeizer, 1985; Frostick & Steel, 1993; Leeder et al., 1998; Gawthorpe & Leeder, 2000; Frostick & Jones, 2002) and is just as important in the CIB. However, the interplay between tectonics and climate is the focus of this chapter as the two are often overlooked as working contemporaneously to alter the deposition at a rift basin margin.

3.2 Stratigraphy

Synrift sedimentation preserved along the northern margin of the CIB is well exposed at the site of the village of Nuevalos. Here, the relationship between basement rocks, exposed synrift sediments and postrift fill can be observed and studied in detail (Fig. 3.2).

This synrift fill can be divided into two main environmental settings, continental and marine, and is highlighted by the deposition of Buntsandstein and Muschelkalk facies over a c. 10 Ma period (Figs. 3.3, 3.4 and 3.5). Dating and correlation of beds resulted from research work, including palynological studies, on similar deposits in the south of the CIB and in areas of the Iberian Basin to the South East of the CIB (López-Gómez et al., 2002) (see Fig. 3.4).

3.2.1 Continental Sedimentation

The continental sedimentary record along the northern margin of the Central Iberian Basin can be divided into two main facies types: alluvial fan and playa lake. They have been named, by this study, the Monterde and Nuevalos Formations respectively (Fig. 3.4) and were laid down in a semi arid climate during synrift stages of basin evolution.

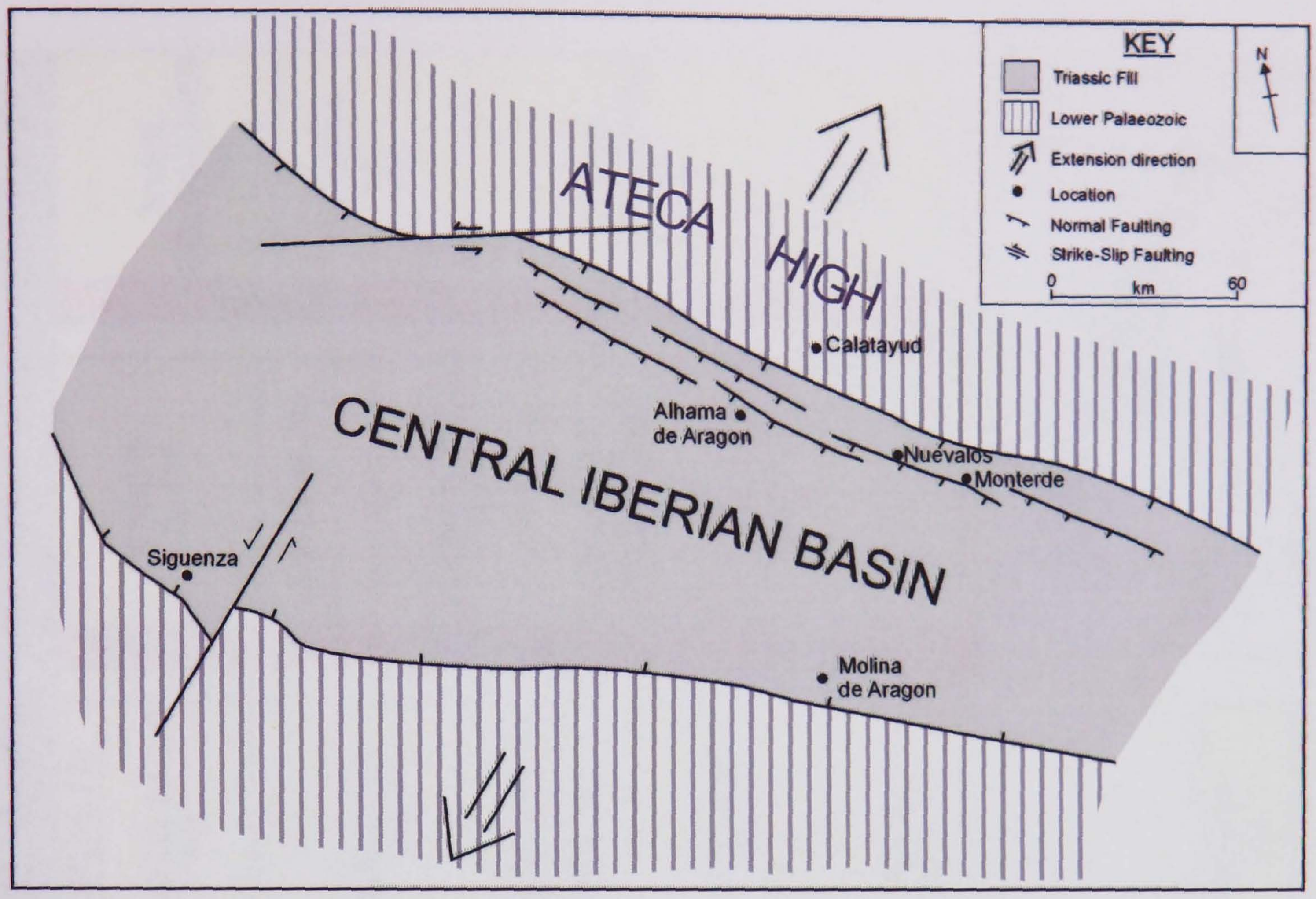


Fig. 3.2: Sketch location map of the Central Iberian Basin, central Spain.

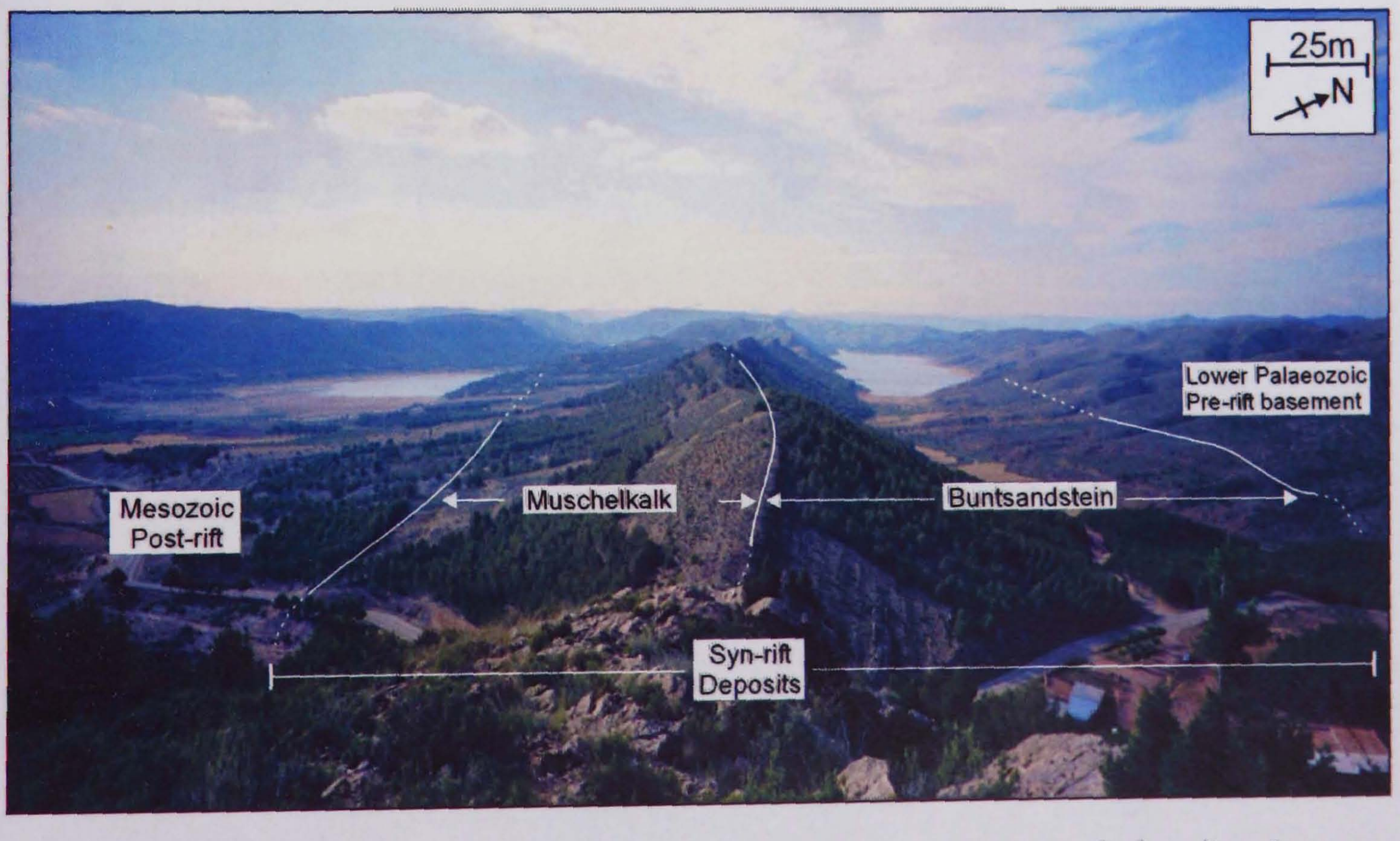


Fig. 3.3: Complete sequence of outcrop at Nuevalos location and representative of other sites along the northern margin including Monterde

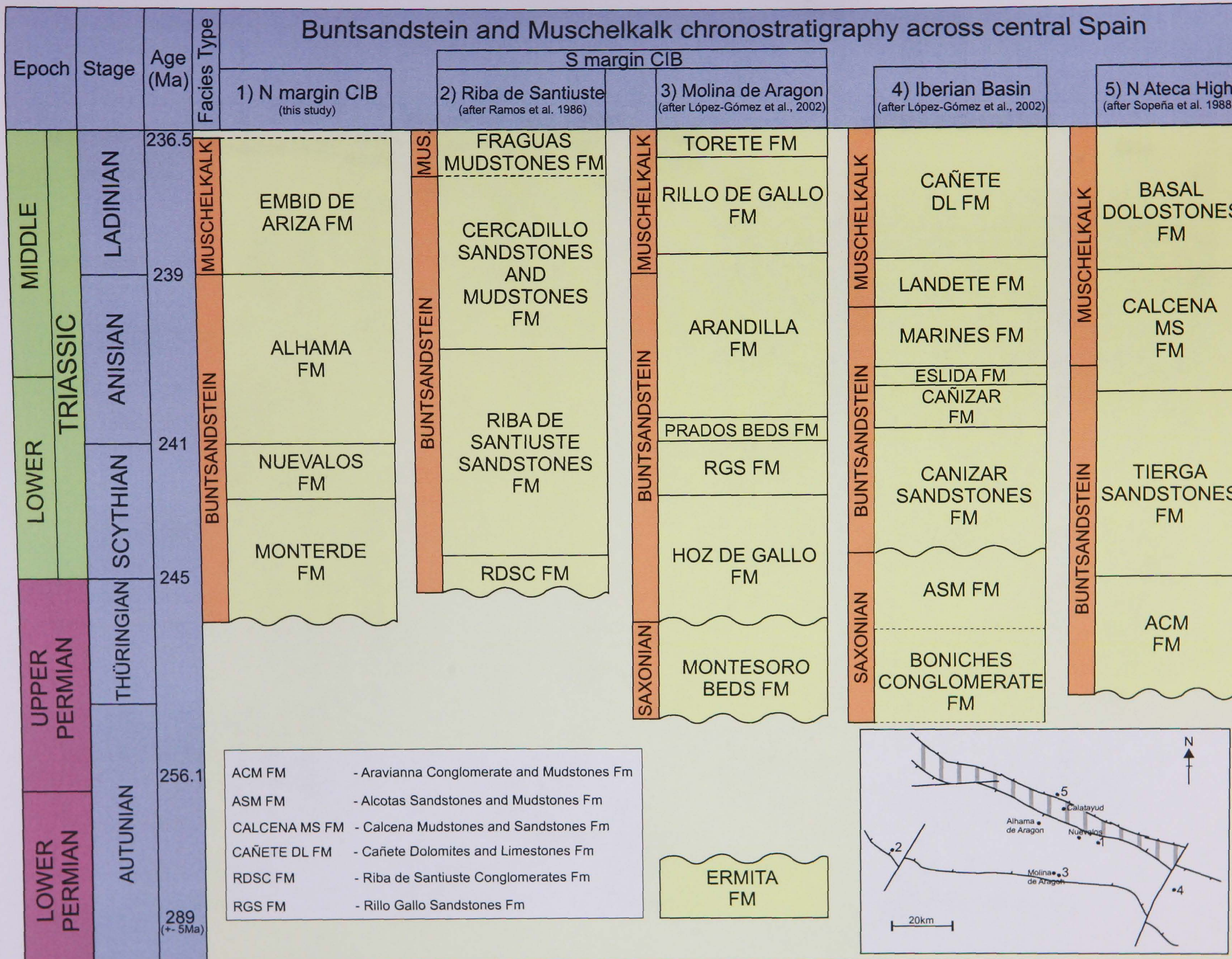


Fig. 3.4: Table of correlated stratigraphy across the Iberian Ranges during the Permo-Triassic. Age dates based on palynology and radiometric dating.

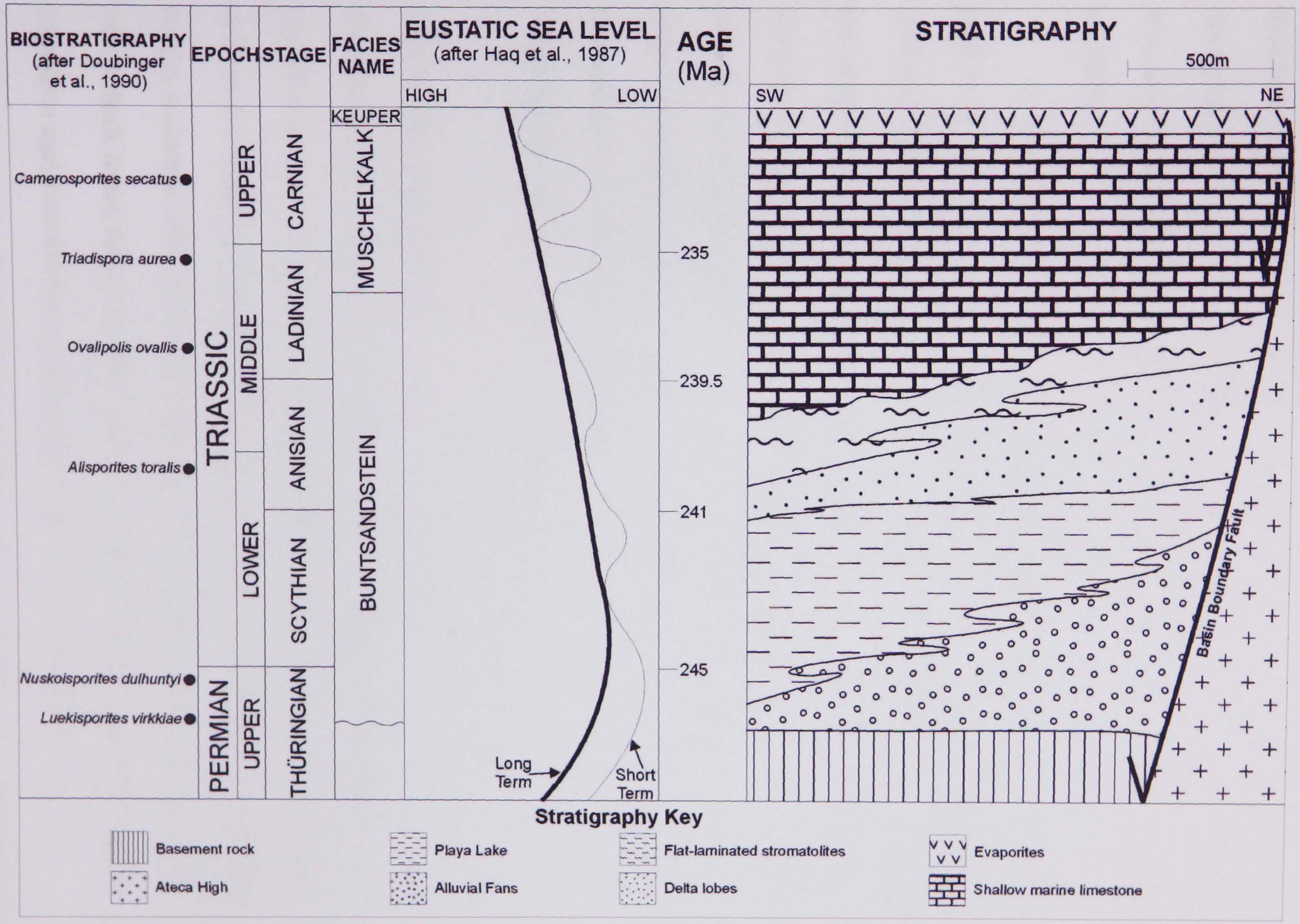


Fig. 3.5: Stratigraphic facies table for northern margin deposits in the CIB

The Monterde and Nuevalos Formations (Buntsandstein facies) are interpreted as the product of alluvial fan and playa-lake deposition in fault bounded half-grabens, responding to differing rates of tectonic subsidence and fault growth. These basin margin continental clastics are interpreted to represent rift climax with active deposition over much of the CIB (Ramos et al., 1986; Sanchez-Moya et al., 1996; López-Gómez et al., 2002).

In addition to the continental Buntsandstein deposits there are also units of shallow marine carbonate rich sandstone that are influenced by continental conditions during periodic sea-level regressions. Through detailed investigation, these deposits of the Alhama Formation are found to represent delta lobe systems entering the basin along the same sediment supply routes as the alluvial fans. This discovery means that not only is a complete transitory sequence from continental to marine sediments preserved in Permo-Triassic age outcrops, but that systems along the northern margin operated under an extended temporal framework from Upper Permian to Mid Triassic influencing the associated CIB stratigraphy.

3.2.2 Marine sedimentation

The transition to overlying marine sedimentation is characterised by a regional unconformity that is believed to be associated with a regional tectonic event causing uplift of the Ateca High and fault activity (López-Gómez et al., 2002). These northern margin sediments, believed to be the top of the Buntsandstein facies and base of the Muschelkalk facies, formed as delta lobes. The Alhama Formation, Anisian (Middle Triassic in age), contains the sediments that support the observation of a facies unconformity between Buntsandstein and Muschelkalk, a division identified within the present day Permo-Triassic CIB outcrops.

Above this unconformity lie the deposits of the Muschelkalk facies which are composed of predominantly marine limestone, Ladinian (Late Triassic in age) and shallow marine algal horizons with minor sandstones of the Upper Alhama/Embid De Ariza Formation. This signifies the onset of late stage rifting and the slow decline in Permo-Triassic synrift deposition in the CIB.

3.3 Alluvial fans

3.3.1 Facies Description

This facies association comprises conglomerates, sandstones, mudstones and palaeosols deposited in wholly continental, three-stage alluvial fan development (Figs. 3.7, 3.8 and 3.10).

During the beginning of the Late Permian, alluvial fan sedimentation existed in the Iberian Basin in the southeast portion of the Iberian Ranges (López-Gómez & Arche, 1993). This is contemporaneous with alluvial fan sedimentation in the extreme north-western parts of the Iberian Ranges (Sopeña et al., 1988) (Fig. 3.4). However, along the northern margin of the CIB, sedimentation lay dormant until Upper Permian times when Buntsandstein continental alluvial fans developed (three stage fan development at Monterde for example), constituting the first deposition of the Buntsandstein facies at that location. Alluvial fan sedimentation ceased during the mid- to late-Scythian when clastic flux to the basin became less regular and playa lakes began to form. A lack of playa sediments and periodic drying/high salinity indicators such as desiccation cracks, halite pseudomorphs and varved deposits provide evidence to support this absence throughout the early-Scythian along the northern margin.

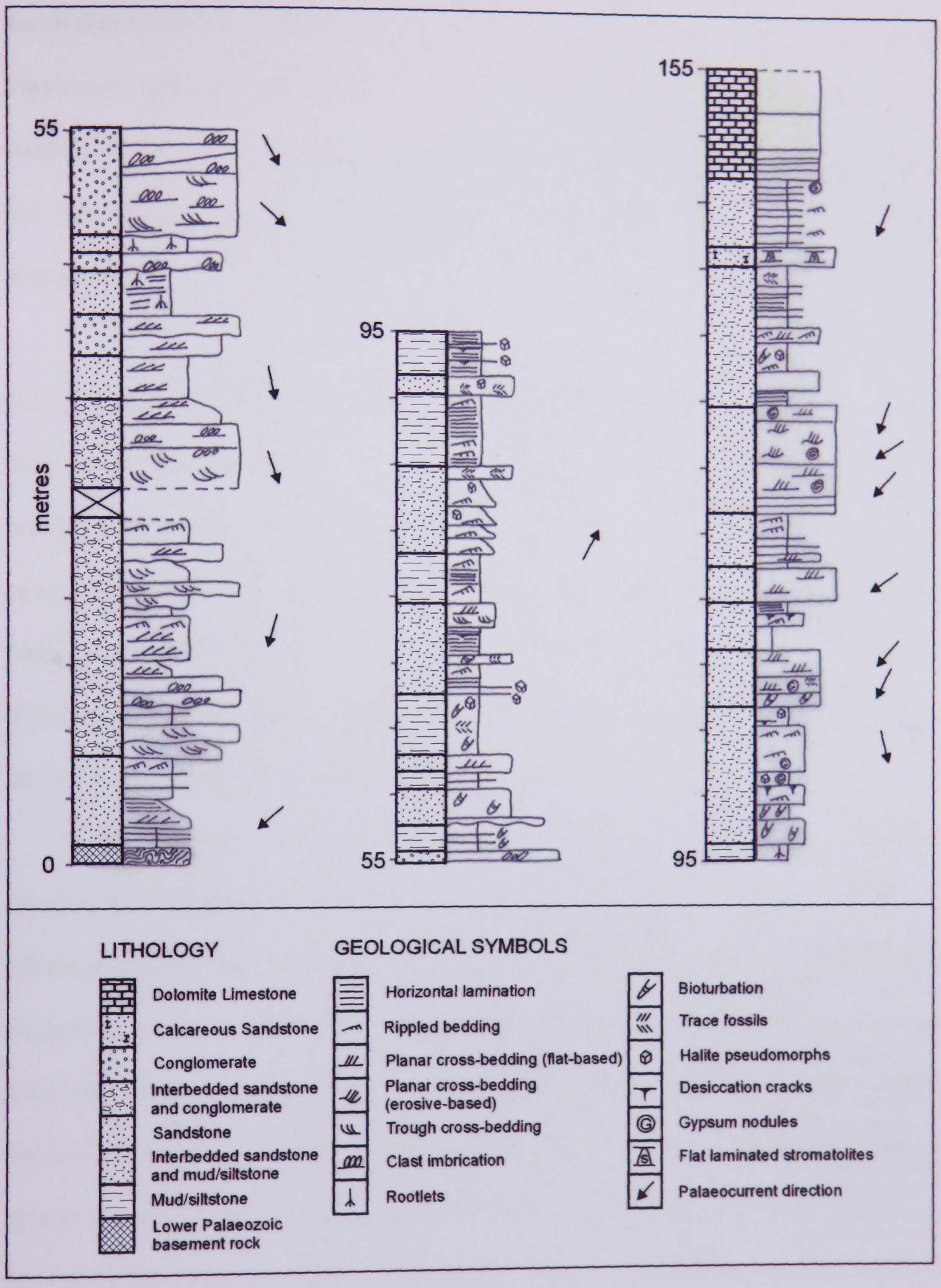


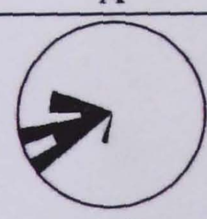
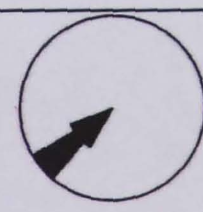
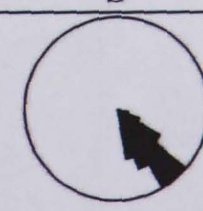
Fig. 3.7: Graphic log constructed from Buntsandstein and Mushelkalk facies exposures at Monterde, along the northern margin of the CIB, central Spain.

Detailed analysis of the three stage alluvial fan deposits at Monterde resulted in three facies distinctions being made: Matrix and clast supported conglomerates; medium- to very coarse-grained pebbly sandstones; and fine-grained sandstones, siltstones, mudstones and palaeosols. From this in-depth analysis, it has been possible to infer the environment of deposition and suggest the processes under which the sediments were deposited.

3.3.1.1 Facies 1a: Matrix and clast supported conglomerates

This facies occurs as a thick (> 30 m) stratigraphic unit that is found as discrete conglomerate bodies along the entire length of the Ateca High, but particularly associated with fault tip relay zones in the hanging wall. Individual sheet conglomerate units extend up to 950 m laterally and single beds range in thickness from 0.5-2.5 m. This facies is characterized by sheets of polymict clast- or matrix-supported conglomerates (Fig. 3.8 and Photograph 3.1).

The conglomerates predominantly show a bimodal grain size with cobble-size clasts and a medium-grained to granular sand-grade matrix dominating the deposits. Clasts tend to be subrounded to subangular with the dominant clast type being various Palaeozoic quartzite cobbles (red, buff, brown and orange) among smaller (<6 cm) grey sandstone clasts. Larger cobble-size clasts exhibit unusual cuspate white marks on their surface (Photograph 3.2). These could be the result of a) percussion marks from the impact of clasts during flow movement, b) post depositional diagenetic dissolution between point contacts of clasts, or c) a more 'extreme' end member is the result of impact fractures from a nearby meteorite impact (Ernstson *et al.*, 2001).

Lithofacies \ Fan Phase		Fan Phase 1	Fan Phase 2	Fan Phase 3
Conglomerates		-	S	A
		S	S	S
		A	A	A
	CS	A	A	A
	MS	S	A	A
Clasts	MCS	256	256	166
	NCL	6	5	8
Sandstones		S	A	S
		A	A	S
		A	S	A
		-	A	A
		S	-	-
Silts/Muds		S	S	S
Rhizoliths		-	A	A
Palaeosols		A	-	S
Palaeocurrent		 n = 89	 n = 70	 n = 103

(S) - Scarce; (A) - Abundant; (-) - Not present
(CS) - Clast supported; (MS) - Matrix supported
(MCS) - Maximum clast size, mm; (NCL) - Number of clast lithologies
(n = 89) - Number of palaeocurrent measurements

Horizontal bedding
Pebble-filled scours/channels
Imbrication
Rippled bedding

Planar cross-bedding
Trough cross-bedding
Horizontal bedding
Small isolated clasts

Fig. 3.8: Tabulated sedimentological analysis of the three-stage fan evolution during the Permo-Triassic at Monterde along the northern margin of the CIB.

Photograph 3.1: Sheets of polymict clast and matrix supported alluvial fan conglomerates at Monterde. (Small plant in foreground is 25 cm across).

Photograph 3.2: Pitted surface of clasts found in alluvial fan conglomerates along the northern margin of the CIB. (Clast is 10 cm long).

A variety of sedimentary structures are observed throughout the facies with some minor scouring on the base of each conglomeratic unit. Large scale planar cross bedding is observed in many of the packages (>1.5 m in thickness), the bases of which display pebble clustering (Photograph 3.3). More than half of the pebble

Photograph 3.3: Pebble clustering and clast imbrication at the base of a conglomeratic unit at the West Reservoir section along the northern margin of the CIB. (Notebook is 20 cm long).

horizons within each bed display imbrication, and have a dip of <30° and maximum coset thickness of 10 cm.

3.3.1.2 Facies 1b: Medium- to very coarse-grained pebbly sandstones

This facies consists of medium to very coarse-grained pebbly sandstones, which occur interbedded between the conglomerate units of facies 1a. The facies forms a lesser component of the Monterde Formation. The sandstones are poorly sorted and contain abundant dispersed granules and small pebbles of quartzite and chert. Sand grains are subangular to subrounded and are associated with abundant mica. The sandstones are strongly reddened in colour, owing to both a hematite coating on the quartz grains and reddened, clay-size matrix.

Photograph 3.4: Segregation of pebbles/gravels and fining upwards within conglomerate packages (Hammer is 20 cm long).

Individual beds extend for up to 500 m in some cases, however they rarely exceed 1.5 m in thickness, and are more commonly are 0.5 m thick. Sedimentary structures are common, with well-developed horizontal stratification that can be well exemplified by segregation of pebble and granule layers (Photograph 3.4). Pebble stringers are common through out the facies. Beds are frequently graded with fining up units. Planar-cross bedding is abundant (Fig. 3.8) with set heights <30 cm and the sets can be arranged in metre-scale stacked units. Trough-cross bedding forms a lesser component, but is arranged in metre scale units. Locally, sand beds are observed to pass laterally into conglomerate beds of facies 1a. The beds form broad sheets laterally continuous for tens to hundreds of metres (frequently up to 500 m). Many of the beds have sharp erosional bases, where, frequently pebbles line the bases of scours. The beds are generally truncated by erosional contacts with overlying conglomerate beds. Palaeocurrent indicators from the cross beds (planar and trough) suggest a variable transport direction, but with a trend up section from south to progressively more southeast. This trend corresponds to Facies 1a.

3.3.1.3 Facies 1c: Fine-grained sandstones, siltstones, mudstones and palaeosols

This facies forms a lesser component, but important part of the Monterde Formation and consists of mature palaeosols and fine-grained sandstones that are poorly sorted and frequently fine up into thinly laminated siltstones and mudstones (Fig. 3.7). Sandstone beds have bed thicknesses of 60 cm or less and are distinguished by high mica content and by marked colour horizonation, with red coloured beds alternating with green/brown coloured beds (Photograph 3.5). The colour transitions are typically diffuse, but sharply change into the associated siltstones and mudstones that overlie (Fig. 3.7).

Photograph 3.5: Red/green colouration changes within the fines due to soil formation, bioturbation and rootlets (Pen cap is 4cm long).

The siltstones and mudstones show abundant colour mottling and irregular, vertical branching, tubular structures with a green colouration probably representing rhizoliths (Retallack, 1988, 2001). Carbonate nodules become more common towards the top of the mudstone beds and are, up to 2 cm in diameter, some with black organic rich centres. Dark reddish brown palaeosols (Munsell hue 10R 3/4) with abundant rhizolith preservation as carbonate nodules occur draped over most of the facies. Gypsum nodules are observed in the upper portion of the palaeosols. Colour intensity and mottling tends to increase towards the top of the palaeosols, where they are sharply truncated by the overlying bed. They are laterally extensive and regularly extend for 800 m or more (Fig. 3.9).

3.3.2 Facies Interpretation

3.3.2.1 Facies 1a

The sediments in this facies are characteristic of low frequency, high magnitude sheet floods and debris flows that occurred in an alluvial fan setting. The lateral extent of the units suggests that each flood event had a tendency to radiate across areas from the basin entry point. The presence of larger clasts within the matrix of granule to medium grained size indicates that the capacity to transport larger grains was high and, during each event, resulted in transportation and reworking of pre-existing clasts.

Minor pebble clusters and common cuspate percussion marks indicate that the depositional flow was of high density, turbulent flow such as that seen in modern day alluvial systems. The similarity in clast provenance means the source for clasts is likely to have come from one or two key local sources high in the Iberian Ranges hinterland, in this case the basement Lower Palaeozoic quartzites of the Ateca High to the north (Fig. 3.2) which doubles as one of the clast source areas for the alluvial

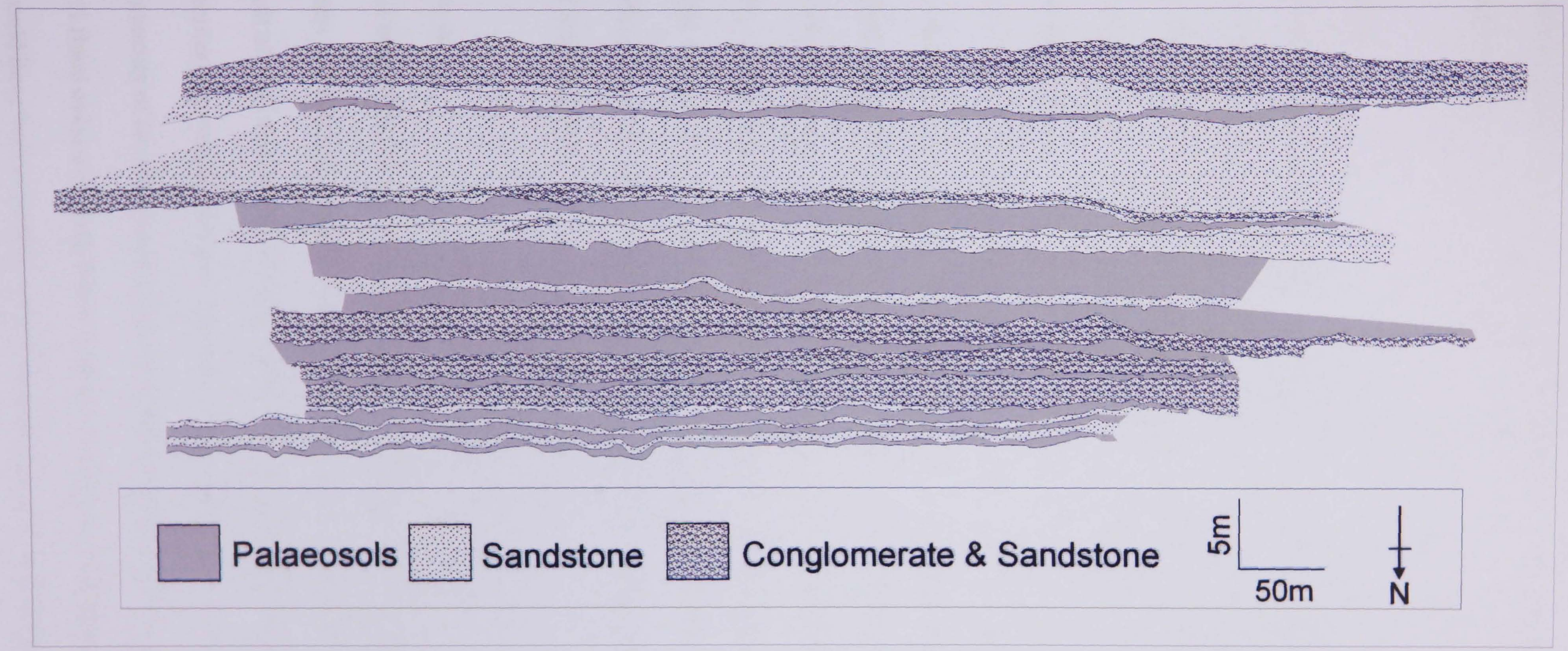


Fig. 3.9: Architectural panel taken from field analysis showing the lateral extent and thickness of the palaeosols and alluvial fan sediments in a chosen section at Monterde.

deposits (Aranda de Moncayo) along the western margin of the Permo-Triassic Ebro Basin (see Chapter 5).

3.3.2.2 Facies 1b

This facies is interpreted as the deposits of shallow sheet flood events or the waning flow deposits of heterogeneous stream floods. The scoured and erosional bases may have been cut during peak flood flow before waning flood conditions deposited the sandstones. Leopold et al. (1964) and Blair & McPherson (1994 a, b) have suggested that scour and fill is common in ephemeral stream systems subject to low frequency, high-magnitude events. The presence of gravel stringers indicates that some bed-load transportation occurred simultaneously with suspension fall-out of sand. Planar and trough cross-bedding record deposition in broad open channels (>150 m wide) that may have been locally confined by facies 1a (similar examples seen in Allen, 1983; Arche & López-Gómez, 1996). These are seen by beds of conglomerates of this facies extending for up to 500m, with metre scale trough-cross bedding also present. Fining up in the sandstone units suggest that the waning of flood flow velocities resulted in progressive deposition of finer fractions.

3.3.2.3 Facies 1c

The sandstone beds in this facies are interpreted as the deposits from flooding of shallow streams operating on the fan surface, which have formed a series of stacked beds as a result of continued events The presence of colour mottling and carbonate nodules (glaebules) represents pedogenic alteration of these beds. Variation of the bed colours and intensity of the rhizolith development reflects varying degrees of palaeosol maturity. Each flood event including sandstone and waning stage siltstones and mudstones would have been subject to surface weathering and pedogenesis until the

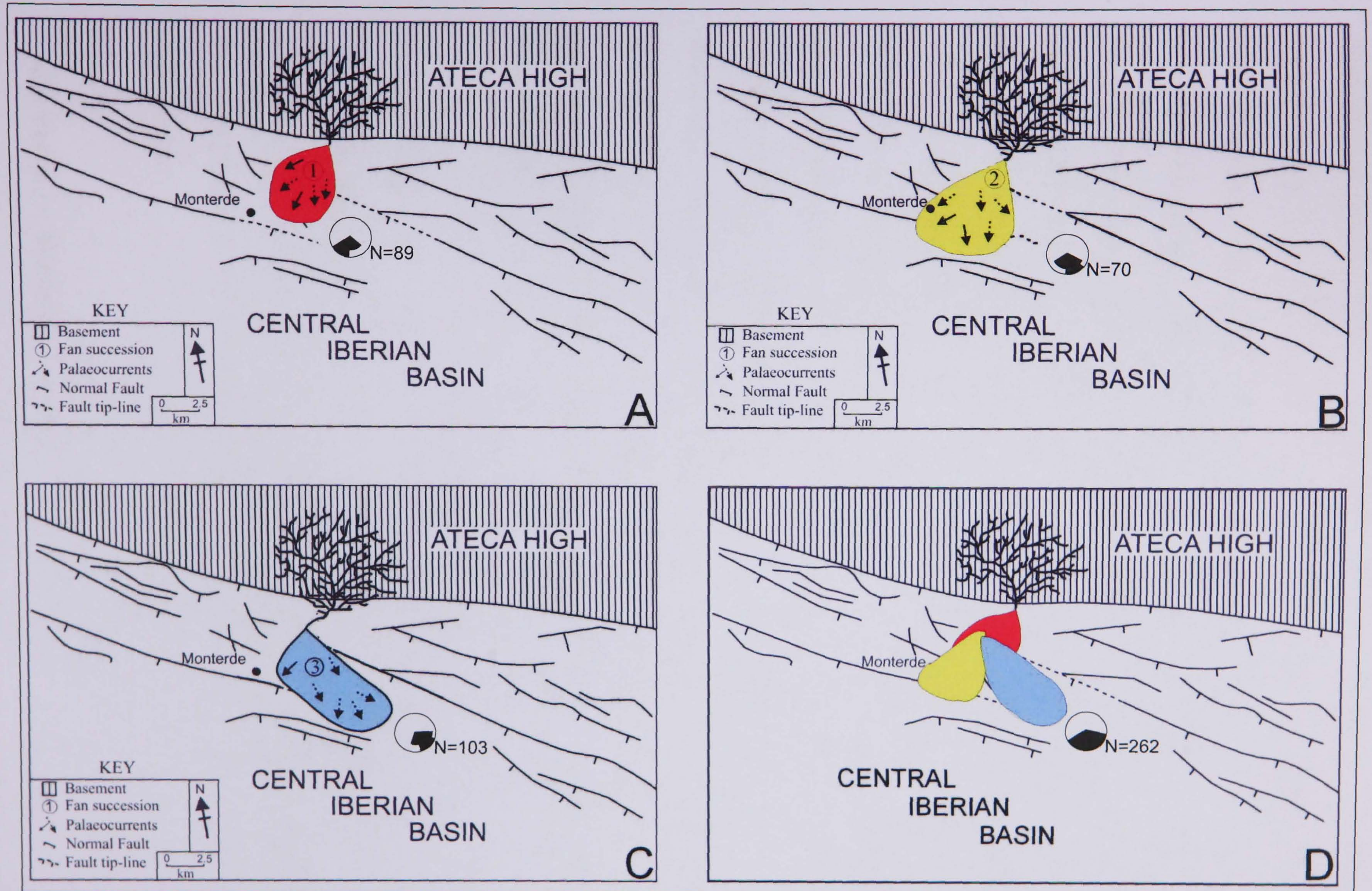


Fig. 3.10 : Diagram showing the three stage alluvial fan development and palaeocurrent directions along the northern margin of the CIB (A, B and C). Section D shows a collation of all three fan stages and total palaeocurrent direction to the S and SE.

arrival of the next event. As a result, a stacked unit comprising multiple pedogenically-modified beds showing varying maturity was built up. The development of palaeosols suggests that sedimentation was punctuated by long periods of non-deposition before renewed activity and erosional down cutting by facies 1a and/or 1b.

The lateral extent of this facies and especially the more mature palaeosols at the top of each unit demonstrates regular important stratigraphic events across the whole of the alluvial fan surfaces of the Monterde Formation. A strong cyclicity in palaeosol development is apparent throughout the whole of the Monterde Formation sediments which can be implemented to build up a timeframe of depositional events, not just one area of the northern margin of the CIB during the Lower Triassic, but by investigating similar outcrops along strike of the whole northern margin. Weissman *et al.* (2002) have already successfully shown that the significance of similar pedogenic facies as stratigraphic markers can form a basis from which sequence stratigraphic models of fan development can be established. Chapter 7 will discuss this application of periodic deposition and utilise Fischer plots and orbital forcing timescales to constrain these events further.

3.4 Playa Lake

3.4.1 Facies description

This facies association represents the development of shallow, saline playa lakes. This facies interfingers in the lower and upper portions with facies association 1 and 3 respectively.

3.4.1.1 Facies 2a: Reddened siltstones and mudstones

The facies contains up to 30 m of siltstones and mudstones that have distinctive red, yellow and green colourations. The red beds range from 10 cm to 30 cm in thickness and are characterised by horizontal lamination and abundant desiccation cracks on the upper bedding surfaces (Photograph 3.6). Halite pseudomorphs are observed on the hardened surface of these horizons (Photograph 3.7) and can be traced laterally up to 600 m across section.

Photograph 3.6: Desiccation cracks on the upper surface of sandstone beds at Nuevalos (lens cap in centre of picture is 6 cm in diameter).

Photograph 3.7: Halite pseudomorphs on the surface of a hand specimen taken from Playa Lake deposits at Nuevalos (large pseudomorph to the right of the image is 2 cm in width).

Within the red-coloured sediment, >10 cm bands of green and yellow siltstones can be found sitting conformably on the laminated sediment. Gypsum nodules that have undergone diagenesis are observed throughout these deposits through analytical laboratory investigation (Warrington, pers. comm.).

3.4.1.2 Facies 2b: Bioturbated mudstones and pedogenesis

This facies is finer-grained than Facies 2a with immature palaeosols facies consisting of reddish (Munsell hue 5Yr) clay-rich sediments that show evidence of strong pedogenic alteration. This pedogenic alteration is shown by thick to very thick continuous clay coatings on grains and palaeosol surfaces, common rhizolith traces, colour mottling decreasing downward in the profile and carbonate and gypsum nodules.

Associated mudstones are strongly reddened in colour with moderate bioturbation, with a bioturbation index of BI=3 to 4 based on the classification of Taylor & Goldring (1993). Identification is difficult, but *Gordia* (unknown grazing traces – Challands, pers. comm.) are particularly abundant on bedding surfaces throughout the facies. Evidence of reptile-like animals walking across the playa sediments is also observed in the form of three-toed footprints on the upper surface of a fine sandstone bed (Photograph 3.8). This suggests these footprints are evidence of some of the first land-walking animals to emerge after the major Permo-Triassic extinction and implies the playa sediments and successive units occurred from the start of the Triassic.

3.4.2 Interpretation

3.4.2.1 Facies 2a

Expansive (< 30 km in length) and prolonged playa lakes have resulted in the deposition of this facies. The fine-grained nature of the sediment is likely to have derived from intrabasinal fines and the toe end deposits of alluvial fan predecessors. It is likely that periodic rises in lake level will have created the less evaporitic fines, represented in this facies by the mudstone beds, and will have interfingered with the

Photograph 3.8: Three-toed footprints in fine-grained Playa Lake sandstone at Nuevalos (pencil tip for scale; footprint is 1 cm (on photo) to SW of the pencil tip).

alluvial fan deposits. As flux to the basin waned, it is likely the landscape along the basin margin experienced increased stability, enabling ponding and subsequent evaporation of remaining water. This evaporation process culminated in the gradual drying up of the playa lakes and the deposition of salt deposits, preserved as halite pseudomorphs, or 'salt-hoppers'.

3.4.2.2 Facies 2b

Periodic drying and shallowing of water level in a playa lake setting ensured distal portions of the alluvial fans were left exposed and subject to desiccation. At times of insufficient evaporite deposition and lack of hyper-saline conditions, the fine-grained, red sediments tended to mature, forming weak soil horizons that were later buried and preserved as palaeosols. Associated with the development of poor pedogenesis formation is the occurrence of the bioturbated mudstone and surface grazing traces which could suggest the existence of non-marine ponding on the distal fan areas (Arche pers. comm.).

3.5 Delta Lobe and Shallow Marine

3.5.1 Facies Description

The facies association comprises sandstones, siltstones, mudstones that were deposited in a deltaic setting with closely associated shallow marine facies.

3.5.1.1 Facies 3a: pebble rich and coarse- to medium-grained sandstones

This facies development forms the bulk of the sandstones for the Alhama Formation, with individual beds up to 4 m thick and can thin laterally to less than 1 m (Fig. 3.7). The facies is characterized by poorly sorted medium- to very coarse-grained pebbly white coloured sandstones (Photograph 3.9). The sandstones are moderately well sorted with well-rounded quartzite pebbles less than 3 cm in diameter.

Erosive bases and flat tops are common for all the sandstones. The bases are characterised by pebble rich coarse-grained sandstones, with rare broken shelly lags and plant material (carbonized tree branches and leaf debris) that are frequently carbonate cemented. It is possible to find 'rip-up' fragments of underlying mudstone and siltstone in the lower 5 cm of some sandstone units. The bases of many of the sandstone beds are moderately bioturbated (BI= 2 to 3) and the grazing traces of *Palaeophycos*, *Thalassinoides* and rare *Planolites* (Photograph 3.10).

Photograph 3.9: Thick, repetitive units of white deltaic sandstones at Nuevalos (notebook is 20 cm long).

Photograph 3.10: Trace fossils on the base of deltaic units at Monterde. Those traces identified include *Palaeophycos*, *Thalassinoides* and rare *Planolites*. (Hammer is 30 cm in length).

The facies contains numerous low-angle cross-stratified beds, in which individual foresets dip between 5° and 15 ° and are up to 4 m in height and cut into by overlying beds. Regional dip in this area is sub-horizontal and is not seen as a major influence on the orientation on the deposits. No observable bioturbation of cross-beds is present, although some feeding traces can be seen on foreset surfaces. Granule to pebble lags and rare stringers, are present. High-angle cross-stratified beds occur towards the top of the facies unit, with forests dipping between 9 ° and 26 ° and are usually associated with poorly developed trough cross-bedding. Cross-beds dip in two main directions, towards the SSW and S, with less common foresets dipping to the SSE. Occasionally, ripple lamination (<5 cm) can be observed in the upper 10 cms of thinner sandstone beds.

3.5.1.2 Facies 3b: laminated siltstones and mudstones

This facies occurs between the sandstone beds of facies 3a and progressively thins up section. A deep red, and occasionally green, colouration of these fine sediments is common. This facies is finely laminated and ranges from 10 to 40 cm thick. A high content of muscovite mica is noted and some minor mixing and disruption of the laminated bedding. Rare small-scale asymmetrical ripple-lamination (<4 cm in height) is seen in the siltstone horizons.

This facies tends to be erosively cut into by overlying sandstone packages forming a sharp contact. Where an upper surface of the mudstone/siltstone can be studied, discreet halite pseudomorphs can be seen in addition to a poorly developed, haematitic, hardened crust.

3.5.1.3 Facies 3c: Laminated algal and bioclastic sandstone

This facies consists of fine- to medium-grained sandstones, containing what appear to be abundant and prominent, undulating laminations (<1 cm in thickness) (Photograph 3.11), together with burrows of *Skolithos* and *Planolites* and some broken shelly lag deposits.

These deposits occur at the top of the Alhama Formation, as an individual bed usually no more than 1 m thick, and extend laterally through the locations of Monterde and Nuevalos for up to 15 km. However, the facies is occasionally broken up into discrete sections by the underlying sandstone geometries of facies 3a.

Photograph 3.11: Algal laminations (top left) capping a sequence of partially reddened deltaic sandstones at Nuevalos. (Notebook is 20 cm in length).

3.5.2 Interpretation

3.5.2.1 Facies 3a

The poorly sorted nature of the sandstone, the presence of erosional bases with shelly lags, and plant material suggests this facies represents a series of rapid marine depositional events, such as that of clastic input on a delta lobe. The presence of *Palaeophycos* and *Thalassanoides* trace fossils (Photograph 3.10) indicates that this facies was laid down in a fairly well oxygenated, marine environment representing a transgressive surface. It is thought that this is a transgressive surface because it represents a transition between continental/playa sedimentation and marine deposition and contains characteristics of both. Bromley (1996) explains that some occurrences of grazing traces, such as *Palaeophycos* and *Thalassinoides*, are opportunistic and tend to dominate shafts and channels in particular, created in this instance by lobes of sediment travelling down the basin margin.

The low angle nature of the cross bedding and absence of bioturbation suggests less time for colonisation and that these beds were deposited in a slightly less active depositional regime and quicker than the lobe events. These beds represent stabilised deltaic activity sustained by frequent clastic input at the basin margin.

3.5.2.2 Facies 3b

Interbedded deltaic sandstones and siltstones indicate that sea level during the deposition of this facies tended to fluctuate leaving the mid- and upper areas of the fan lobes exposed and susceptible to maturation. Stable routing systems, seen from mapping and logging of sediments, and occurrence of outcrops in fixed places along the ancient margin meant the majority of sediment was deposited by continued flux from the hinterland to the basin. The dominance of mudstones and siltstones in this facies reveals that deposition was in a reduced energy system, when the flood events that created the delta lobes, were waning. Erosive contacts between this facies and that of Facies 3a show that after a period of waning, a regeneration of clastic flux occurred, causing erosion and cutting of the underlying beds. The environment itself is of relatively high salinity still indicated by the reoccurrence of halite pseudomorphs in the sediments.

3.5.2.3 Facies 3c

The deposition of this facies is interpreted as the result of marine flooding across the delta tops and intervening areas prior to the marine Muschelkalk facies that overlies conformably. There is a lack of supporting evidence such as fossils to add this theory. The presence of algal laminations/stromatolites provides evidence for marine conditions and shows that the Muschelkalk was truly marine at the time of deposition. It also seems likely that there was a reduced clastic input and low sedimentation rate, allowing the abundant growth of laminated stromatolites (Photographs 3.11 & 3.12). This facies development is similar to other transgressive shallow marine sandstones observed in deltaic successions (Dorsey *et al.*, 1995).

Photograph 3.12: Close-up view of the algal laminations observed higher up the succession at Monterde and Nuevalos and seen in Photograph 3.11 (Hammer head is 9 cm across).

3.6 Depositional Model

Deposition occurred in a range of continental to shallow marine clastic environments associated with alluvial fans, playa lakes, deltas and localised shallow marine depositional systems. These facies and associated stratigraphy are summarised in Figures 3.5 and 3.11.

Conglomerates, sandstones, mudstones and palaeosols (facies 1a -1c) were deposited in alluvial fan environments that passed up into playa lake sediment of Facies Association 2. During this period, basin subsidence is high, though lateral movement along the basin boundary appears doesn't appear to have been significant, and tectonically active basin boundary faults control the entry points for clastic input to the rift basin margin. Evidence for this is seen in modern day surface mapping, examination of the sediments and associated palaeocurrents and from comparison with similar synrift sediments globally (see Chapter 6). Delta lobe sandstones and siltstone/mudstone deposits of facies 3a and 3b (the evidence for which is discussed in section 3.5.2), thought to have existed in fluctuating transgressive (transitory) marine conditions, superseded the alluvial fans. Facies 3c represents a further flooding surface as shallow marine conditions begin to dominate the basin allowing the growth of flat-laminated algal mats and the deposition of bioclastic sandstones. Tectonic activity along the basin margin at this point is thought to have died out (López-Gómez et al., 2002) but it is thought some subsidence continued enabling creation of some accommodation space.

The final flooding surface and a point where basin subsidence and clastic input is low, results in the deposition of wholly Muschelkalk facies across the basin margin.

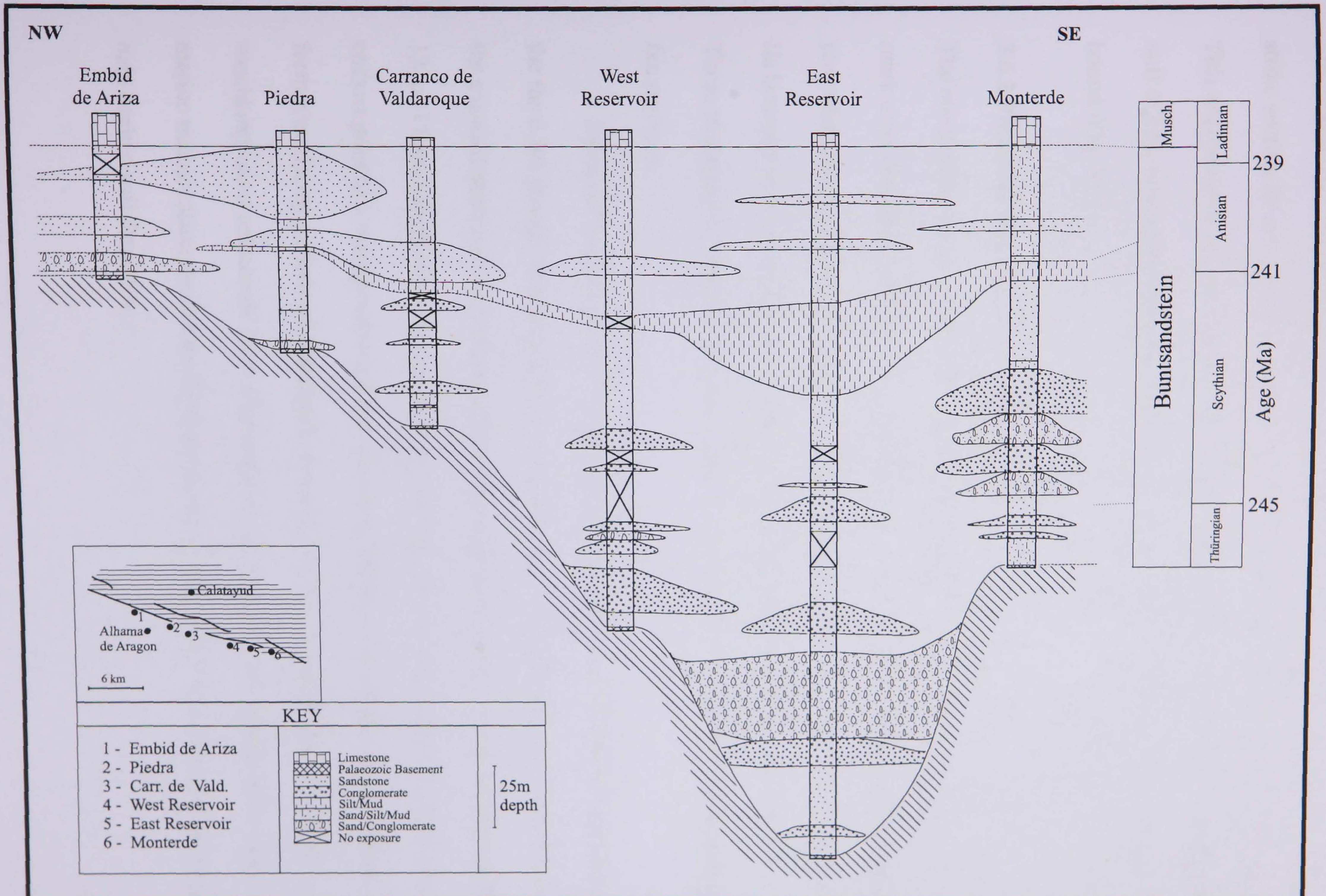


Fig. 3.11: Lithological correlation panel along strike of the northern margin of the CIB resulting from in-depth field investigations and graphic log construction. Time equivalent lines have been added against the age dates to hint at contemperaneous depositional episodes.

3.6.1 Architectural and stratigraphic evolution along the northern margin

The stratigraphic evolution of the north-eastern margin of the CIB, along a c. 15 km strike section from the village of Monterde to Nuevalos, will be discussed in this section. This analysis is based on detailed graphic logging and physical correlation (i.e. walking-out) of key, regionally extensive stratigraphic surfaces and the stratal units that they bound (Fig. 3.11).

3.6.2 Palaeosol surfaces (PS-1 to PS-17)

The moderately mature palaeosols from alluvial fan facies association 1 (facies 1c) mark extended periods of fan exposure, hiatuses in open fan deposition, and therefore, unconformities between the various stratigraphic units (Fig. 3.12). The sediments that lie between these unconformities represent open-fan deposition (Facies 1a and 1b). These stratigraphic units are laterally extensive and extend across most of the alluvial fan surfaces.

Palaeosol Surfaces 1 to 11 (Fig 3.12) represent the main pedogenic hiatuses of the three fan phases occurring along the margin (Fig. 3.10). Alluvial fans formed and on the exposed surfaces of each influx of coarse clastic event, soil horizons developed. PS-12 to -17 are related to the second fan stage during which alluvial fans and playa lake coexist prior to a transgressive marine incursion, leading to fan deltas and palaeosol formation during periods of quiescence. Finally, FS-1 to –3 (which in this scheme would represent palaeosols 18 to 20) completes the sequence of pedogenesis as the marine transgression dominates the depositional setting sat the basin margin, allowing only limited soil formation.

3.6.3 Flooding surface 1 (FS-1)

This flooding surface is regionally extensive and can be traced across the entire study area (Fig. 3.11 and 3.12). It marks the base of the delta lobe sandstone succession of the Alhama formation. Across much of the study area, FS-1 is marked with a sharp facies

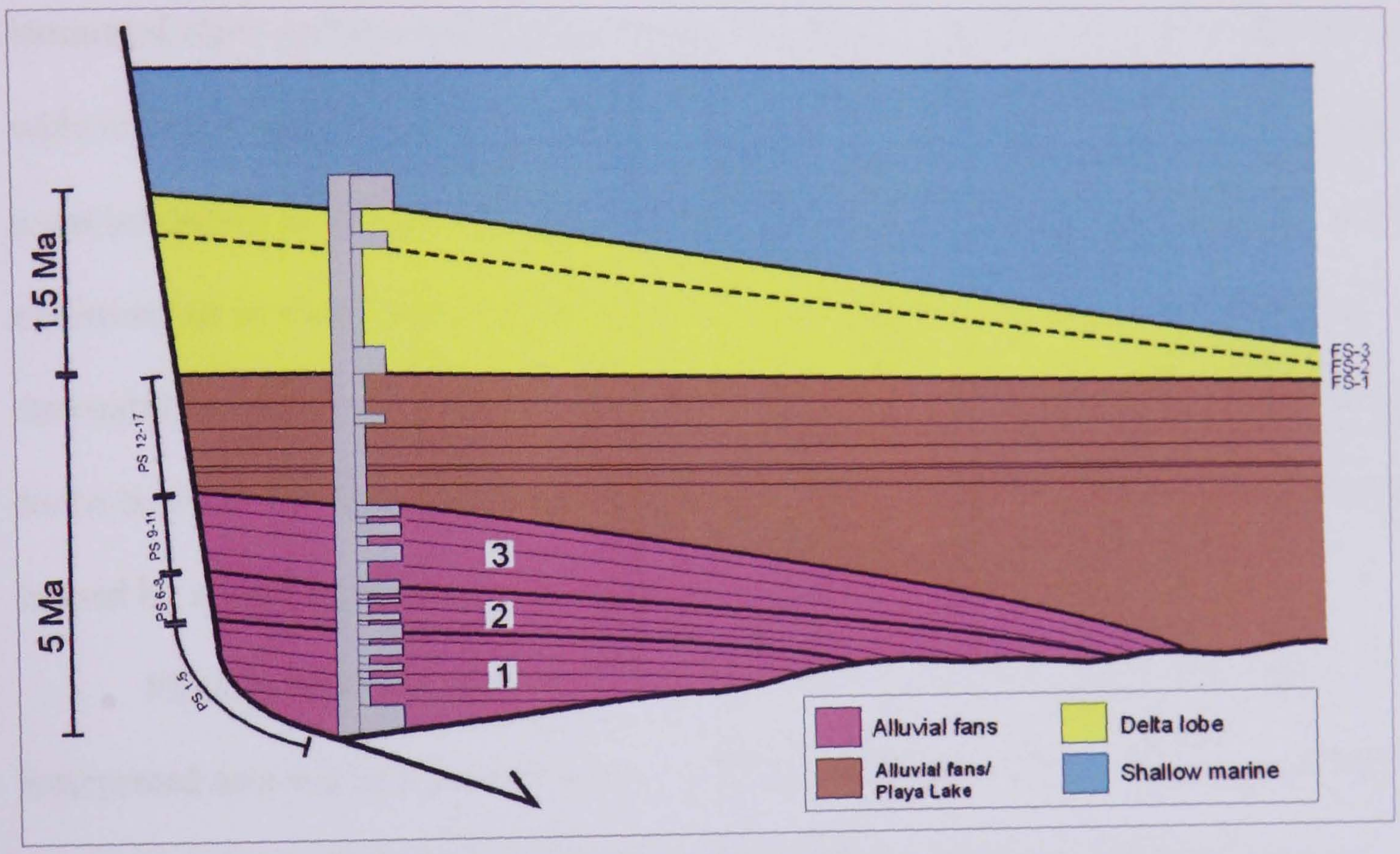


Fig. 3.12: Schematic section perpendicular to strike of the CIB northern margin showing sequence stratigraphic divisions through marginal sediments

change from playa lake sediments of facies 2a and 2b to the deltaics sandstones of facies 3a. The flooding surface is marked by the occurrence of poorly sorted sandstones, which are usually carbonate cemented and an abundance of broken shelly debris. The surface is always moderately bioturbated with *Palaeophycos, Thalassinoides* and *Planolites.*

The flooding surface of this initial transgressive event (TST) represents an important event marked by the deposition of the first marine sediments of the Buntsandstein facies in the CIB and renewed sediment supply to the basin margin. The presence of FS-1 is related to a tectonically controlled sea-level rise and renewed Ateca High fault activity. This marks the time of deepening of the CIB along its north-eastern margin probably due to increased subsidence rates.

3.6.4 Flooding Surface 2 (FS-2)

Flooding surface 2 is a marine flooding surface marked by the facies transition from delta lobe and associated deposits of the Upper Buntsandstein (Facies 3a and 3b) to the laminated algal sediments of the upper Buntsandstein facies (Facies 3c). During a basin-wide marine transgression (TST), the presence of algal-laminated stromatolites suggests areas bordering the previously formed fan lobes were flooded creating a shallow marine environment in which algal growth thrived. This led to the development of laminated stromatolites, and even poorly formed stromatolite domes. The absence of sediment flux to the basin at this time allowed a sustained period of continued algal mat development helped by tectonic-quiescence along the basin margin.

FS-2, in comparison to FS-1, represents the continued Tethys realm and is interpreted as a regional eustatic sea level rise because there is no evidence in outcrop to suggest a sustained return to continental facies and the succession continues to show shallow marine trace fossils of *Palaeophycos* and *Thalassinoides*.

3.6.5 Flooding Surface 3 (FS-3)

The third marine flooding surface (FS-3) is marked by the facies transition from the upper sections of the Buntsandstein facies to that of wholly marine Muschelkalk facies. Advanced stages of Tethys transgression meant that land surfaces had now been flooded and marine conditions dominated the whole of the CIB. Basin subsidence is greatly reduced, or of little influence, and whilst the basin boundary faults are still tectonically active, they have a lesser influence on rift basin sedimentation (López-Gómez et al., 2002). In a sequence stratigraphic context, this flooding surface marks the evolution from a Transgressive Systems Tract to that of Highstand Systems Tract (HST) conditions.

3.7 Structural controls on sedimentation

In this section, the control of relay zones in the hanging wall of the Monterde and Nuevalos faults at Monterde and Nuevalos (Figs. 3.2, 3.10 and 3.11) are combined with the facies development and stratigraphic evolution. The studied section enables an insight into the structural evolution and resultant control on synrift alluvial fan, playa lake and deltaic sedimentation.

3.7.1 Relay zones along basin margins

During the deposition of the Monterde formation the Monterde and Nuevalos faults are interpreted by this study to not have been linked and separated by a relay-zone situated to the north of the present-day location of the village of Monterde and Nuevalos (Fig. 3.2). This interpretation is based on a) the longevity of alluvial fan sedimentation entering the basin located at the relay-zone; b) the lateral variation in thickness from Monterde (c. 150 m) to <30 m within 1km along-strike; and c) the variation in palaeocurrents up section from the south to the east southeast for the progradation of the alluvial fan sediments (Figs. 3.7 and 3.10).

Relay zones or transfer zones form important structural elements in extensional basins, accommodating displacement changes between individual fault and basin segments (Fig. 3.13).

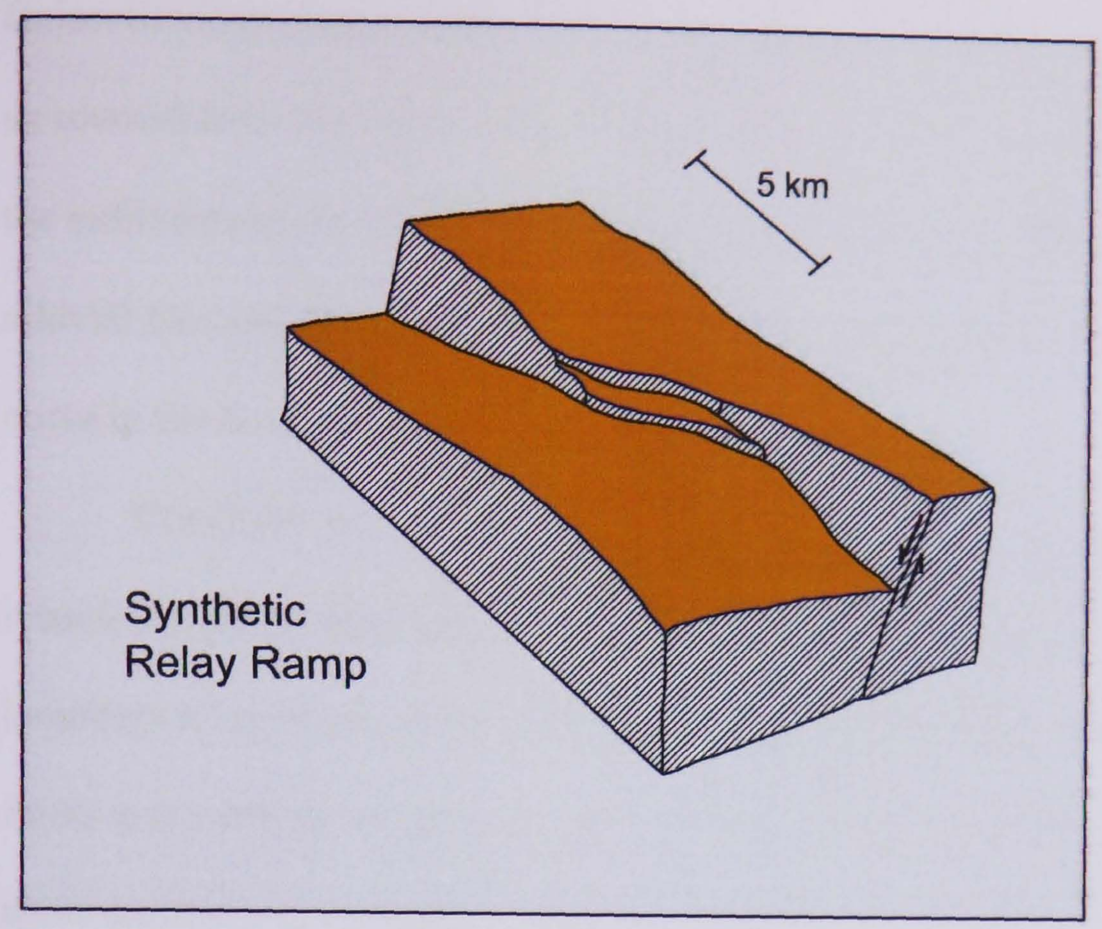


Fig. 3.13: Schematic diagram of a stepped relay ramp structure such as that see at the northern margin of the CIB.

They commonly represent footwall topographic lows and form a focus for syntectonic drainage systems and act as routes for drainage to rift basin margins (e.g. Morley *et al.*, 1990; Frostick & Steel, 1993; Gawthorpe & Hurst, 1993; Frostick, 1997; Gawthorpe & Leeder, 2000; Frostick & Jones, 2002). Therefore, it is inferred that drainage was focused through this relay zone from the Ateca High, where an alluvial fan evolved with its spatial distribution controlled by the fault tip topographic development. During the deposition of the Nuevalos Formation, playa lakes developed in the hanging wall of the faults, within the study area and along strike parallel to the Ateca High. These playa lakes filled the topography related to tectonic subsidence and interfingered with the toes of the alluvial fans. Although deposition in the hanging wall records a cessation in tectonic activity at the basin margin, sediment was still transported through the relay zone.

The following relative sea-level rise that resulted in the formation of FS-1 and the drowning of the previous synrift sediments sees shallow marine and deltaic sediments prevailing (facies 3 a-c) during an initial transgressive systems tract. These deposits, which make up the Alhama Formation, supersede the alluvial fan and playa facies. Evidence from close comparison of the fan sediments (which palaeocurrents tell us sourced from the hinterland) and playa deposits suggests that fines that contribute to the sediments of the playa lakes are sourced and reworked from distal portions of the alluvial fans and from intrabasinal locations. These are similar to the processes that occur in the East African Rift Basin (see Chapter 6).

Continued readjustment of the palaeocurrents (inferred as evolution of the breached relays) suggests tectonic activity is still ongoing but breaching of fault boundary relay zones, means there was a shift away from the smaller segmented normal faults that made up the sections of the Nuevalos and Monterde faults. Fault tips along these smaller normal faults would have become relatively inactive resulting in dormant basin boundary relay zone structures. These stabilised relay structures now the product of faults connecting and increasing in size, represent an evolution of fault propagation and breaching whilst maintaining the topographic layout along strike of the margin (Morely et al., 1990; Gawthorpe & Leeder, 2000).

3.7.2 Longevity of basin margin systems

Previous models of rift basins have indicated that the control and positioning of drainage outlets into a rift basin occurs along the margin only in the short term, with subsequent evolution and development occurring with continued tectonic activity. Furthermore, it is suggested that the spacing of sediment pathways is typically regular and evenly spaced (Leeder & Jackson, 1993; Talling *et al.*, 1997; Gawthorpe & Leeder, 2000).

Along the northern margin of the CIB, sediment flux entered the basin via structurally controlled conduits, which the continued deposition of sediments of the Alhama Fm and Nuevalos Fm indicate existed up until late stages of basin development and rift evolution. Rather than incision occurring at these locations along the basin margin (of which no evidence of down-cutting or terracing is seen), it is thought that the overriding control on flux to the basin was these routing systems.

Talling *et al.* (1997) described how a significant regularity in the spacing of drainage outlets appears on linear fault blocks. The ratio at which supply points to the adjacent parts of the basin, it was suggested, can influence the spatial scale of lateral facies variations. However, it is acknowledged that outlet spacing is determined during the early stages of basin fault evolution and can therefore be shaped by other initial conditions such as slope and physiography of the margin.

At the Monterde and Nuevalos sections (Fig. 3.2 and 3.10) we see the fan deposits that occupied irregularly spaced entry points situated along the margin of the CIB. Whilst irregular spacing of conduits cannot be inferred from two locations alone, analysis of additional outcrop locations along the palaeomargin, and the varying distances between them, indicate the likelihood that there was no regularity (see Fig. 3.11 for insert map of outcrop locations). This contradicts the patterns of regularly spaced sediment conduits (Alexander & Leeder, 1987; Gordon & Heller, 1993; Leeder & Jackson, 1993; Jackson & Leeder, 1994; Talling *et al.*, 1997; Gawthorpe & Leeder, 2000) and indicates that new models are needed to understand these complex rift basin margin histories. These irregularly spaced sediment conduits were used by the alluvial fans (PS-1 to -5), alluvial fan and interdigitated playa lake systems (PS-6 to -11) and then fan delta lobes (PS-12 to –17 and FS-1/FS-2), the development of which continued unhindered into the middle Triassic (FS-3). This along strike component of variability in the positioning of sediment flux inlets and physiography has a pronounced effect on spatial and temporal stratigraphic development, yet it is possible to identify several units that persist laterally. These facies units suggest that similar facies were deposited contemporaneously along the basin margin, during the fluctuating marine transgression (FS-1 to -3) thanks to long-lived sediment supply routes and that there was a gradual, staggered change to marine conditions. Evidence for this comes from the interbedding of the deltaic sandstones and mudstones/palaeosols and the increase in carbonate rich shallow marine sandstones with steadily increasing abundance of shallow marine trace fossils.

The continued input of sandy sediment through stabilised supply rotes along strike of the basin margin can be observed within the facies. For example, the fan delta lobe facies of FS-2 is composed of several poorly-cemented, carbonate rich sandstone units - evidence suggesting the influence of the Muschelkalk carbonate platforms establishing towards the central basin areas to the East during the Anisian (Tucker *et al.*, 1993). These shallow marine facies are believed to have existed at the same time the sandy fan delta facies of the Alhama Formation (Facies 3a and 3b) and provide strong evidence that clastic sediment supply to the basin was sustained from the same outlets along the margin into the middle Triassic.

3.8 Depositional Overview

A comprehensive discussion of the ideas formed from the information in this chapter will be available in Chapter 7. However, in order to appreciate each area of the CIB and their relation to each other it is necessary to summarise the findings from the sediments found at the Northern margin of the CIB here first.

Detailed study of preserved Permo-Triassic sediments and reference to existing literature (Doubinger et al., 1990; Arche & Lopez Gomez, 1999) reveal that the deposition of continental Buntsandstein facies and subsequent Muschelkalk facies at the northern margin of the CIB occurred in a semi-arid climate during the Upper Permian and Early Triassic. This is apparent, among other factors, from red, oxidised sandstones, presence of haematitic crusts on some horizons and clasts and the supposed palaeogeography of the Iberian Microplate at that time. It is climate along with other allocyclic controls of sea level and tectonics that influenced the depositional systems in the CIB. From our appreciation of the succession of depositional environments along the northern margin of the CIB it is possible to further understand the complex sedimentation history across the Iberian Ranges during the Permo-Triassic.

3.8.1 Alluvial Fan Deposition

Conglomerates, sandstones, mudstones and palaeosols (facies 1a-1c) were deposited in alluvial fan environments that passed up into playa lake sediment of facies association 2. During this period, basin subsidence is high and tectonically active basin boundary faults control the entry points for clastic input to the rift basin margin. The fans were largely fixed to one point along the basin margin, and when looked at on a larger scale along the palaeomargin, show irregular spacing between entry-points to the basin (Figs. 3.11 and 3.14a). The size and extent of the fan at Monterde is thought to be 1-1.5 km across at its widest point, meaning that formation of bajadas - continuous ramps forming from the coalescence of laterally adjacent alluvial fans (Collinson, 1996) - was uncommon, if present at all.

Each conglomeratic unit within the logged sections represents a high magnitude, low frequency event on the fan surface, deduced by the irregularity of conglomerate beds throughout the outcrop sequence at Monterde, Nuevalos and other locations. The alluvial fan deposits (Monterde Formation) lying directly on Lower Palaeozoic basement rock at Monterde (see Fig. 3.7), teach us that debris-laden flows and sheet flood deposits occurred sporadically over at least 4 Ma, at this location (Fig. 3.15). In-between these 'flashy' events on the fan surfaces, periods of quiescence and non-deposition were experienced and immature palaeosols formed over the majority of the alluvial fan surface. This is presented in Fig. 3.9, where it is possible to pick out the major palaeosol horizons and lateral continuity across a distance of up to 800 m in some instances. The absence of channelisation on the fan is interesting and is likely to be because pulses of sediment, covering the majority of the fan surface periodically, overwhelmed the fans and prevented development of channels. Laterally extensive palaeosol horizons confirm this. These characteristics of the interacting fan/palaeosol deposits are observed in all locations studied along the palaeomargin of the CIB, where there are such deposits preserved.

Palaeocurrent evidence from the conglomerate and sandstone of the Monterde Formation shows that there was an overall southerly basinward migration of the whole fan at Monterde, in three identifiable stages (Fig. 3.10). This is predominantly due to structural development of sediment pathways along the fault-controlled basin boundary, which rotate and divert the flux in a southerly direction, and will be addressed in Chapter 7. The change from southerly to south easterly of the palaeocurrents is testament to this.

3.8.2 Playa Lake Deposition

Facies Association 2 represents the deposits of a playa lake that existed in intrabasinal areas of the CIB. At Monterde (Figs. 3.1 and 3.2), the Nuevalos Formation is exposed as 33 m of mudstones and siltstones with classic playa lake environmental indictors such as halite pseudomorphs and desiccation cracks. Determining the size of the playa lake is difficult due to poor modern outcrops towards the centre of the CIB. However, it is evident that the lake level periodically encroached on the alluvial fan sediments, as highlighted by the transitional nature of Facies 1 to Facies 2. This 'interfingering' of alluvial and playa lake sediments has been recorded in modern analogues in Death Valley, California (Jansson *et al.*, 1993) and can be tied to this example in the ancient rock record. Talbot *et al.* (1994) show that Late Quaternary playa sediments of Central and East Central Australia favourably compare to those of British Triassic playa sediments in West Somerset. Using modern analogues such as Australia and California has helped us to understand the playa environment and accurately interpret similar ancient sediments.

Playa lake sedimentation lasted until the end of the Scythian (Lower Triassic), when Facies Association 3, the Alhama Formation, consisting of predominantly marine sediments, superseded Facies 2.

3.8.3 Delta Deposition

Stabilised conduits located irregularly along strike of the margin of the CIB ensured that the flux of clastic sediment to the basin continued into the Middle Triassic (Anisian) (Figs. 3.14b and 3.15). The thick units of medium to coarse sandstone interbedded with silts and mudstones show an increase in shallow marine sedimentary structures and trace fossils and southerly palaeocurrents. This suggests the deposits are likely to have been entered the basin from the north and laid down during gradual sea level rise, possible as prograding delta lobes. Named the Alhama Formation, the sediments represent sustained deposition from continental settings to a more marine influenced setting in the CIB.

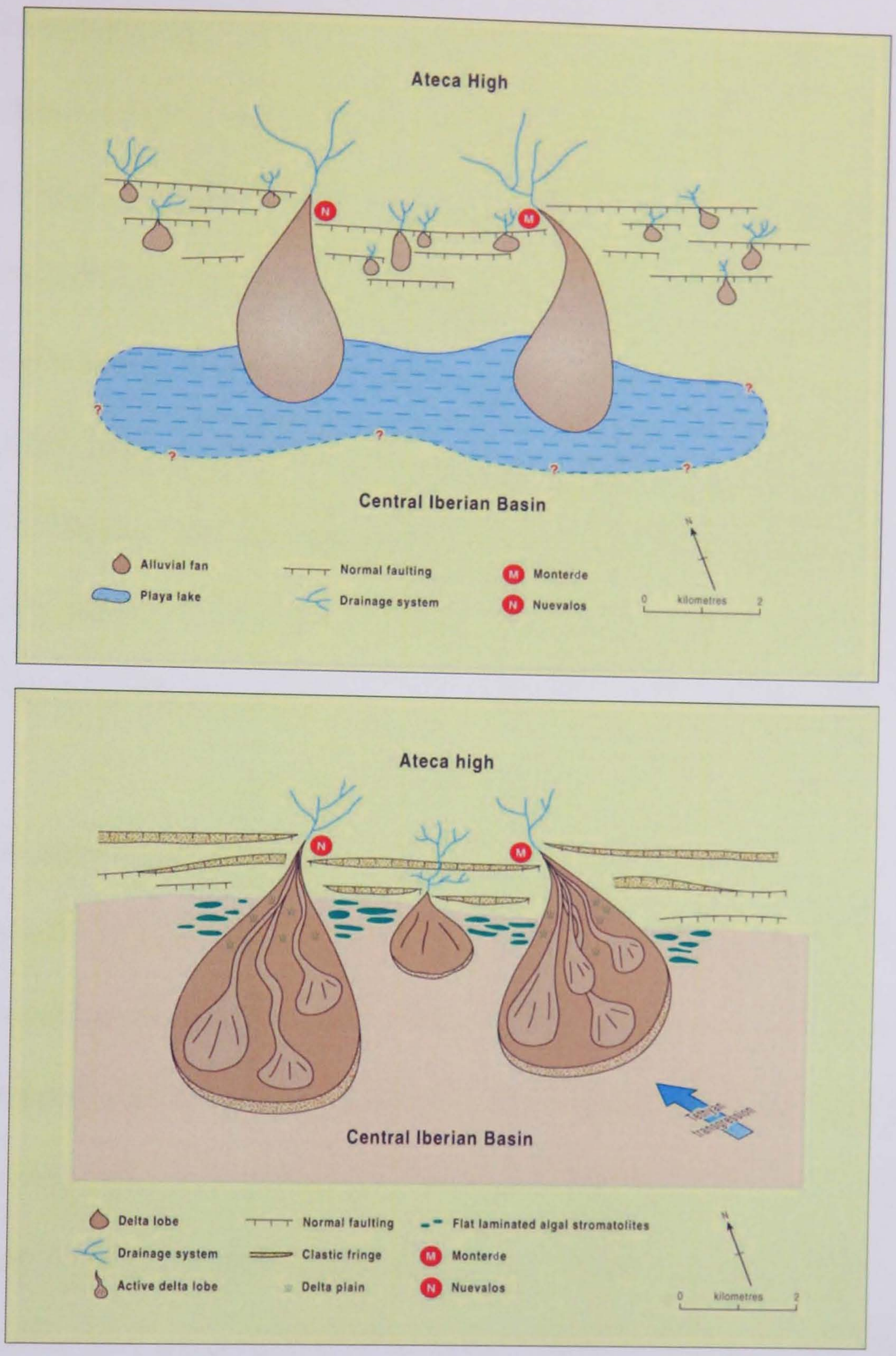


Fig. 3.14: (a) Alluvial fan and Playa Lake deposition along the northern margin of the CIB; (b) delta lobes form at the margin reutilising the routing systems previously filled with continental depositional systems.

This along strike component of variability in the positioning of sediment flux inlets and physiography has a pronounced effect on spatial and temporal stratigraphic development, yet it is possible to identify several units that persist laterally. These facies units suggest that similar facies were deposited contemporaneously along the basin margin, during the fluctuating marine transgression (FS-1 to 3) thanks to long-lived sediment supply routes.

The continued input of sandy sediment through stabilised supply rotes along strike of the basin margin can be observed within the facies. For example, the fan delta lobe facies of FS-2 is composed of several carbonate rich sandstone units - evidence suggesting the influence of the Muschelkalk carbonate platforms establishing towards the central basin areas to the East during the Anisian (Tucker et al., 1993). These tidal flat and lagoonal facies are believed to have existed at the same time the sandy fan delta facies of the Alhama Formation (Facies 3a and 3b) and provide strong evidence that clastic sediment supply to the basin was sustained from the same outlets along the margin into the middle Triassic.

3.8.4 Shallow marine deposition

During late stages of basin development, wholly marine conditions prevailed with the Tethys Sea covering much of the CIB, with only the highest areas of the Ateca High remaining exposed. Synrift sedimentation had now switched from the sandy flux of the delta lobes to carbonate rich packages of sediment, of Muschelkalk facies (Late Triassic, Ladinian, in age). The presence of stromatolites in the lower portions of the Muschelkalk limestone, interbedded with minor sandstone packages, indicate deposition in a shallow marine environment, which in this case was during a sea level rise. As well as signifying shallow marine conditions prevailed, the presence of stromatolites could also suggest a shut-off of sediment supply. However, thin stromatolite beds and abundant horizons of sediment deposited subsequently indicate that flux did not cease completely in all areas of the fan. This alteration in eustacy can be further interpreted using sequence stratigraphic framework nomenclature of being part of a Transgressive Systems Tract (TST) moving up into the early stages of Highstand Systems Tract (HST)

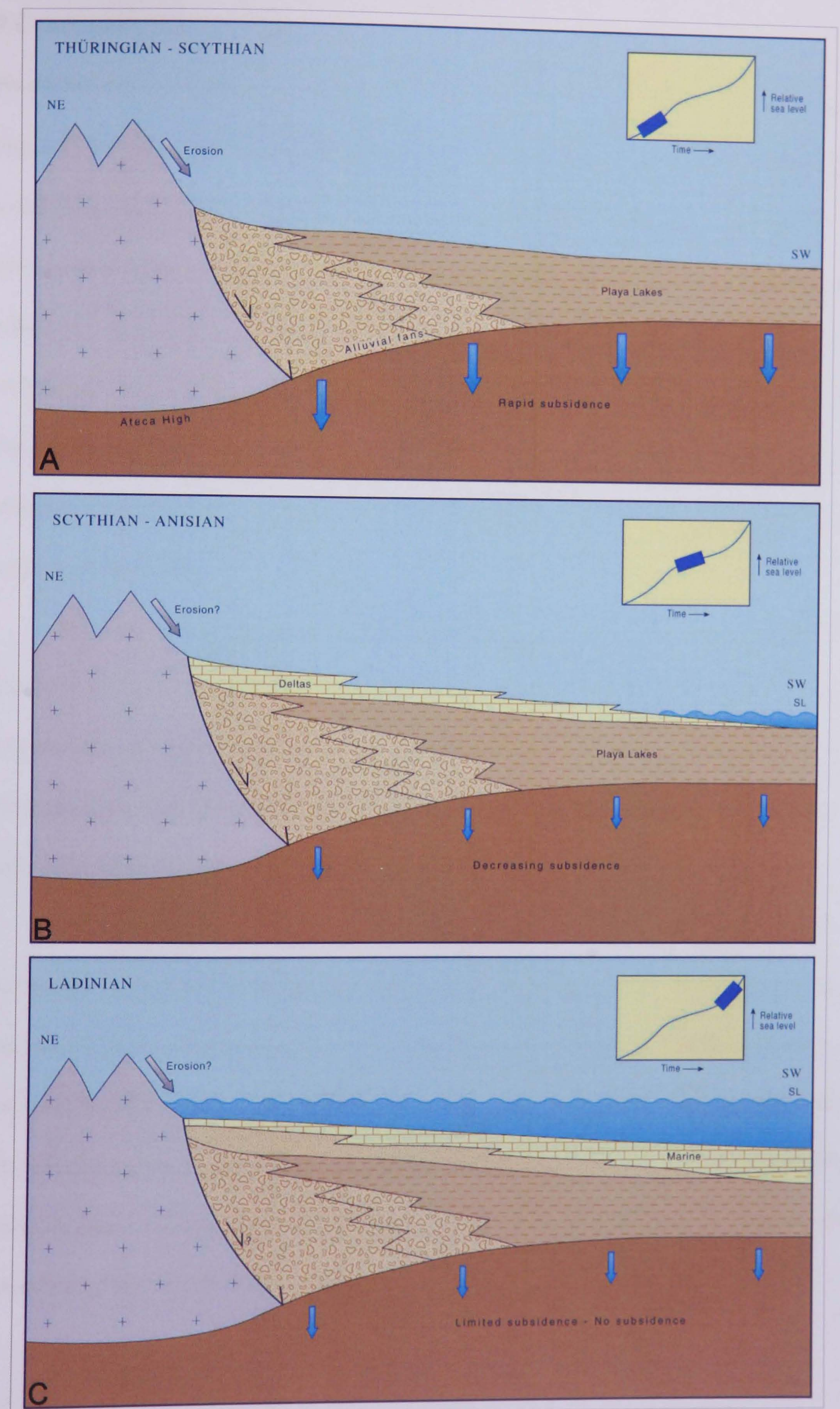


Fig. 3.15: Schematic cross sections through the CIB northern margin Buntsandstein and Muschelkalk facies sediments showing variations in subsidence, depositional system, sea-level and erosion during the Permo-Triassic. A sequence stratigraphic sea-level curve has been applied to the three-stage development of the basin margin systems.

3.9 Conclusion and summary

This chapter has documented the synrift sedimentary facies and architectural changes along a 40 km strike section of the northern margin of the CIB dominated by several normal fault segments (<5 km in length) that are joined by relay zones and transfer faults. Synrift sediment flux entered the basin via structurally controlled conduits with evidence of sustained existence of these conduits until the late stages of basin development and rift evolution (Fig. 3.14), a period of longevity of c. 6.5 Myr. Regional stratal surfaces within the sediments identify time equivalent packages demonstrating variability in architecture and thickness, related to the tectonic development of basin margin normal faults.

An overall model for the Monterde and Nuevalos locations can be devised for the deposition of these continental sediments at the margin of the Central Iberian Basin. In figure 3.15 (a, b and c) shows that a high rate of basin subsidence in the CIB, coupled with high rates of erosion from the hinterland, the Ateca High, results in alluvial fan and playa sedimentation of Buntsandstein facies.

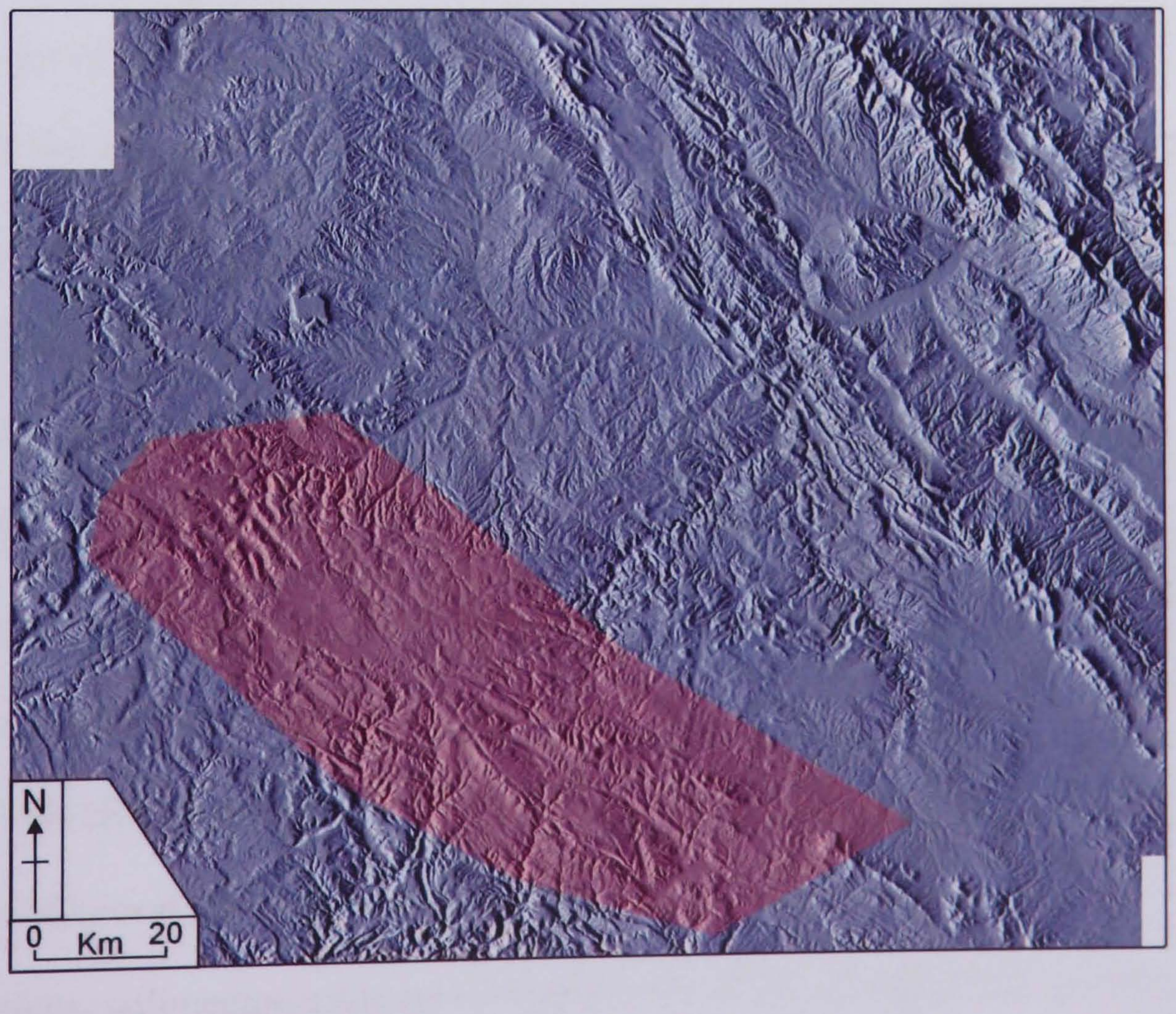
In plan view (Fig. 3.14 a and b), the pathways exploited by the alluvial fans from source to sink are more appropriately indicated and the extent of interfingering between the two facies associations can be observed. Reutilisation of conduits and continued sedimentation at the margin of the CIB, and a rising Tethys Sea produced delta lobes that over time became increasingly carbonate rich. This marked the onset of wholly marine conditions and the eventual flooding of the continental land mass and the deposition of the Muschelkalk facies.

Chapter 4

Sedimentation at Southern Margin and intrabasinal areas of the Central Iberian Basin

Key Findings:

- Intrabasinal highs compartmentalise rift basins and significantly influence drainage patterns within a basin;
- Across basin transfer faults have a more discrete impact on sedimentation and in this study have controlled the sinuosity of the axial flowing river system during the synrift phase;
- The basin parallel and cross-cutting structures have been instrumental in the longevity of the axial flowing river system linking two depocentres (Riba de Santiuste and Rueda de le Sierra) for the duration of *c.*7Ma.



4.1 Aim of the chapter

Over the last decade a revolution in the understanding of extensional rift basins has taken place. This is due chiefly to the recognition of highly extended terrains in both modern and ancient settings and the development of detailed models, which help to explain their evolution (e.g. McKenzie, 1978; Wernickie, 1985; Leeder and Gawthorpe, 1987; Gawthorpe and Leeder, 2000). Simultaneously, the general approaches to basin analysis have also advanced with the development of new analytical techniques (e.g. back-stripping, numerical modelling, isotope stratigraphy) and greatly improved age dating especially of continental deposits, provides new conceptual frameworks for rift basins.

Despite these important advances, the controls on rift basin fill history and syntectonic evolution are still poorly understood. There is debate concerning which processes exert the strongest influence on sedimentation and there is a paucity of well-calibrated models for sedimentation in rift basins. Several proposed models (e.g. Frostick & Steel, 1993; Leeder & Gawthorpe, 1987; Gawthorpe & Leeder, 2000) explain the two-dimensional stratigraphy of simple half-graben models for intracontinental rifts rather well. However, these models have been widely and inappropriately used where they do not reflect the wide range of allocyclic controlling factors, depositional styles and perhaps most importantly the change from basin margin to intrabasinal systems.

This chapter investigates the controls on sedimentation along the southern margin and coeval intrabasinal systems of the CIB. Through, chiefly, field observations, sedimentological, geomorphological and geodynamic data collection, the study serves to explain the longevity of the southern margin system, predominance of an axial drainage and the separation by intrabasinal structures from the northern margin (Chapter 3). The importance of compartmentalisation of synrift fills in the CIB can be used as a template for observation and comparisons with other intracontinental basins.

4.2 Intrabasinal topographic structures and impact on regional sedimentation. Are they important?

In Chapter 3 extensive discussions of rift margin sedimentation, next to the border faults has already been undertaken. This section aims not to repeat the many important issues raised, but will expand upon the far-field effects of the main rift border faults and the impact of intrabasinal synthetic and antithetic faulting.
It has been widely stated that the development of depocentres, and associated accommodation space, in central basin areas is due to the growth and development of rift border faults (e.g. Alexander & Leeder, 1999; Gawthorpe & Leeder, 2000; Lærdal & Talbot, 2002).

The stratigraphy of rift basins is dominated by episodic and cyclical events of sedimentation. These occur though pronounced events of aggradation, incision and periods of non-deposition and/or erosion. The episodic deposition of individual beds to the development of large-scale stratigraphic sequences occurs over a wide range of spatial and temporal time frames. Most interpretations of the episodic sedimentation are attributed to allocyclic (e.g. tectonism, climate and base level) and autocyclic (hydraulics, channel form) controls. However, the influence of border faults in rift basins upon far-field sedimentation (intrabasinal) has largely been neglected and the influence of geomorphic systems that become linked through time and their inherited internal oscillations have an important impact upon the resulting stratigraphy (Humphrey & Heller, 1995). The synrift stratigraphic record will record the tintinnabulation (repetitive oscillations from a single perturbation) of various events within the basin over time and may convolve previous records of tectonism and climate. In fact it seems likely that the axial fluvial system that dominated sedimentation along the southern margin of the CIB does not wholly reflect the synrift changes but those that took place prior to deposition and are still playing 'catchup'.

The tintinnabulation of the perturbations in the stratigraphic record can be well exhibited along the southern margin of the CIB where through the interaction of border faults, transfer faults (e.g. Teruel and Sigüenza faults, Fig. 4.1), and inherited palaeotopography controlling the sediment distribution through the compartmentalisation of the basin. Previous studies of rift basins neglect the structural components orientated normal to the rift axis and it is these components that can have the greatest impact on sedimentation and associated facies distributions.

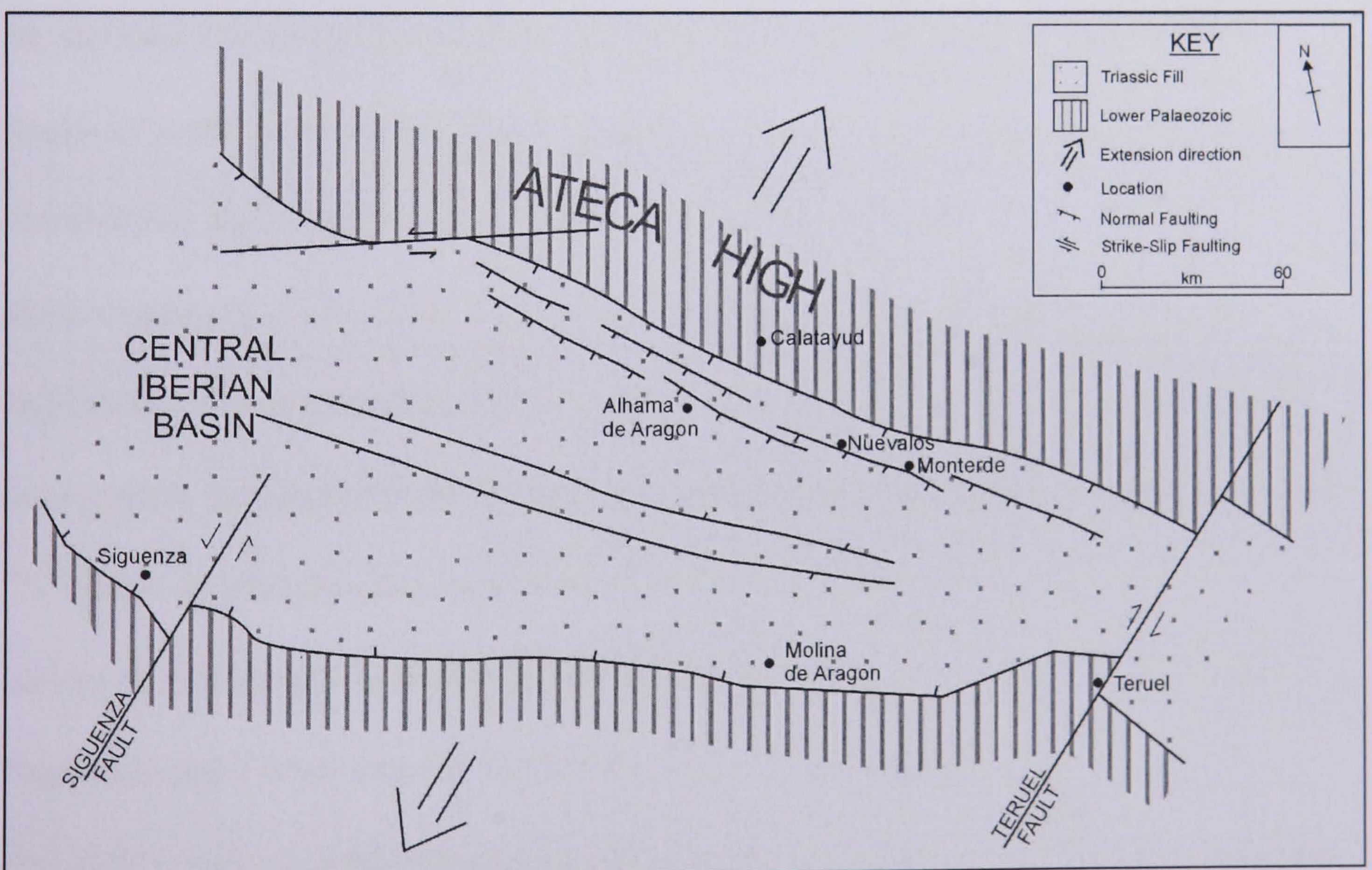


Fig. 4.1: Sketch map of the CIB showing the location of the Sigüenza and Teruel faults along the southern basin margin.

Topographically low areas within the rift basin form major sediment transport pathways that vary between individual basins due to differences in sediment supply, regional gradients and structural segmentation of the basins. The appraisal of sedimentation in rift basins by Frostick and Steel (1993) implies that synrift sedimentation, is controlled overwhelmingly by the interplay of fault-block geometry, drainage area characteristics and the rate of fault movement, as well as eustatic and climatic influences. Numerous half-graben models for rift basin sedimentation already exist in the literature (e.g. Bridge & Leeder, 1979; Alexander & Leeder, 1987; Peakall et al., 2000), but these neglect the sedimentation towards the rift basin axis (intrabasinal) where according to Humphrey & Heller (1995) basin margin controls will impact upon the far-field sedimentation. This can be easily exemplified by a river system changing its character due to fault-induced changes in basin floor gradient. The tectonically controlled change in basin floor gradient can result in a meandering system changing to a braided system (see later in this chapter).

The compartmentalisation of a rift basin resulting from intrabasinal highs, can be separated into two components; i) intrabasinal highs orientated parallel to the basin axis and basin margin faults (antithetic and synthetic fault systems and; ii) intrabasinal highs that cross-cut the basin, transverse to the axis (transfer faults). Both examples can be found within the CIB and offer very different sedimentary signatures. The intrabasinal high (Fig. 4.1) is thought to have formed a prominent topographic barrier between the northern and southern basin margins (Chapter 3 and 7), which divided drainage and associated depositional systems up. The lack of interaction between the facies adds evidence for this occurring. In comparison the Sigüenza and Teruel transfer faults (Fig. 4.1) accommodated significant stresses through transpressional movements, but also, and perhaps more importantly for later discussions controlled the regional gradients of the basin floor.

4.3 Structure of the Central Iberian Basin

The regional structure of the Iberian Ranges and the CIB has already been discussed at depth in Chapter 2. However, the intrabasinal high and the Sigüenza and Teruel transfer faults deserve to be discussed here in some further detail due to their importance on synrift sedimentation.

It is deduced from geological mapping and satellite images (Figs. 4.1 and 4.2) that the basin margin fault systems have played a very important and long lived role in controlling sedimentation. But equally the more discrete intrabasinal high and transfer faults have had major implications on the sediment flux and dispersal in the CIB.

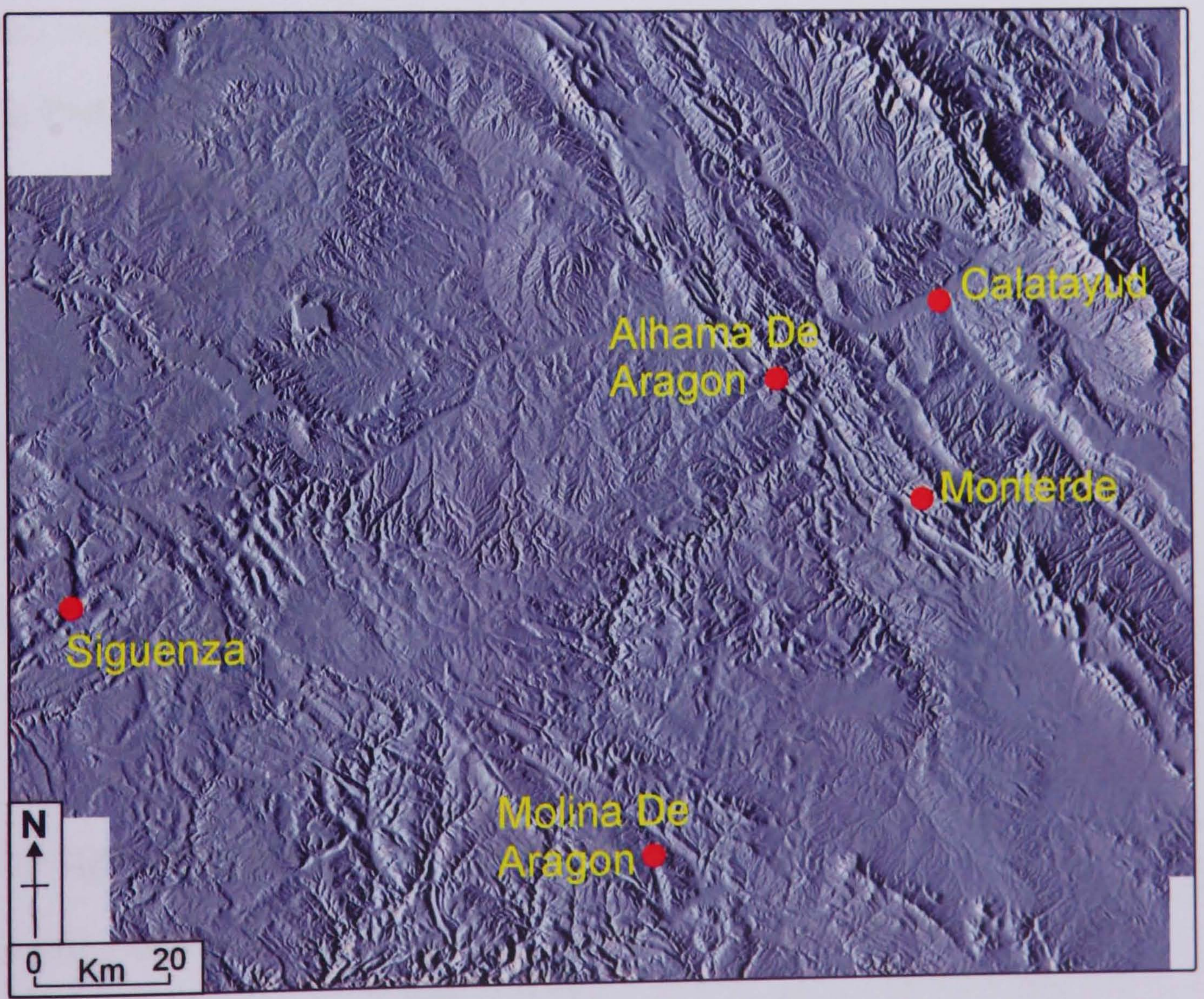


Fig. 4.2: Satellite image of the modern day Iberian Ranges showing a signature of the wedge shaped geometry of the CIB.

4.3.1 Intrabasinal High

The few studies that have recognised the importance of intrabasinal highs (e.g. Gordon & Heller, 1993; Anders & Schlische, 1994; Lærdal & Talbot, 2002) have generally been more concerned with the structural implications. Intrabasinal highs frequently define the boundary between two fault segments that often have a strong strike-slip component (e.g. Wheeler, 1987). Studies of the rupturing of rift basins recognise the persistence of intrabasinal highs that can result in long-term displacement deficits. Furthermore, Wheeler (1987) recognised that intrabasinal highs are often discrete structures and usually partially covered by sediments for much of their life (this seems a very likely occurrence for the CIB). However, even a small topographic expression will have a large impact upon sedimentation patterns (e.g. Peakall, 1998). It seems plausible that any tectonic activity away from the basin margins may trap fluvial and alluvial systems and move them away from their optimum gravitational position in the basin. The highs may also act as drainage divides, floodwater dams, act as areas ripe for pedogenesis and for localised erosion. The intrabasinal high of the CIB has been inferred and cross-referenced from the facies development, drainage patterns and structural implications from (Chapters 3, 5 and 6 as well as this chapter) based on reactivation of basin centre faults the Alpine orogenesis.

4.3.2 Sigüenza and Teruel Transfer faults

A transfer fault is a fault that links two normal faults and transfers displacement between them (Peacock et al., 2000). This has obvious implications for basin bounding normal faults and associated sedimentation where much of the research literature has concentrated its efforts in recent years (e.g. Alexander & Leeder, 1987; Gawthorpe & Leeder 2000). It is well documented that axially flowing river systems during synrift phases are strongly influenced by normal faulting along the basin margin and creation of rollover anticlines. An extensive literature base already exists on the architecture of axial flowing rivers through half-grabens and their associated stacking patterns (e.g. Allen 1983; Bridge & Leeder, 1979; Alexander & Leeder, 1987; Peakall, 1998 and many others). However, the along strike variations from upstream to downstream of axially flowing rivers has never been studied in detail before and the importance of faults cutting the basin floor will be discussed in this chapter for the CIB. The CIB provides an ideal opportunity to study the spatial and temporal variations of the synrift sedimentary fill and associated tectonism of an ancient rift basin.

4.4 Outcrop locations

The locations to be studied in this chapter along the southern margin are more widely spaced than described in Chapter 3 to provide coverage of the regional affects of the intrabasinal high and transfer faults on sedimentation.

Three important sections have been chosen, these are, Molina de Aragon (Rillo de Gallo) and Sigüenza (Rueda de la Sierra and Riba de Santiuste) (Figs. 4.1 and 4.2). These sections were chosen because of the ease of access, excellent exposures and proximity to known active faults during the synrift phase of the Permo-Triassic (López-Gómez et al., 2002; Ramos et al., 1986; Sopeña & Sánchez-Moya, 1997). The outcrop spacing will document two important physiographic characteristics of the basin; i) the change in downstream gradient of the basin floor from the NW to SE and; ii) the documentation and comparison of facies and alluvial architecture from the most northerly corner of the basin to the southern depocentre next to the Teruel transfer fault.

4.5 Stratigraphy

Previous work on the CIB has been unable to completely evaluate all of the stratigraphy formed across the CIB as a whole or its relation to the adjoining Iberian Basin and it is hoped this thesis study will go some way to address this. Studies on the stratigraphy of the CIB (e.g. López-Gómez et al., 2002; Ramos et al., 1986; Sopeña & Sánchez-Moya, 1997) have concentrated on the southern margins of the basin and the correlation between areas along that margin, namely Molina de Aragon (Rillo de Gallo) and Riba de Santiuste (near Sigüenza). However, the stratigraphic relationships in a broader regional context across the whole of the CIB are less well understood and provide a complex pattern of associated formations. In particular, the deposits of the northern margin and their correspondence with counterparts preserved at the southern margin are of importance as well as links that can be made with well-studied deposits in the Iberian Basin to the southeast (López-Gómez & Arche, 1997). Figure 4.3 comprehensively ties all the formations and facies found in these areas together into a coherent whole. Age dates for the figure and in this text have been obtained from Van Wees et al. (1998; Table 1).

4.5.1 Rueda de la Sierra and Rillo de Gallo

Outcrops at Rueda de la Sierra bear resemblance to sediments found at Rillo de Gallo (Sopeña et al., 1988) but offer further information about sedimentation in this area.

Before deposits were laid down anywhere across the rest of the basin sedimentation in the region of Sigüenza, in the CIB, began in the Lower Permian

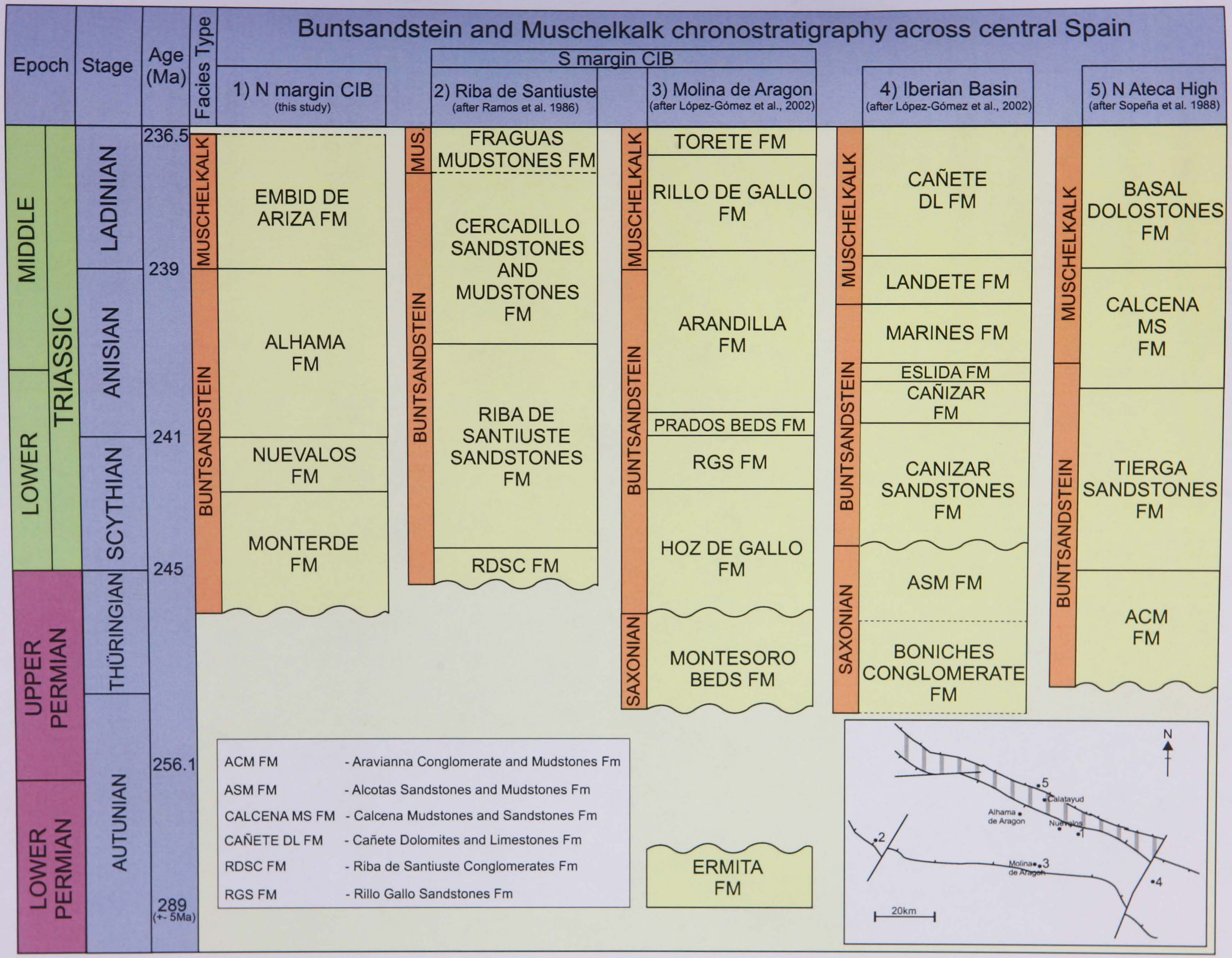


Fig. 4.3: Stratigraphic correlation table across the entire Iberian Ranges showing contemporaneous formations laid down by contrasting depositional systems.

(Early Autunian) (Fig. 4.3). These deposits consist of up to 300 m of breccias and sandstones overlain by ash-flow type volcaniclastics, above which lie deposits of the Ermita Beds, successive interval beds of grey-black mudstones, ash beds and dolomites believed to have formed in a lacustrine setting (Marfil et al., 1987-1988; Sopeña et al., 1988) with macro and microflora (Virgilli et al., 1984). This formation is not seen at the location of Rueda de la Sierra, but can be located and studied nearby, behind the village of Rillo De Gallo (Fig. 4.4).

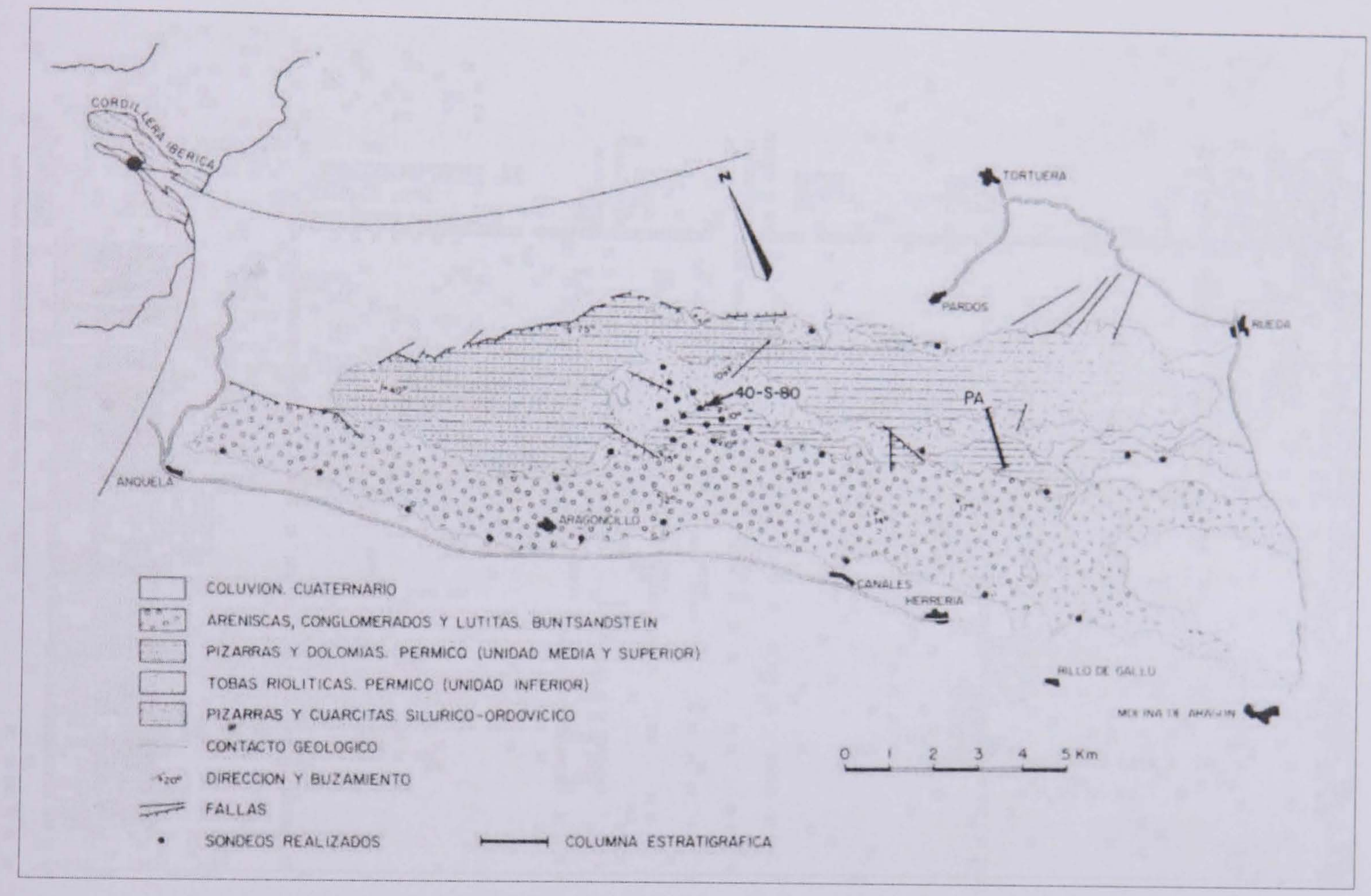


Fig. 4.4: Sketch map of the Permo-Triassic geology west of the village of Rueda de la Sierra and north of Rillo de Gallo (both near Molina de Aragon). (Taken from Marfil et al. 1987-1988)

The Ermita Beds have been described previously in the literature and will not be included in the analysis of facies types in this chapter.

Outcrops near Molina de Aragon, in and around the village of Rueda de la Sierra (and Rillo de Gallo) contain the Montesoro Beds of pre-Buntsandstein facies, lying unconformably on the Ermita Beds. The deposits are Thüringian in age and consist of 120 m of red-coloured sandstones, breccias, and siltstones laid down in continental settings (Fig. 4.5). The Montesoro Beds can be stratigraphically linked to similar deposits to the southeast in the Iberian Basin, tying in with red-bed conglomerates of the Boniches Formation and red sandstones, siltstones and occasional conglomerates of the Alcotas Fm (López-Gómez et al., 2002) (Fig. 4.3).

Sediments of the Buntsandstein facies follow on from the Montesoro Beds, at Rueda de la Sierra and Rillo de Gallo, and are composed of two main continental successions that can, in most cases, be linked across basins. The lower succession contains laterally restricted fanglomerates of the Hoz De Gallo Fm of Late Thüringian - Early Scythian age followed by the Rillo Gallo Sandstones, which are slightly more widespread. These two formations have an equivalent of the Cañizar Sandstones in the Iberian Basin, both of which are contemporaneous to the deposition of Buntsandstein deposits, as the Monterde Fm and Nuevalos Fm, at the northern margin of the CIB (Fig. 4.3).

The upper succession of deposits of the Buntsandstein seen in outcrops behind the village of Rueda de la Sierra and near Rillo de Gallo, near Molina De Aragon, are also continental in origin and are made up of four formations: Prados Beds, Arandilla Fm, Rillo De Gallo Fm. (sometimes called the Rillo Fm), and the Torete Fm. The Prados Beds are composed of irregularly distributed sandstones and siltstones, as is the Arandilla Fm, of Anisian (Lower - Middle Triassic) age, and Rillo De Gallo Fm (late Anisian in age). All link to deposition of further Cañizar Sandstones and more predominantly Eslida Fm red sandstones in the Iberian Basin (Arche & López-Gómez, 1999). Analysis of the deposits at the northern margin of the CIB reveals coeval deposition of the Alhama Fm sediments, laid down before onset of the Ladinian (Upper Triassic) and indicates that eustacy played a an important but not singularly dominant role in sedimentation.

Finally, the Torete Fm and subsequent formations are composed of thick units of pale pink/yellow coloured carbonate-rich sandstones. It is thought that they represent a transition into marine limestone deposits (Muschelkalk facies) because of the presence of shallow marine trace fossils on the underside of the carbonate-rich sandstone beds. The equivalent limestone formation can be found to the southeast (northwest of Teruel) where the Tramacastilla Fm exists (López-Gómez et al., 2002). Whereas at the northern margin of the CIB these deposits are still described as the Alhama Formation, but are characteristic of the algal stromatolite and thin carbonate sandstone units, moving into the Mushelkalk dolomite limestones displaying lateral extension and are equivalent to the Cañete Dolomites and Limestone of the Iberian Basin (Fig. 4.3).

4.5.2 Riba De Santiuste

The deposits studied in this area provide information that contrasts to that found near Rueda de la Sierra, the northern margin of the CIB or outcrops in the Iberian Basin. The stratigraphy at Riba de Santiuste is less complex and represents a complete transition from Buntsandstein and Muschelkalk facies deposition (Figure 4.3).

Deposition at Riba de Santiuste occurred away from marginal areas (towards the basin centre) of the CIB but retained an influential proximity to the southern basin margin faults, occupying a prominent place in the hanging wall of the basin. Work on the deposits here has identified a probable tectonic signature of rift-initiation contained within the sediments (Sopeña & Sánchez-Moya, 1997). It is noticeable that deposits of Permian age are less abundant than the counterparts in other areas of the Iberian Ranges (López-Gómez et al., 2002). The oldest Buntsandstein deposits sit unconformably on top of Permian basement rocks at Riba

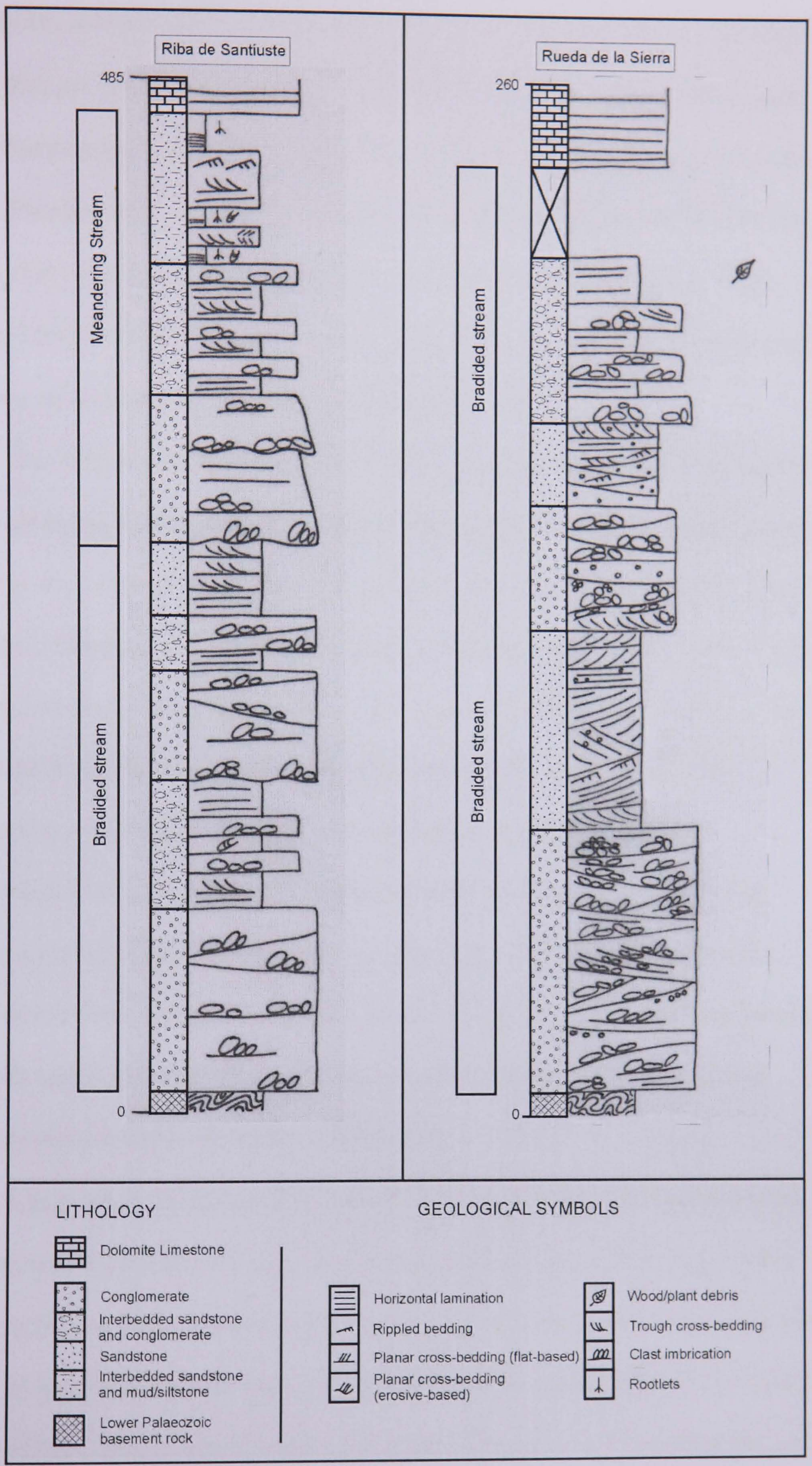


Fig. 4.5: General graphic logs constructed from outcrops at Riba de Santiuste and Rueda de la Sierra showing lithologies and facies information.

de Santiuste, and are called the Riba de Santiuste Conglomerates (RSC). Thüringian in age, they are predominantly composed of pebble-rich red beds with some minor interbedded sandstone units (Fig. 4.5) and correlate with Autunian deposits in other basins (Sánchez-Moya et al., 1996; López-Gómez et al., 2002). Figure 4.3 indicates that the RSC link favourably with the Alcotas Mudstones and Sandstones of the Iberian Basin, the Hoz De Gallo Fm in and around Rueda de la Sierra, and the early evolution of the Monterde Fm at the northern margin of the CIB.

The Riba de Santiuste Sandstones (RSS) which succeed the RSC up section have a strong correlation with the Cañizar Sandstones in the Iberian Basin (López-Gómez et al., 2002). Its equivalent in the CIB is believed to be a collective of the Rillo Gallo Sandstones, Prados Beds and the Arandilla Fm (Scythian-Anisian in age) heading east along the southern margin (Ramos et al., 1986), whereas at the northern margin the Nuevalos and Alhama Formations are coeval with the RSS. The sediments that characterise the RSS are subordinate conglomerates with discontinuous red coloured sandstone packages and occasional mudstones that indicate a period of early rift climax in this area of the CIB (Sopeña & Sánchez-Moya, 1997). Palaeosol development in these red beds is common (Alonso-Zarza et al., 1999) which also provide clues to the tectonic development of the CIB and indicate pauses in sediment supply to the basin.

Lying above the RSS at Riba de Santiuste is the Cercadillo Sandstones and Mudstones (CSM) (Ramos et al., 1986; Sánchez-Moya et al., 1996). They are the lateral equivalent of the Rillo de Gallo Fm and Torete Fm at Rueda de la Sierra and consist of sandstones, mudstones and infrequent conglomeratic beds. At the northern margin of the CIB they are representative of the upper parts of the Alhama Fm and the onset of Muschelkalk facies deposition. In the Iberian Basin, their time equivalent would be the Eslida Fm, Cañete dolomites and limestones, and the

Landete dolomites, Anisian-Ladinian in age (Ramos et al., 1986; López-Gómez et al., 2002). These sediments suggest the continued climax of rifting across the basin, as marine sandstones and limestones of the Muschelkalk facies succeed continental, non-marine deposits.

4.6 Continental Fluvial

4.6.1 Facies descriptions

Along the southern margin of the CIB lies what appear to be a diverse range of conglomerate and sandstone fluvial lithofacies dominate the sedimentary fill (e.g. Ramos & Sopeña, 1983; Ramos et al., 1986) (Fig. 4.5). The following facies analysis provides evidence to support this. This facies is studied on the southern margin to establish a better understanding of i) the sediment supply routes with both transverse and apparently axial systems active; ii) changes in base level control on the gradient of the fluvial systems and; iii) to appreciate the importance of intrabasinal structures controlling depositional patterns and processes.

4.6.1.1 Facies 1a: Fine- to coarse-grained sandstone

The facies consists of horizontally bedded fine- to medium-grained sandstones, red in colour. Each bed is <10 cm thick and displays lamination (<1 cm) in parts. Within some of the beds are small lenses of coarse sandstone and even granule-sized grains, which show a slight yellow discolouration on their base.

On the base of many of the medium-grained sandstone beds, gravel clusters are observed (<1 cm clasts). It is towards the top of these same beds that immature palaeosol (entisol) development occurs in the form of partial laminations, obscured by maturation of the sediment and minor rootlets, as well as discolouration to a red/grey, crumbly top-horizon.

4.6.1.2 Facies 2a: Matrix and clast supported massive sheet conglomerates

Facies 2a forms a large proportion of the lowermost conglomeratic deposits in both the Rueda de la Sierra and Riba de Santiuste sections. They consist of poorly sorted matrix and clast-supported conglomerates in units <2.5 m thick, extending laterally for tens of metres in each direction (outcrop permitting). The clasts are predominantly composed of quartzite and are well rounded to sub rounded with pitted surfaces. Each

Photograph 4.1: Bedded conglomerate (10 m thick) in outcrop at Rueda de la Sierra

'pit' is between 4 mm and 1.5 cm in size, white in colour, and shows negative relief (Photograph 4.2). Clast size varies from 3 cm to 20 cm in size. A sandy matrix is sometimes observed in the clast supported beds.

Photograph 4.2: Probable clast dissolution marks on the surface of pebbles found in southern margin fluvial conglomerates (White circular mark in top right corner is 1 cm wide).

The matrix-supported conglomerates have a medium grained red sandy matrix and some imbrication is observed (Photograph 4.3). Poorly defined imbrication can be picked out from some of these beds showing a north-north easterly direction. These beds are more laterally persistent than their clast supported counterparts and can be traced for up to one hundred metres at Riba de Santiuste.

Photograph 4.3: Clast imbrication in conglomerates observed at Rueda de la Sierra. Palaeodirection is from left to right of the image (Tape measure indicates 10 cm).

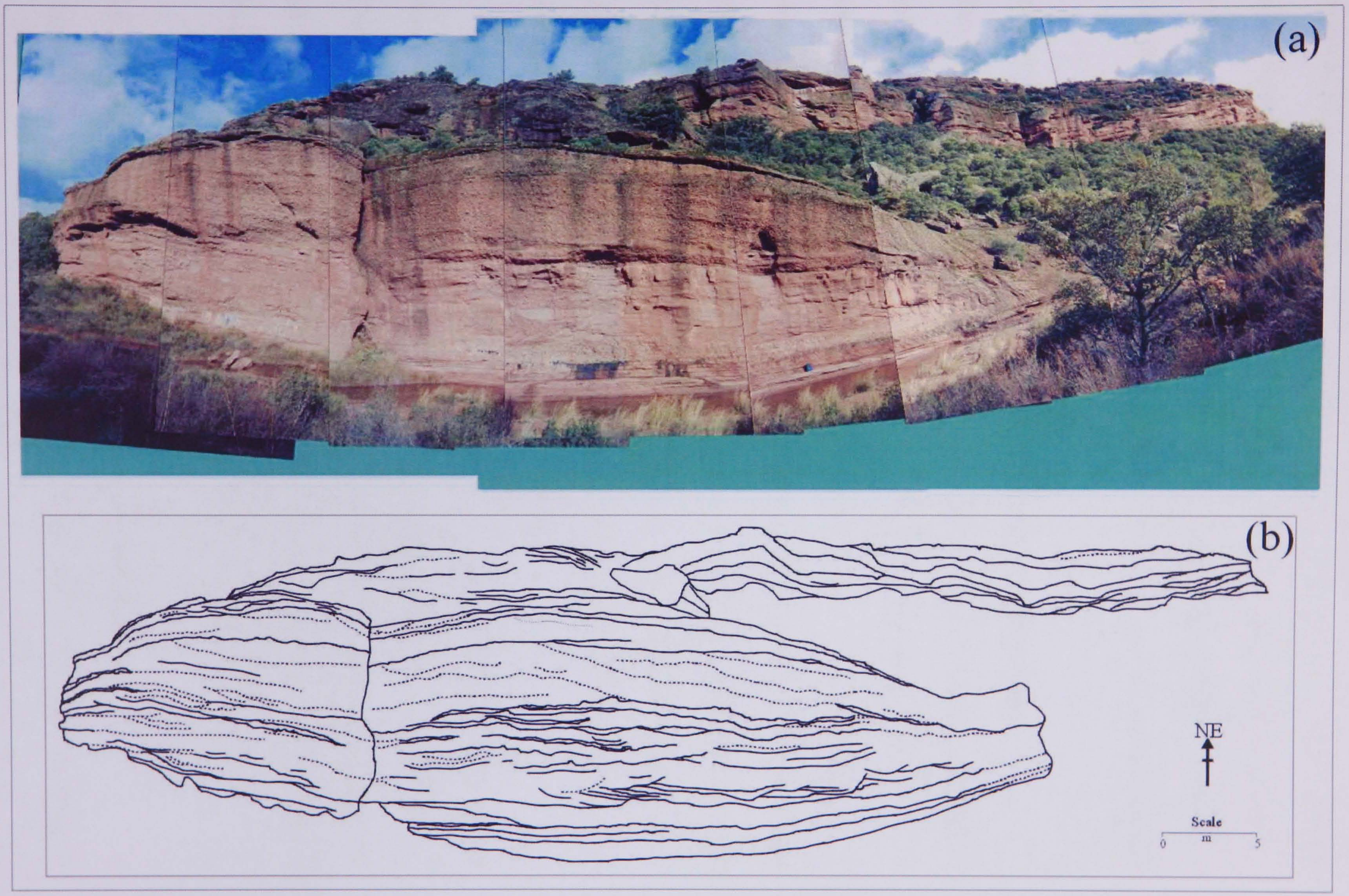


Fig. 4.6: (a) Photo montage of the lowermost Buntsandstein sediments at Riba de Santiuste, near Sigüenza; (b) Sketch taken from the photo montage in *a* showing detail of the bedding surfaces and cross-stratification.

The architecture of each sheet unit is poorly defined again due to restrictions enforced by quality of the outcrop at this section. However, it is possible to identify a slight convex upwards nature to the units, or scouring from an overlying bed. In many cases, where scouring is apparent, poorly sorted pebble clustering occurs. Crude stratification is noticeable, but lacks definition for sedimentological purposes.

4.6.1.3 Facies 2b: Clast supported lateral accretion conglomerates

This facies occurs sporadically throughout the lowermost to mid sections of both locations. A maximum of 1.6 m in thickness, units of this lateral accretion conglomerate display clast supported quartzite pebbles, 5 cm - 30 cm in size, in wedge shaped geometries (Fig. 4.6 a & b). Each of the beds, which tend to have flat bases, fails to laterally persist for more than 10 m in either direction and is often seen passing across into crudely stratified conglomerates of Facies 2a. Imbrication of clasts is common and shows a south to south-easterly palaeocurrent direction, a contrasting direction to that of the accretion movement.

Within each accretionary unit, small (<3 cm thick) beds of red sandstone are observed which seemingly drape over the conglomerate horizons intermittently. They take the form of clear internal surfaces dipping gently in the direction that the bed pinches-out. Small clustering of gravel and pebbles is noted and overlies each of these drapes, showing further vague but identifiable imbrication structures.

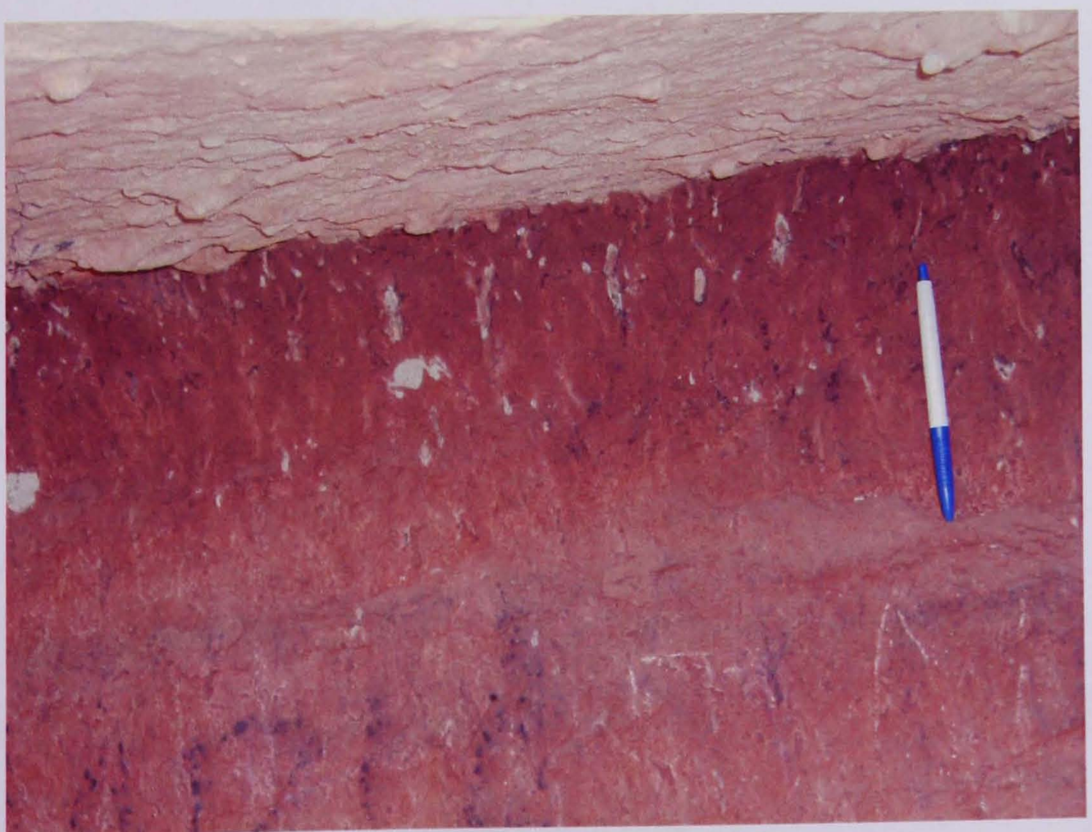
4.6.1.4 Facies 2c: Clast supported channel fill conglomerates

Units of facies 2c are made up of conglomerate beds <2 m in thickness and extend laterally for up to 8 m. They consist of gravel to pebble sized clasts (<3.5 cm) with a high proportion of sandy matrix than found in the other conglomeratic facies. Improved sorting is noticeable in distinct horizons within the packages of conglomerate and some crude fining upwards trends can be observed especially as the strong scouring and erosive contacts delimit tops and bases of the beds. In the scours, pebble clustering is observed and strong imbrication can be measured throughout the majority of the unit (south easterly).

Varying scales of trough cross stratification can be seen within the gravels and pebbles ranging from 1.3 m to 4 m in size. These can be isolated features that pass laterally into one another or they can stack in a multi-storey fashion on top of one another. In the case of the latter, scouring and accumulations of larger clasts is common.

4.6.1.5 Facies 2d: Fine to medium sandstones and palaeosols

Interspersed throughout the conglomeratic units are small beds of fine to medium red coloured sandstone, maximum 40 cm thick. The beds often take the shape of the underlying stratigraphy, either as a drape over a convex upward unit or as a gently dipping horizon overlying in a lateral accretion bed. In other cases, this sandstone is scoured into by the erosive overlying geology, in many cases a conglomerate unit.



Photograph 4.4: Palaeosol and rootlet horizon at top of fine sandstone unit (Rillo de Gallo, Molina de Aragon) (Pen is 13 cm long).

These sandstone beds have vague stratification showing horizontal lamination or shallow cross stratification and in odd cases distinctive bioturbation.

Commonly, the sandstone appears to have matured, displaying discolouration, mottling and rootlet growth, and has lost its internal structure. In these cases, some rootlets can be identified and weak colour mottling can be observed (Photograph 4.4). These horizons tend to occupy the top 5 cm of the sandstone horizons and show enough characteristics to be classified as a palaeosol, likely to be an entisol as classified by Retallack (1998, 2001). Gypsum nodules and evidence of calcification are absent in these palaeosols unlike those seen on the northern margin of the CIB.

4.6.1.6 Facies 3a: Very coarse-grained channel fill sandstones

Thick units (<3 m) of very coarse-grained red transforming to cream coloured sandstone as you move up section form this facies type. Tabular cross stratification and dipping foresets (15°) provide structural interest, whereas the beds themselves can extend for up to 100 m. Palaeocurrent directions gleaned from the sedimentary indicators suggest palaeoflow was to the east-southeast. Isolated clasts of rounded to sub rounded quartzite are seen scattered through the units, but they take no particular orientation normal to the bedding. Where trough cross-bedding occurs, an erosive base can be seen cutting into the underlying sediment. However, many of the tabular cross-stratified units have relatively flat bases.

4.6.1.7 Facies 3b: Medium grained channel fill sandstones

Similar to Facies 3a except there is a marked increase in the abundance of trough-cross stratification. The palaeocurrent direction of the majority of these structures is to the east. Beds tend to be less laterally extensive (<30-40 m) and have maximum

Photograph 4.5: View of very coarse grained channel sandstones at Riba de Santiuste, located along the southern margin of the CIB.

thickness of 3.5 m (Photograph 4.5). This facies is red in colour with some yellow and green discolouration towards many of the bases and contains high mica content. Beds are often discontinuous along strike and isolated clasts are found within the beds showing no particular sedimentological features such as imbrication.

The architecture of the channels shows finer sediments either side of the channel form, deposits which occasionally contain rootlets and minor bioturbation horizons (3 cm thick) especially on the top surfaces of the beds.

4.6.1.8 Facies 3c: Palaeosol and rhizolith horizons

Facies 3c is best represented by the upper sections of Riba de Santiuste, but can also be located at the mid portions and upper units of Rueda de la Sierra. This facies consists of sediments likely to be mature palaeosols, due to their colour mottling, rootlets and lack of internal structures, and rhizolith horizons up to 20 cm in thickness in parts. The palaeosols at Riba de Santiuste in particular have been the subject of intensive study and were found to be reaching up to stage III on the Machette scale by Alonso-Zarza et al. (1999) with calcified nodules on occasional horizons.

The palaeosols and to some extent the rhizolith horizons extend for hundreds of metres laterally. However, an overlying sandstone bed commonly erosively cuts into the top surfaces of the horizons. The palaeosols have acquired a deep red colour, similar to that of the surrounding host sandstone geology, and show green and yellow colour mottling and faint rootlet traces. Relict bedding is occasionally preserved at the base of the horizons.

4.6.2 Facies Interpretation

4.6.2.1 Facies 1a

This facies represents the Montesoro Beds, easily seen in the Rueda de la Sierra sections, near Molina de Aragon, but absent in the Riba de Santiuste sections. Ramos et al. (1986) defined these beds in similar locations and outcrops as being upper regime flat bedding developed during initiation of an episode of increasing energy, due to a change in flow stage. This change in flow stage is likely to be the onset of clastic flux and fluvial development along the axis of the basin. Lenses of coarse-grained sandstone within horizontally-bedded sandstones, and gravel clusters add a weight of evidence to this likelihood and palaeosol development indicates periods of exposure existed in-between flow events. After this, which Facies 2, 3 and 4 are testimony to, flow regime was extremely high with the energy required to transport large clasts great distances.

4.6.2.2 Facies 2a

According to Ramos & Sopeña (1983) this facies, which is the most frequent of the facies types (especially at Rueda de la Sierra/Rillo de Gallo), can be associated with all the other facies types in section. Often they can alternate with one another,

Photograph 4.6: Cross-bedded and accretionary red sandstone units (centre of image) sandwiched between conglomeratic units at Rillo de Gallo (thickness of cross-bedded sandstone is 2 m).

separated by a bed of alternative facies or small sandstone intervals (Photograph 4.6). The convex upward nature of the facies lends weight to the interpretation that these are barforms and the sheet conglomerates formed as longitudinal bars similar to those in modern gravely braided streams. However, it is unlikely that these will be one single event indicated by the erosional tops to some of the beds. Within the conglomeratic beds, small horizons can be picked out with scoured or erosively based bottom surfaces representing one of the many depositional events occurring at this point in time.

The large clasts contained within this facies suggest deposited occurred as a result of high energy floods within the stream capable of carrying sizeable clasts which are then deposited during waning flow. Clustering would then occur as larger clasts trapped others behind them, initiating a vague bar from which a more established one could develop (Photograph 4.7).

Photograph 4.7: Imbricated and clustered clasts within facies 2a (30 cm ruler for scale).

During waning flow, when the energy of the flow had reduced, bar growth is likely to have remained dormant with flow continuing around the bar. The presence of sandy intervals in this facies suggests relative dormancy whilst the accumulation of sediment to distinguish individual bars can be found laterally in the sections.

With the matrix supported conglomerate facies, it is possible that high-energy flow during flood stage would carry sand in suspension as well as larger clasts and a sudden reduction in energy would deposit the sediment. There is also the influence of frequent minor depositional events from small alluvial fans (recognised by the matrix supported sediments) entering the basin from the nearest margin – the southern margin. There is a strong possibility these would interact with the fluvial system at the foot of the fans and toe cutting and interbedding would occur as they entered, flowing northwards, perpendicular to the fluvial channel.

4.6.2.3 Facies 2b

These accretionary deposits are likely to be the modification of these bars during waning flow (Ramos & Sopeña, 1983). Lateral foreset bedding, highlighted by the imbrication of the clasts seemingly occurred. This process is similar to that described by Ramos & Sopeña (1983) where clasts, that could no longer be moved over the bar by high-energy flow due to height of the bar or even waning flow, would often be transported laterally along the margins of the bar. As well as lateral movement, vertical accretion would have also occurred simultaneously (Photograph 4.6). This is related to water depth, thus thinner foresets are observed on the tops of bars and thicker forms occur laterally and downwards nearing the bottom of the bar.

Flow stage alteration is recorded by the presence of sandy intervals and drapes within the accretionary facies. When flow waned, less coarse clasts could be carried by the flow, therefore resulting in the transportation and subsequent deposition of sand over the bar form.

4.6.2.4 Facies 2c

These sorted, trough-cross bedded channel sandstones suggest that around each of the bar forms in the fluvial system, sat channel forms which continued to transport sediment during periods of reduced flow. Though it is likely many of the channels passed into the bars transitionally, it is the formation of multi-storey channel patterns that is the most striking in these sections. Channels cut into each other vertically and laterally, sometimes removing all evidence of a previous channel.

The sporadic appearance of small sand intervals within the multi-storey forms indicates that variations in the flow, settling or abandonment of channels occurred. It is this type of conglomerate channel facies that is indicative of braided streams, in this case due to the size of the units, a large stream (see Allen, 1983; Ramos & Sopeña, 1983).

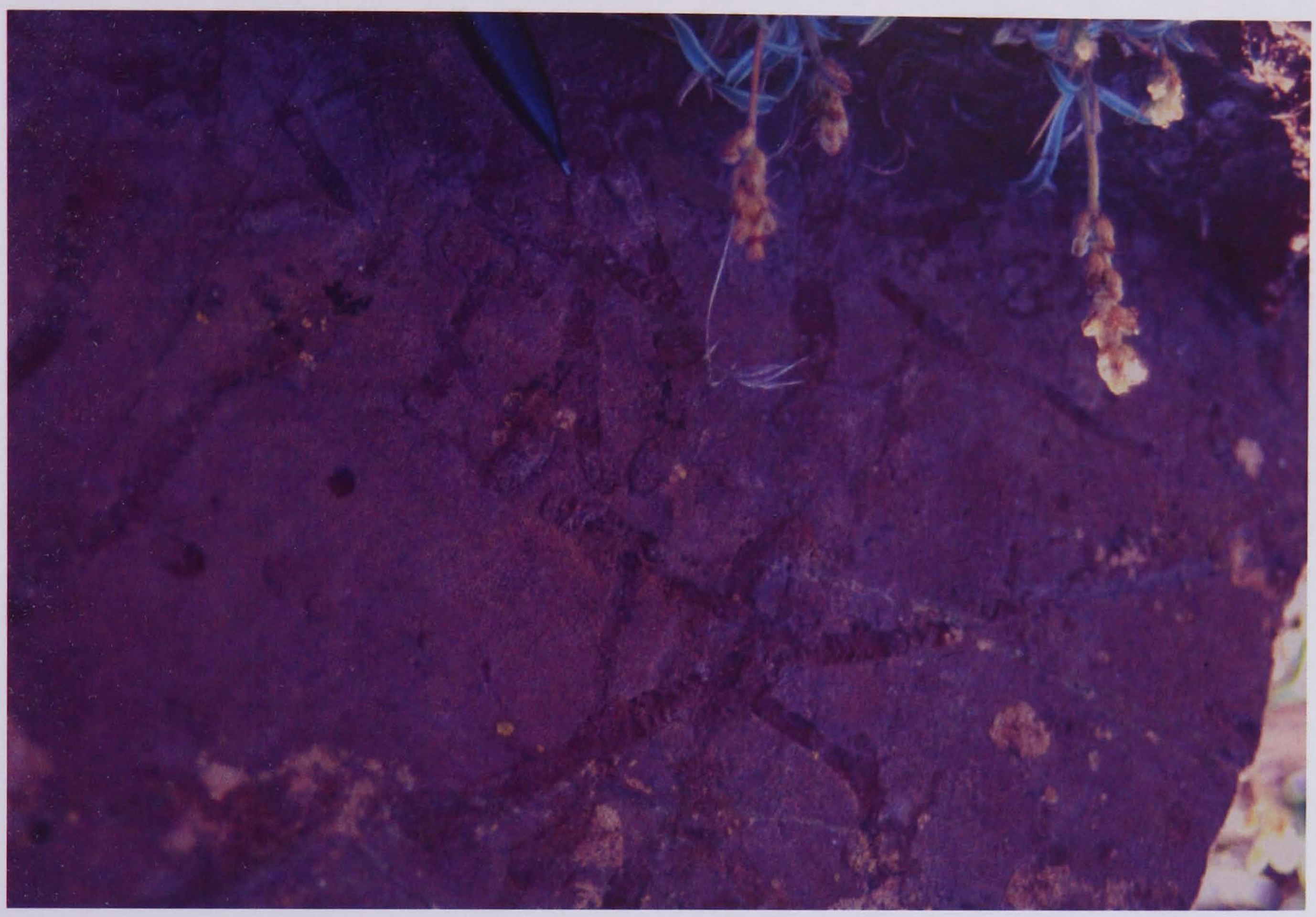
4.6.2.5 Facies 2d

Suspension settling of sediment often results in a drape of fine to medium sandstone that can form part of a bar under waning flow regime in the stream. As described earlier in Facies 2b and 2c, the deposition of this sediment is through either suspension settling in a channel or as a drape over a longitudinal bar in a braided stream.

However, the presence of bioturbation (Photograph 4.8), rootlets and pedogenic alteration to some of the sandstone indicates that there were periods of quiescence on bar surfaces or at the margins of channels. It is the latter that could have these deposits as their floodplain counterparts, which would explain why there has been time for a palaeosol to form on what is considered an active stream belt. This feature is seen more in Riba de Santiuste where channel conglomerates and sandstones are common, and is not seen in this form at Rueda de la Sierra save for infrequent appearances underlying coarse sand units. This will be explained further in section 4.8 where a depositional model is discussed.

4.6.2.6 Facies 3a

Thick units of coarse-grained, tabular cross-stratified and trough cross-bedded sandstones, extending for at least 100 m, indicate high-energy deposition during possible flood events in channels. The vast lateral extent and continuity of the units suggests confinement of the channels was rare and often they coalesced and covered large areas of the fluvial system. Bar surface, accretionary surfaces and floodplains deposits were also present and would have been susceptible to raised water levels.



Photograph 4.8: Bioturbation in the weathered red sandstones of facies 3b (tip of pen for scale)

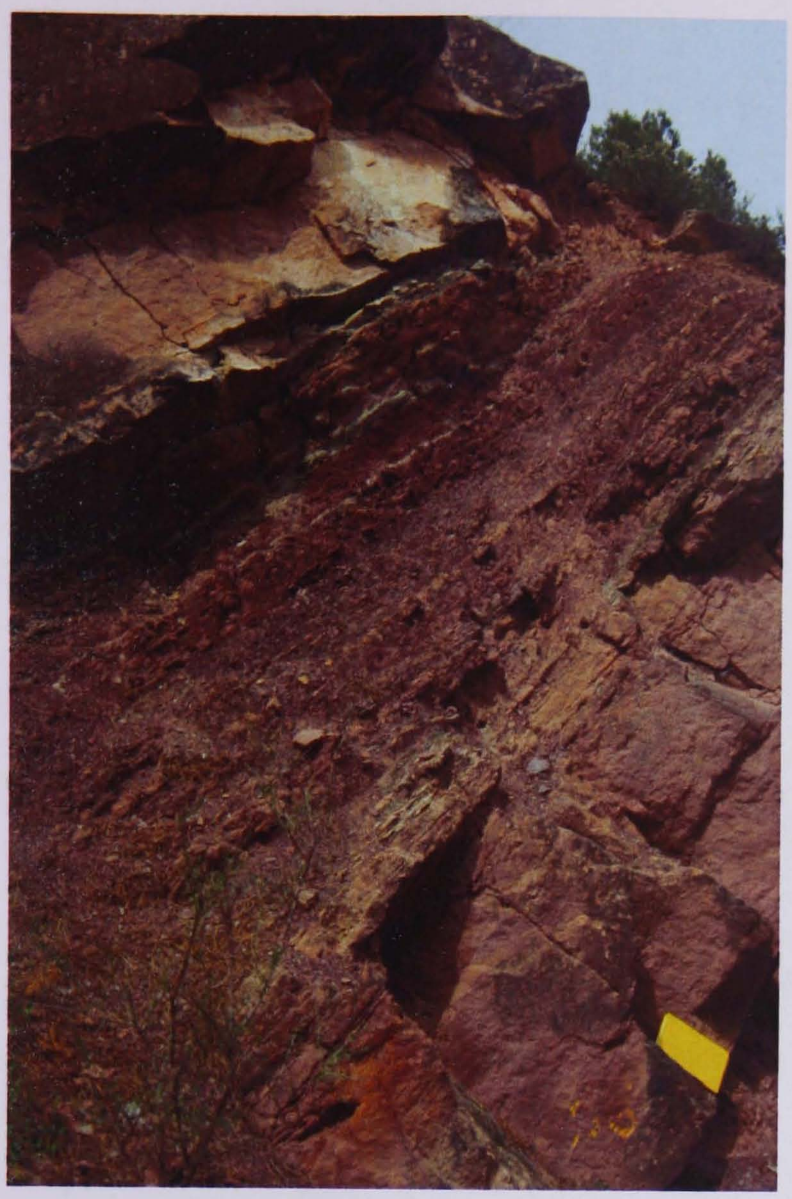
The presence of isolated pebble clasts indicates that flow was either strong enough to transport such grain sizes or that periodic fluctuations of flow energy within the channel occurred giving rise to interspersed clasts that lack depositional orientation.

4.6.2.7 Facies 3b

The lateral extent of these channel forms is smaller than that of Facies 3a, and it can be inferred from this evidence that the channels were more confined within a particular area. In addition, the existence of fine sediments, bioturbation and rootlets adjacent to the channel features and strong palaeocurrent directions indicates floodplain/overbank deposits on the periphery of a meandering style fluvial system with reasonably high-energy flow in the channel. As with many of the red coloured sandstone beds, the environment is thought to be semi arid, desert like with sparse vegetation in areas without contact to water and occasional haematitic crusts on clasts and bedding.

4.6.2.8 Facies 3c

The palaeosol profiles observed (Photograph 4.9), with their gradational bases and abrupt top contacts, all confirm that they are pedogenic in profile (Alonso-Zarza et al., 1999). It has been determined that calcite was the primary precipitate within the soil, which was replaced by dolomite at a later date. Relict bedding and the fact that bedding can be seen to alter along profile suggests the relationship with the host bedrock is important to the development of the soils. Should a floodplain or area of non-deposition frequently experience influxes of sediment, then palaeosols are less likely to form. Whereas, low frequency, high magnitude splays from the fluvial system (in this case a channel) into the floodplain area result in the time and quiescence necessary for pedogenic development. From these rates of basin subsidence can be analysed and a larger picture of basin development can be formed.



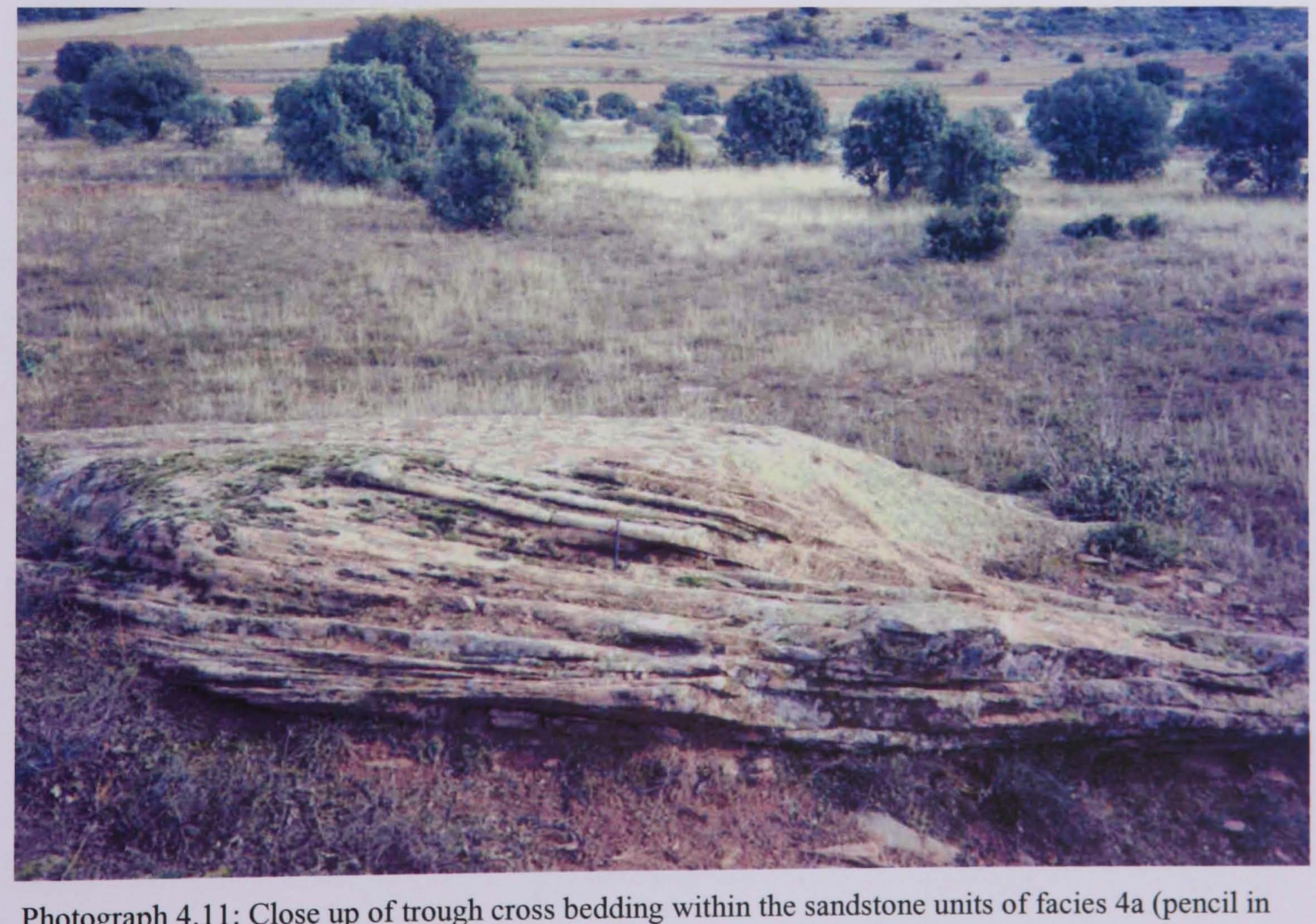
Photograph 4.9: Multiple palaeosol horizons within thick sandstone units at Riba de Santiuste (notebook is 20 cm).

4.7 Fluvial Deltaic

4.7.1 Facies 4a: Pebble rich, coarse to medium grained carbonate sandstones

This facies is identified as a yellow to white coloured coarse sandstone fining upwards to medium sandstone in the majority of outcrops (Photograph 4.10). Bed thickness is up to one metre, though this varies, as the sediments tend to pinch out laterally. Internal sedimentary structure takes the form of trough cross bedding (Photograph 4.11) from which some palaeocurrents can be identified in a south-easterly direction. Units of this facies occur in outcrop at intervals along hillsides. From this topographic outcrop feature it is possible to determine the lateral extent of each bed as 30 m. Fossil content

Photograph 4.10: Castle at Riba de Santiuste sitting on stacked Buntsandstein deltaic units.



Photograph 4.11: Close up of trough cross bedding within the sandstone units of facies 4a (pencil in centre of picture is 20 cm long).

in the form of shredded, undeterminable leaf and plant debris is observed at the base of many of the beds at Rueda de la Sierra.

Clasts of gravel and pebble size (<10 cm) are littered throughout the beds. They are predominantly made of quartzite and display little or no palaeocurrent flow indictors such as imbrication or pebble clustering.

4.7.2 Facies Interpretation

4.7.2.1 Facies 4a

The evidence from a thick sequence of discontinuous, trough cross-bedded sandstones in this facies demonstrates what was probably the prolonged existence of an active in the southern areas of the CIB. The nature of the outcrops and visible bedforms, in addition to the palaeocurrent evidence, suggests these deposits are characteristic of a meandering fluvial system with levees and floodplain areas. The grain size of the sediment indicates that flow energy was reasonably high – enough to transport an abundance of pebble-sized clasts in short bursts – and the channel was confined to 30 m in width. The discovery of plant debris (Photograph 4.12) implies vegetation growth adjacent to the channel area, which when flooded would cause destruction and transportation downstream of the leaves and stems. Palaeocurrent evidence obtained from trough cross bedding shows the meandering stream flowed towards the southeast, parallel to the southern basin margin.

The strongly cemented carbonate content of the sandstone (and rare shallow marine trace fossils) suggests this facies is due to the increasing presence of shallow marine conditions entering the CIB from the east. As with the sandstone near the top of the CIB northern margin sections, the sandstone channels at the southern margin have been affected by the encroaching sea level and upon entering the shallow marine conditions are likely to have produced a delta or estuarine type environment.

Mixing of the sediments would have occurred in such a scenario, hence the increased carbonate content in this sandstone.

Photograph 4.12: Plane debris on the base of a pale sandstone unit at Rueda de la Sierra (pencil is 15 cm long).

4.8 Depositional Model

The aim of this section is to now draw together the evidence from the facies observations and explain the broader sedimentation history of Rueda de la Sierra and Riba de Santiuste. The ideas discussed here serve to support findings about the Permo-Triassic synrift sedimentation in the southern areas of the CIB (see also Chapter 7).

4.8.1 Rueda de la Sierra: Braided Fluvial System

Facies 1a represents the initial stages of braided fluvial development directly on top of the basement rock, which forms the floor of the CIB. Identified as the Montesoro Beds in Fig. 4.3, these actually compose the 'Saxonian' Facies (Thüringian, Upper

Permian) type, preceding the Buntsandstein of the Lower Triassic. There is no lateral equivalent in the CIB, however the Iberian Basin to the southeast contains the Boniches Formation and the Alcotas mudstones and sandstones which were laid down contemporaneously (López-Gómez & Arche, 1997; Arche & López-Gómez, 1999) (Fig. 4.3).

From these initial stages of river drainage development, a fluvial system sustained and grew. Facies 2a represents a high energy braided stream that transported large clasts (>20 cm) long distances. A multitude of different coloured quartzite clasts seen throughout the conglomeratic units have a provenance to the western areas of the CIB (including the southwest and northwest). As barforms developed in association with perennial braided fluvial activity, the depositional environment established itself further along the southern margin.

Contemporaneously, evidence of alluvial fans is seen interacted with the major axial fluvial system running parallel to the basin margin. This resulted in the introduction, incorporation and subsequent reworking of suspended sediment and clasts from debris flows and sheet floods. Facies 2b indicates that braided stream evolution continued within the axial system with migrating surfaces developing along bars. The presence of finer-grained sediment within these deposits elucidates towards a punctuated waning in flow associated with bar systems.

The braided fluvial system through time became more complex, as Facies 3a indicates. These very coarse-grained channel fill sandstones suggest a degree of channel confinement, but over a much larger area than solely flanking longitudinal bars. Following this, perennial flood events and increasing water depth became the controlling factor on the nature of the braided fluvial system at the Rueda de la Sierra location. Longevity of both the braided river system, and the processes controlling its sustained influence on the southern areas of the CIB, is a key factor in the evolution of this depositional system. Collaborating outcrop evidence throughout the CIB and palaeocurrent indicators suggest the fluvial system linked two depocentres (one at Sigüenza section, Riba de Santiuste, and the other near Molina de Aragon, east of Rueda de la Sierra) providing a supply route for drainage between the two despite cutting across a transfer zone with a changeable basin floor gradient. It is this importance of longevity of the river system and along axis intrabasinal connectivity between two areas of sediment accommodation that is rarely discussed in ancient rift sedimentation models in the literature.

The westward transgression of the Tethys Sea started to influence the fluvial deposits sedimentologically and eustatically observations from outcrop sediments in Facies 4a suggest. Sediments at Rueda de la Sierra signify the presence of carbonate rich sediment in the fluvial channels and there is evidence of vegetation growing on the banks of the braided stream that has been washed away by violent floods (Photograph 4.12).

Finally, all these Buntsandstein deposits were flooded by transgression of shallow marine conditions, resulting in Muschelkalk facies deposition in the form of limestone and marl, during the Mid-Upper Triassic.

4.8.2 Riba de Santiuste: Braided to Meandering Fluvial system

Facies 2a (matrix- and clast-supported conglomerate units) forms only a small part of a large accumulation of sediment (1 km thick in places) (Fig. 4.5). As at Rueda de la Sierra, a large perennial fluvial system existed which was energetic enough to transport coarse grain sizes great distances. Sheets of conglomerate are common at the base, as are sheet units of coarse sandstone, representing waning flow conditions. Matrix supported conglomerates are common, outcrop locations of which are found in modern day gullies. The matrix-supported facies are, according to Ramos (1979) and Ramos et al. (1986), the remains of alluvial fans entering the basin perpendicular to the southern margin and flowing northward into the axial fluvial system.

Over a short space of time, the sheet conglomerates became increasingly channelised, and fluvial barforms can be picked out from the cliffs geology in the area. However, braided fluvial development was not fully established and for an initial period, though there is evidence for preliminary multi-channel fluvial activity. Subsequently, channelisation consumed the braided system and a contrasting fluvial system began to evolve, judging by the change in facies and indicated by the clast-supported channel fill conglomerates of Facies 2c interpreted as meandering fluvial deposits. Low sinuosity channels developed, stacking of channels occurred and then sinuosity increased as seen from medium-grained sandstone deposits in Facies 3b and a wider range in palaeocurrent directions collected from the sediments. These medium-grained channel fill sandstones suggest that there existed a perennial, stable, meandering stream running axially along the basin.

Fine-grained sandstones and palaeosols of Facies 2d highlight that the stream flow waned periodically resulting in the deposition of fine sandstone drapes over underlying sediments. When abandonment of the channel occurred, due to channel accretion or switching of the meander belt, the fine sediments hosted vegetation leaving rootlet traces and small animals which create bioturbation.

Flanking the meandering channel existed floodplains and overbank sinks that trapped and accumulated fine sediments resulting from flood events (discussed earlier in this chapter). Facies 3c represents the periodic drying-out and sub-aerial exposure of the floodplains occurring during episodes of non-deposition. Palaeosols of varying degrees of maturity formed in the overbank areas before an influx of clastic detritus came along and flooded them again.

Facies 4a completes the section and is similar in composition to that seen at Rueda de la Sierra. Cemented carbonate sandstones (with occasional and rare shallow marine trace fossils) with isolated clasts and distinctive trough cross bedding are observed and signify the transition of shallow marine conditions southeast of the CIB during the Mid-Late Triassic. It is thought, from facies analysis and palaeocurrent indicators consistent with eastward flow that the fluvial system entered the shallow sea at this point. The westward migrating Tethys marine transgression took longer to reach Riba de Santiuste, explaining the presence of a larger volume of continental sediment at this location than at Rueda de la Sierra. It is the change in fluvial facies throughout the sediments in outcrop at Riba de Santiuste that illustrate the changing perennial river system over time along the southern margin of the CIB.

4.9 Discussion

4.9.1 Basin floor gradients

Rivers are sensitive indicators of tectonic subsidence, uplift and tilting. In tectonically active areas, and especially during synrift phases of rift basins, tectonics can be recognised as an important control on gradients, water supply, stream power, shear stress, long profiles, terrace patterns and channel sinuosity (Seeber & Gortniz, 1983; Ouchi. 1985; Räsänen et al., 1987; Jones 2002; Frostick & Jones 2002). Such tectonic activity can operate over a wide range of spatial and temporal time frames (see Fig.1 in Frostick & Jones 2002). For example, periodic activity of a fault crossing a river valley may result in local changes in slope, river diversion and changes in the channel pattern over a period of 100's to 1000's of years.

Ouchi (1985) and Burnett & Schumm (1983) reported a series of experiments to simulate the effects of uplift and subsidence on river longitudinal profiles. It has been suggested that changes in slope imposed on the longitudinal profile of a river are compensated initially by changes in sinuosity, so that the along-channel slope remains constant (Fig. 4.7). Thus, an increase in slope leads to an increase in sinuosity of a channel, and vice-versa. There are limitations to the ability of rivers to change in this way and it seems that changes in sinuosity can only account for small amounts of tectonic uplift to maintain a constant slope profile. The effect of uplift along Sigüenza transfer fault in the CIB demonstrates an important change in sinuosity for the axially flowing long-lived river that existed for the whole of the synrift phase on the southern margin, a period of c. 7Ma (Fig. 4.7). The changes in sinuosity determined from changing palaeocurrent evidence in the fluvial faceis allow relative timing of the fault activity to be determined.

The response of a river to tectonic forcing depends also on the rate of deformation to relative rate of river erosion and deposition, and in turn related to stream power and bank erodability (Jones, 2002). If the rate of deposition and erosion is sufficiently large, along-stream changes caused by tectonism can be easily accommodated. However, if the rate of deposition and erosion is not sufficient then river diversion may occur (e.g. Jones, 2004). River diversion is most likely to occur in areas of reduced down valley gradients. However, the impact of the Sigüenza transfer fault on drainage, demonstrated by the marked change in fluvial style (similar examples of which are further explained by Burnett & Schumm, 1983 and Ouchi, 1985) clearly documents that the fluvial system throughout the synrift phase (Permo-Triassic, ~250-239 Ma) was able to keep pace with the tectonic activity and records periods of tectonism whilst the fluvial systems existed. The topographic expression on the basin floor, by the Sigüenza transfer fault was probably only a few metres, but was regionally significant through block faulting and rotation in

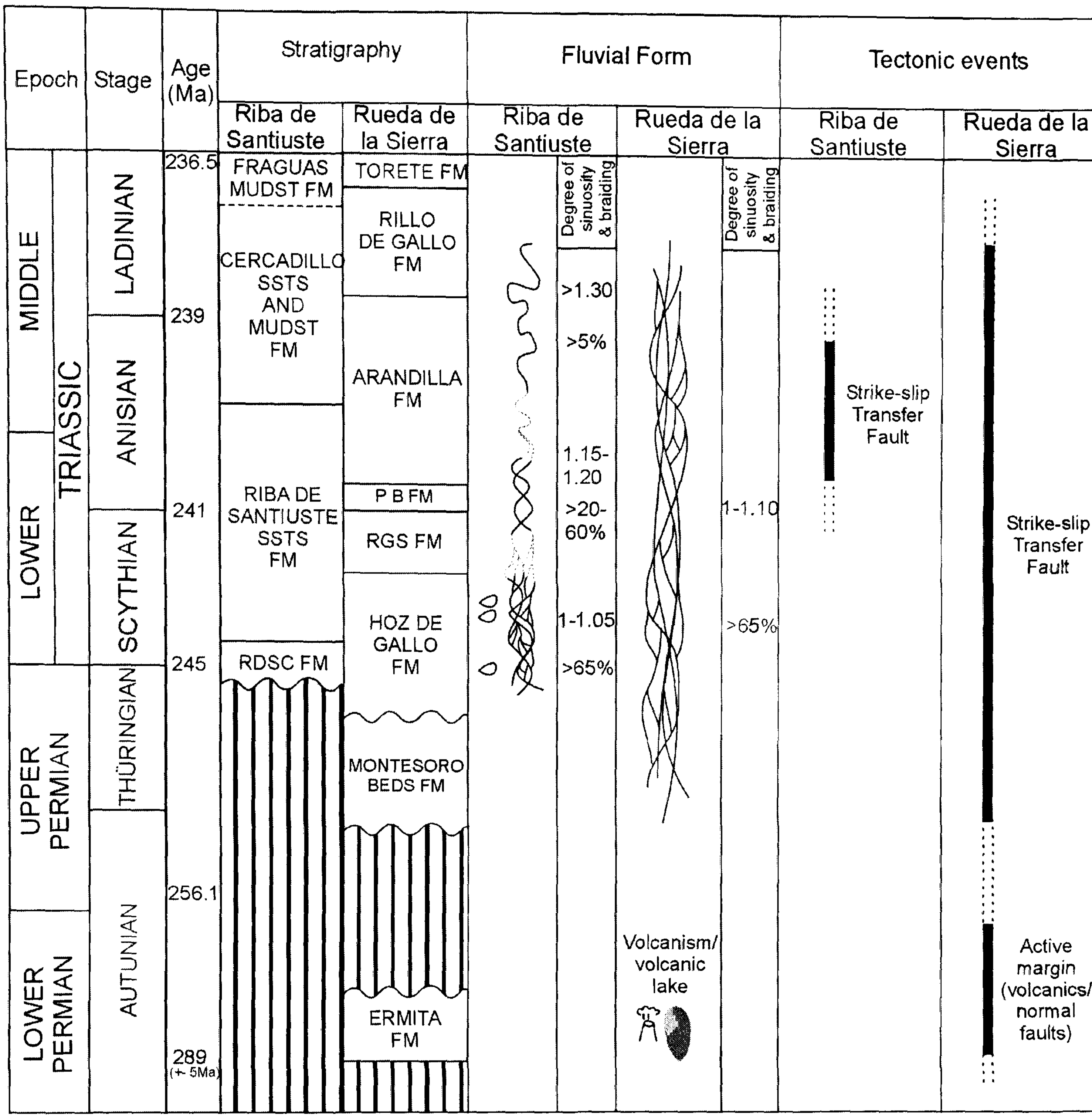


Fig. 4.7: Tabulated stylistic comparisons of the fluvial systems versus tectonic events at Rueda de la Sierra and Riba de Santiuste along the southern margin of the CIB. Fluvial form and Degree of Sinuosity adapted from Burnett & Schumm (1983) and Ouchi (1985) and from findings from this study and represent only a comparative, diagrammatic representation of the processes in the CIB.

correspondence with the Teruel fault (transpressional events; Figs 4.1 & 4.2). The important observation of understanding tectonic controls on fluvial systems in the CIB, is the downstream changes in basin floor gradient altering the sinuosity of the axially flowing river system. The river was still able to maintain an equilibrium profile either side of the Sigüenza transfer fault and became fixed in position for the entire synrift episode of the CIB. This is an important new result from this chapter and illustrates that across valley structures, frequently neglected in many studies, are as important (and perhaps more so) as along valley basin margin structures for controlling sedimentation and timing of tectonic events.

4.9.2 Intrabasinal highs

Intrabasinal structures, such as faults, parallel with the basin bounding fault system can result in tilting of the flood plains in a cross-valley direction. A widely documented response of rivers to the cross-basin component of tilting is for periodic diversion of the river towards the down tilted area (e.g. Alexander & Leeder, 1987; Peakall, 1998; Schumm et al. 2000; Peakall et al. 2000; Gawthorpe & Leeder, 2000). This results in asymmetrical channel belt positioning, where the active channel occupies the lowest part of the floodplain and abandoned channels occur on the up-slope (and up-dip) side towards the basin centre.

The CIB does not conform to the half-graben models of tilting and river positioning. This is thought to be primarily due to an intrabasinal high located along the axis of the CIB (Figs. 4.1 and 4.8). This area of high ground separating northern and southern areas of the CIB is believed to have existed due to the lack of interaction between the opposing areas of the rift basin and the presence of smaller alluvial fan deposits with southerly palaeocurrents that originated from raised catchments in the basin centre. Directional evidence from the fluvial systems of the southern areas of the CIB and the restricted extent of the playa and alluvial fan facies of the northern CIB also lend weight to this theory. The intrabasinal high has influenced sedimentation in the CIB and especially along the southern margin, in various direct and indirect ways. These are discussed below:

1) It has been recognised that one possible explanation for the development of intrabasinal highs is to accommodate along-strike deficits in basin margin fault displacements (Anders & Schlische, 1994). Such deficits are

incompatible with scaling relationships obvious between fault displacement and length of large faults. The theoretical compartmentalisation of the CIB, supported by facies evidence and directional data, confirms this idea and although the intrabasinal high in the CIB did not play a major role in accommodating stresses and transferral of movement across the rift, it certainly was important. Lærdal & Talbot (2002) recognised several syn- and antithetic faults and associated structures. Again, these did not play a major structural role, but influenced sedimentation and drainage pathways. Similar results have also been concluded elsewhere along the East African Rift (Frostick, 1997) and provide an excellent modern analogy to the Permo-Triassic synrift phase of the CIB.

2) The intrabasinal high compartmentalised the CIB into two separate halves during active synrift sedimentation. In the north, alluvial fan and playa lake sediments dominate the succession (Chapter 3) whereas in the south, axially-flowing braided and meandering rivers deposited over c. 1 km of sediments (Fig. 4.5). The compartmentalisation of basins and impact on sedimentation is well documented in the literature for compressional tectonic settings (Coney et al., 1996; Giles & DeCelles, 1996; Gupta, 1997; Jones, 2004). The current models for rift basins (e.g. Alexander & Leeder, 1987; Miall, 1996; Gawthorpe & Leeder, 2000) often illustrate intrabasinal highs in their models but do not document the importance on sedimentary facies development and compartmentalisation of the basin. The CIB provides one of the first documented ancient records that an intrabasinal topographic structure can have upon sedimentation patterns (Fig. 4.8)

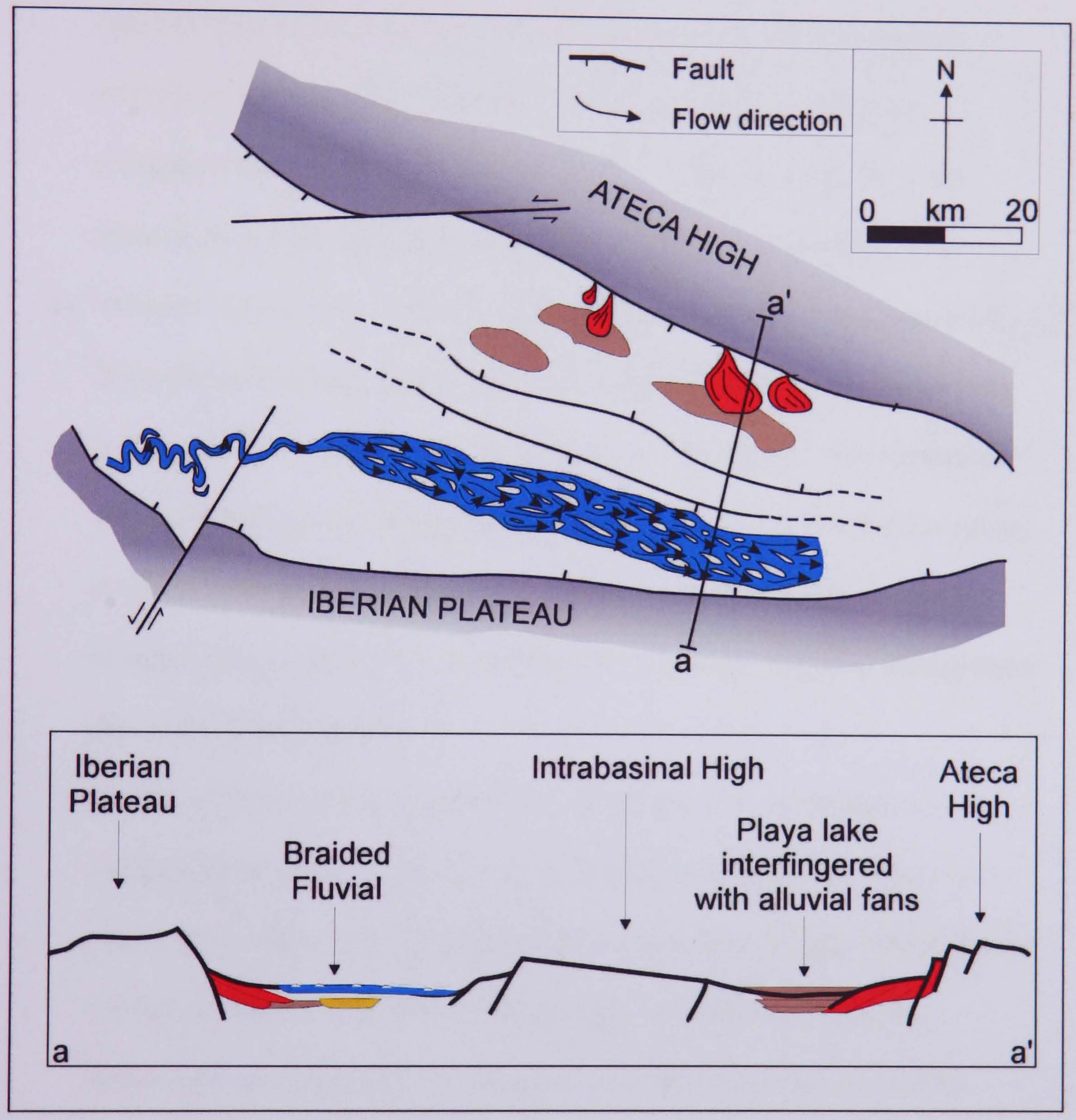


Fig. 4.8: Plan view and cross section sketches of the CIB showing compartmentalisation of the depositional systems by the intrabasinal high.

3) In theory, the intrabasinal high, through its kinematic linkage with basin margin faults, is likely to have balanced displacements across the basin. This could be inferred from the longevity of the axial fluvial system, and it's continuity, and the lack of avulsion or transverse basin floor tilting recognised in the sedimentary facies of the succession, especially in the absence of alluvial fan toe cutting (often related to avulsion) (Fig. 4.7).
4) The axial fluvial system during the Permo-Triassic linked two depocentres (Riba de Santiuste and Rueda de la Sierra) and was of particular importance for transferral of sediment flux through this portion of the basin. However, through inference and literature published on the East African Rift (as above) it seems likely that a hanging wall drainage, resulting in small, southerly directed, alluvial fans (from the intrabasinal high) contributed to the sediment flux to the basin (Fig. 4.8)
5) Recent results of fault linkage (hard and soft) and their associated topographic expressions (Peakall et al., 2000) have shown that many rivers can be easily diverted by small amounts of relief. This is a plausible scenario for the intrabasinal high of the CIB as it appears from facies analysis discussed in previous sections that some diversion of the fluvial systems probably occurred.

4.10 Conclusions

The Permo-Triassic synrift phase along the southern part of the CIB, a period of c. 7Ma, records the landscape evolution and changes in sedimentary facies patterns. The southern part of the CIB illustrates the influence of cross-cutting and basin parallel tectonically active structures upon drainage pathways and sedimentary fills. The excellent exposure of the synrift fill provides one of the first detailed investigations of a Permo-Triassic rift system and the complications created to sedimentation through intrabasinal tectonics. The key important new findings are:

1) The stark contrast in continental facies compared to the northern margin of the CIB identifies the importance of intrabasinal highs and axis parallel structures controlling drainage patterns and sediment flux;
2) Intrabasinal highs through synrift phases of rift development will compartmentalise the basin;
3) Structures normal to the basin boundary faults e.g. major transfer faults can cause diversion of contemporary fluvial systems, or as seen in the CIB change their sinuosity and correspondingly record phases of synrift tectonic activity and transpressional events.
4) The intrabasinal and basin margin structures of the CIB helped influence and control the sedimentation along the southern basinal areas as seen by the compartmentalisation, and the change in sinuosity, of each fluvial system. These factors have been instrumental in the longevity of the axial flowing river system linking two depocentres (Riba de Santiuste and Rueda de la Sierra) for the duration of *c.*7 Ma.

Despite the many difficulties in understanding the synrift phases of ancient rift basins, due to postrift covering fills, the CIB, due to fortuitous erosional and later inversion tectonics, provides a very valuable example of synrift sedimentation and factors controlling sediment dispersal in the basin.

These results from the CIB demonstrate that current thinking, based on modern rift basin examples (e.g. Red Sea/Gulf of Suez, Egypt; Rio Grande, USA), is not wholly applicable to ancient rift systems. Part of the reasoning may lie with the incomplete stage of evolution of the modern rifts and different plate tectonic frameworks, especially when compared to the CIB and its association to Pangaea.

Chapter 3 and 4 have documented the intrabasinal sedimentation and important primary allocyclic controls determining the landscape evolution for the Permo-Triassic synrift fill.

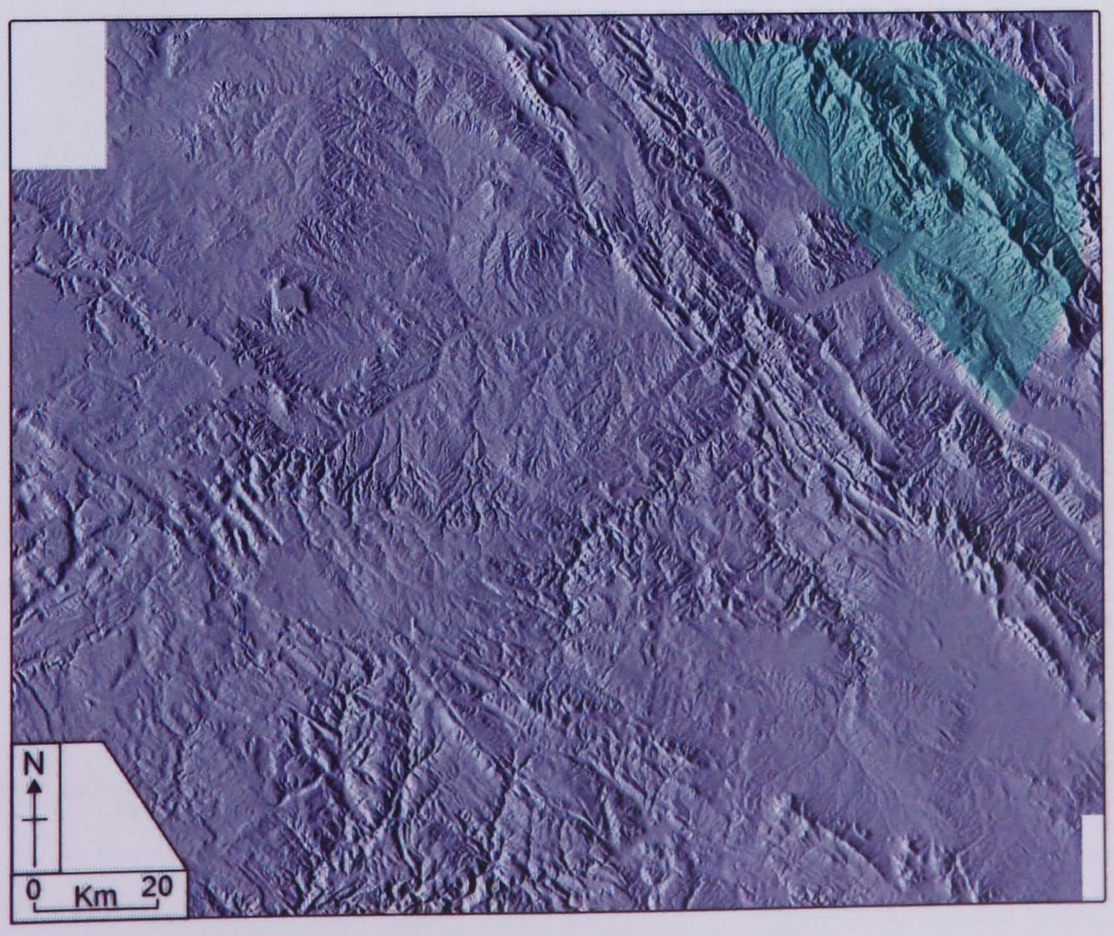
Many of the controlling factors discussed in these chapters will be developed further Chapter 7, but it is also important to document what was happening outside and along the CIB boundary faults. This will be illustrated in Chapter 5.

Chapter 5

The Permo-Triassic Ebro basin: sediment flux interplay with the Central Iberian Basin

Key Findings:

- An important axial drainage system evolved that through a period of c. 8 Ma of the late Permian to early Triassic and become established as one of the important sediment supply routes.
- Differential uplift of the hinterland drainage basin accounts for the switching of axial drainage systems and sediment flux during the early stages of infill for both the CIB and Ebro basin.
- Competition between two neighbouring rift basins for sediment flux has not been previously recognised and identifies the need for large-scale regional studies.
- Climate controlled drainage development through discharge variability determined from the fluvial architecture and the recognition of perennial river development.
- The study illustrates, the role tectonics and climate have to play in controlling the evolution, behaviour and competition of fluvial systems during the synrift phases of ancient rift basins.



5.1 Aims: two competing rift basins for sediment flux

Contemporaneous sediments of the Permo-Triassic Ebro basin along the north-eastern margin of the Ateca High, near Calatayud (Fig 5.1), will form the focus of this Chapter. The Ebro basin is thought to have shared the same provenance area as the Iberian basins supplying similar coarse, clastic quartzites and micaceous sandstones to fluvial systems and smaller alluvial depositional systems sourced along the northeastern margin of the Ateca High.

Models of rift basin sedimentation in the literature (Frostick & Steel, 1993; Leeder & Gawthorpe, 1987; Gawthorpe & Leeder, 2000) often concentrate on the development of single, isolated rift basins and rarely incorporate the effects of adjacent rift basins that provide a more detailed understanding of the regional synrift fills.

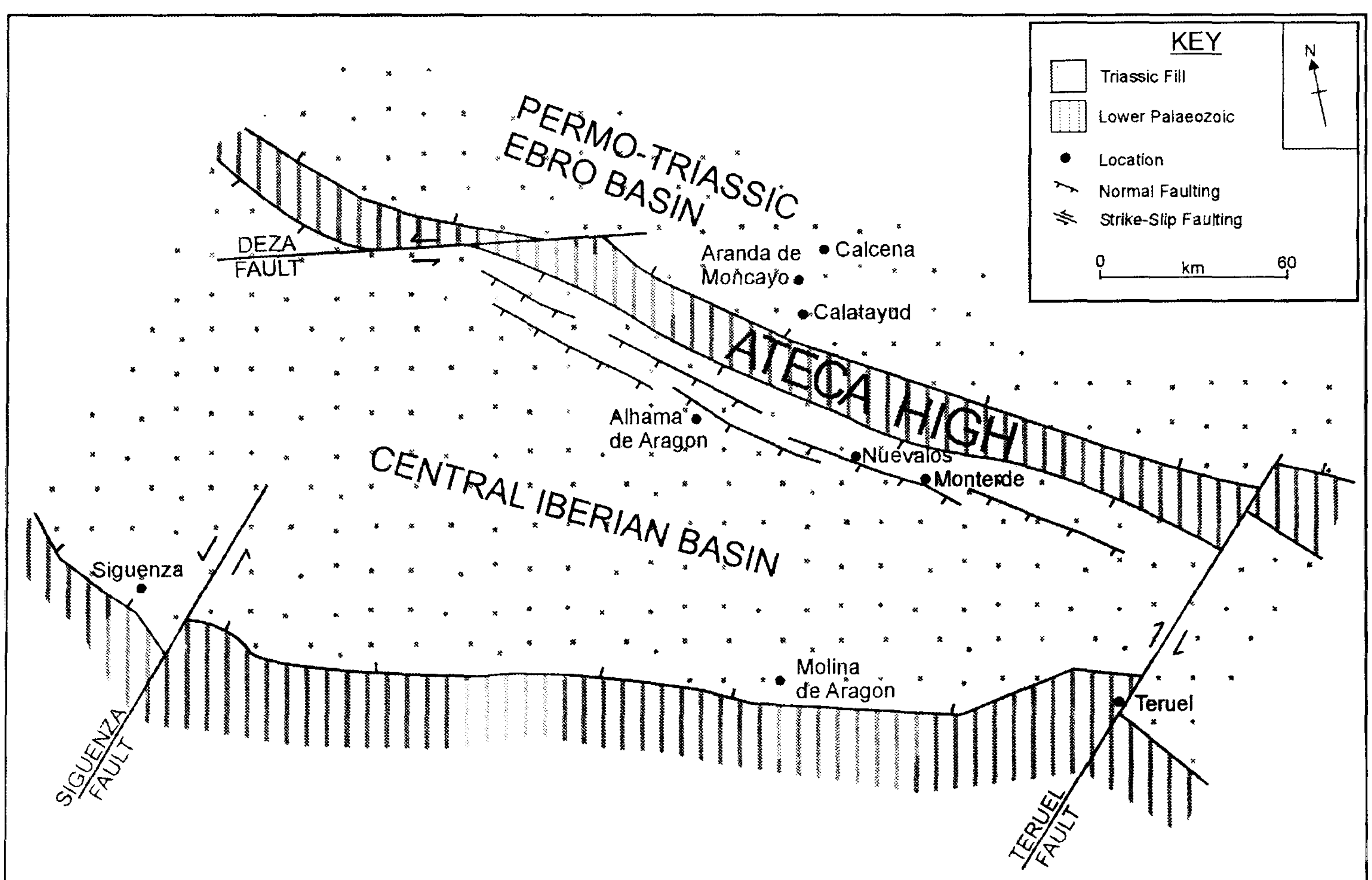


Fig. 5.1: Sketch map of the Ebro Basin and Ateca High in relationship to the CIB of Chapters 3 and 4.

This chapter aims to highlight the controls on sedimentation in a coeval rift basin and draw comparisons to the CIB and the Iberian Basins in general. A regional stratigraphy has been constructed in which time-equivalent facies and formations can be correlated across the basins (Iberian Basin and the CIB) and Ateca High. New ideas regarding basin interconnectivity in the Iberian Ranges, central Spain, will be explained and a detailed architectural study aims to investigate the role of fluvial drainage during the Permo-Triassic before the onset of the Tethyan marine transgression (TST and HST).

This chapter will consider the overriding controls on sedimentation at the western margin of the Permo-Triassic Ebro Basin and analyse the facies, drainage network development, styles of deposition and related architecture of sedimentary units observed in outcrop.

5.2 Overview and current state-of-play

The present-day Iberian, Catalan and Pyrenean Ranges, and the Ebro foreland basin (Fig. 5.1), situated in the north eastern Iberian Plate are the geomorphic expression of basin inversion, thrusting and foreland basin evolution during the Alpine orogenic events. However, like so many Spanish basins, the Iberian and Ebro basins had similar multiphase evolutions for the Permian and Triassic. Most of the late Palaeozoic to early Mesozoic rifting in the Ebro basin are covered by post rift sediments predominantly from the Pyrenean Mountain belt, where for the Tertiary the Ebro basin is a foredeep basin (*sensu* DeCelles and Giles, 1996) with up to 4 km of Tertiary sediments preserved. However, beneath this thick cover well logging studies (e.g. Jurado, 1989) and seismic data sets (e.g. ECORS Pyrenees Team, 1988, Choukroune, 1989; Salas et al., 2001) show a clear synrift sedimentary fill for the Ebro basin, and very similar to the CIB that has been the main focus of the previous chapters.

The resulting landscape rapidly produced by regional tectonics will evolve primarily through a series of erosional and depositional modifications of the slopes produced by normal faulting. It is the interplay between these processes that also controls the stratigraphic and structural architecture of a rift basin fill. Most studies document a single fault segment and the associated sedimentary fill (e.g. Alexander & Leeder, 1987) or may present a model for the general facies patterns of a synrift fill (e.g. Gawthorpe & Leeder, 2000). The Ebro basin and CIB systems provides a unique opportunity to compare and contrast between the contemporaneous ancient synrift fills of two rift basins that are back to back with each other.

Drainage basins play an exceedingly important role in the erosional processes (e.g. Leeder & Jackson, 1993; Hovius, 1996 and many others), providing the sediment flux from tectonic uplands that is dispersed and deposited over the basin floor. Other factors being equal, such as climate and rock types, the larger the drainage basin, the larger the sediment flux shall be. The drainage basin is perhaps one of the most fundamental units of landscape development, but little is known how a shared drainage network, as agreeable clast provenance studies suggest the CIB and Ebro Basin had, supplies sediment to a basin and how it is dispersed into two competing rift basins.

It is the aim of this chapter to examine the drainage and depositional environments of the north western portion of the Ebro basin where fortuitous excellent preservation of the synrift phase allow direct comparison with the CIB. One of the key aims is to determine the impact of intrabasinal structures upon a developing drainage system and how the establishment of a drainage system can impact upon sediment flux to the neighbouring basin.

Another key reason for the selection of the Ebro basin in comparison to the CIB during the Permo-Triassic is the clear recognition of the synrift sedimentary fills and appreciation of the tectonic-drainage relationships for an ancient basin system. However, the field observations also demonstrate an important stratigraphic interplay between the rift basin margins and perhaps, uplift-rejuventation-sediment flux switching of drainage and depositional systems across the rift basin margins. Similar occurrences have been previously documented for the East African Rift (e.g. Frostick, 1997 and there in), but important new findings from this study will be presented for competing rift basins in an ancient setting.

5.2.1 Geological setting

The Permo-Triassic Ebro Basin formed at the same time as the CIB and Iberian Basin. As the Iberian microplate underwent clockwise rotation during Late Carboniferous - Early Triassic, major strike slip faults to the north and south, triggered inland crustal extension forming rift basins occupying central regions of the Iberian Peninsula (López-Gómez et al., 2002; see Chapter 1). During the Late Permian - Early Triassic, a Hercynian basement lineament, known as the Ateca High, bordered a system of half grabens to the south under an extensional structural regime. North of the Ateca High, basin development also occurred and progressed through rift, platform, strike-slip and finally foreland basin settings.

Opposing borders of the Ateca High developed as a series of rift basins during the Late Carboniferous to Early Permian times (López-Gómez et al., 2002). The Iberian intracratonic rift basin evolved into a number of asymmetric sub-basins, south of the Ateca High, each with their own history and separated by NE-SW trending faults. This area of uplift, bordering the northern margin of the Iberian Basin and CIB, acted as a partition between the rift basins and similar basins evolving in the north, representing the lowermost limit of the modern day Ebro Basin (Fig. 5.1).

The Ebro Basin, a present-day foreland basin situated south of the Pyrenees, existed as an extensional rift basin during the Permo-Triassic and assumed its modern configuration during the Pyrenean Orogeny (Muñoz, 1992; Puigdefábregas et al., 1992). A series of post-Hercynian structural events shaped the geometry and style of the area during the Permo-Triassic (Chapter 1). Late-Palaeozoic to early-Mesozoic tectonics meant northern borders of the Ateca High existed as an extensional rift margin accommodating several 'tecto-sedimentary cycles' related to progressive stages of structural evolution (Puigdefábregas & Souquet, 1986). Lineaments stretching NW-SE, E-W and NE-SW controlled the orientation of basin margins, the former running normal to the Ateca High. Rift basin extension resulted in andesite-rhyolite and Late-Palaeozoic to early-Mesozoic basaltic volcanism for a short period followed by sedimentary sequences of alluvial fans, slope breccias and red mudstones influenced by eustacy, subsidence, local tectonics and sediment supply.

Further extension during the late-Mesozoic initiated basin widening and the development of a shallow water platform that played host to shallow marine seas and lagoonal sediments linked to the opening of the Tethys to the East. Flooding of the major basin boundary structures occurred and resulted in their drowning during the mid-Triassic (López-Gómez et al., 1998).

Subsequent uplift of the Pyrenees and basin reconfiguration, during the late-Mesozoic, occurred after an increase in regional compressional tectonism. Global sea level fall at this juncture (Haq et al., 1987) favouring the emergence of the Iberian Ranges and in particular the northern margin of the Ateca High.

The transition of southern compressional tectonics regime to that of a foreland basin characteristic of the modern Ebro Basin occurred during the Palaeocene and continued into the Eocene. Continued 'cycles' of tectonism and structural re-development continued influenced by well-developed thrust faults bounding the basin margins (Muñoz et al., 1986). Episodic unconformities linked to tectonism are recognisable in modern day outcrops and provide a clue to the complex history of basin development north of the Ateca High in central Spain. Of particular interest is the pattern and direction of drainage axially along the Ebro Basin which originally flowed north-westwards but switched towards the east progressively during the Neogene (Evans & Arche, 2002). Is this progressive change a tectonic control?

There is no evidence that the Permo-Triassic Ebro Basin and the CIB directly connect their drainage areas at any point during the geological history of the Iberian Ranges, however, they did share similar Triassic-age facies: Buntsandstein and Muschelkalk. It is this comparison between adjacent, yet different continental synrift fill that helps us understand the depositional history across central Spain during the Permo-Triassic. Correlation of formations in the different basins provides insight into the range of depositional environments that can exist coevally in a relatively small area of continent and is important in furthering and enhancing our models of arid-climate, rift basin sedimentation.

5.3 Stratigraphy

This section describes the main lithological and sedimentological characteristics of the Permian and Triassic sediments in the Aragonese branch of the Iberian Ranges. The stratigraphy is based on outcrop and well log data in studies by Puigdefábregas & Souquet (1986), Sopeña et al. (1988) and López-Gómez et al. (2002) and combined with new outcrops in this study. Due to the nature of the Mesozoic/Cenozoic post-rift fill and uneven exhumation, Permo-Triassic exposure in the early-Mesozoic Ebro Basin is limited. As well as correlations made in Fig. 5.2, age dates from palaeoflora and isotopic studies (López-Gómez et al., 2002) as well as biostratigraphic data published by Díez et al. (1996) and Rey & Ramos (1991) are used to further constrain the synrift fill.

5.3.1 Late Permian ('Saxonian' Facies)

Sopeña et al. (1988) state that the lowest beds in the succession to outcrop along the northernmost margin of the Ateca High are sediments of Permian age. The small fault bounded rift basin that characterised the Permo-Triassic Ebro Basin, initially filled with red mudstones, alluvial fan deposits, local slope breccias and some volcaniclastics. These 'Saxonian' facies units have been labelled the Araviana Conglomerate and Mudstones Formation (ACM) and Arroyo Riduero Conglomerate, Sandstones and Mudstones (ARCSM) Formation (Puigdefábregas & Souquet, 1986). Outcrops of these beds are best seen in the Moncayo area (Fig. 5.1) and have a

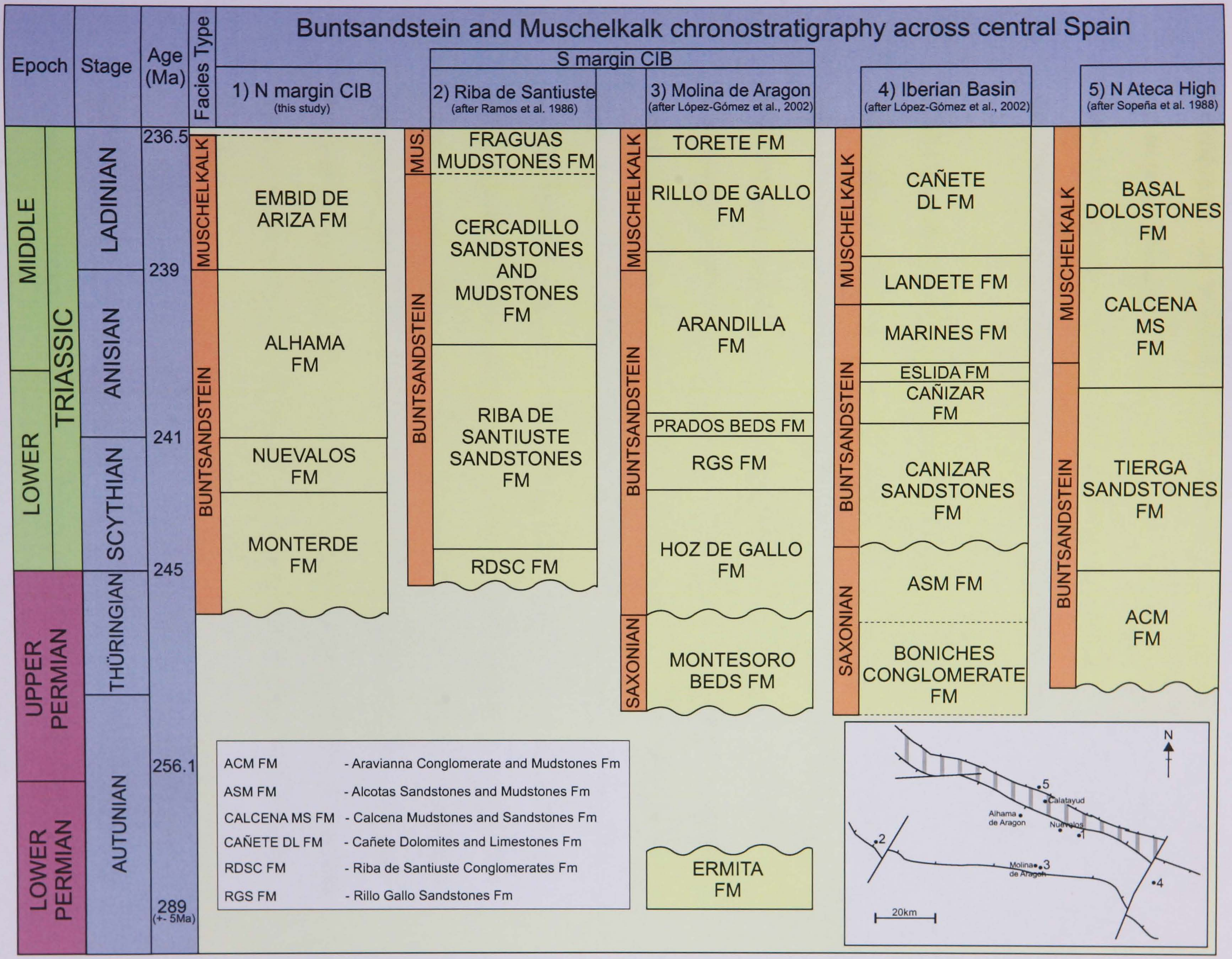


Fig. 5.2: Stratigraphic correlation table across the whole of the CIB, Iberian Basin and the Permo-Triassic Ebro Basin.

thickness over 100 m, although well logs have proved to be of more use in locating the sediments, and lie directly on Hercynian basement rocks (Fig. 4.3). Comparisons can be made between both the ACM and ARCSM sedimentary succession and equivalent 'Saxonian' type sediments of the Montesoro Beds (latest Permian) described at Rillo de Gallo and Rueda de la Sierra in the CIB (Chapter 4).

5.3.2 Latest Permian-Early Triassic (Buntsandstein Facies)

Buntsandstein facies deposits are found, up to 500 m in thickness, in the Moncayo area resting unconformably on Lower Palaeozoic basement or 'Saxonian' facies sediments and are dated as Latest Permian-Early Triassic (Sopeña et al., 1988). Roughly equivalent to the classic Buntsandstein facies of northern Europe (López-Gómez et al., 2002), the red sandstones, mudstones, and occasional conglomeratic units, represent a clear sedimentological evolution from minor alluvial fan systems spilling down from the Ateca High at the southern border to coarse fluvial systems running axially along the southern Ebro Basin boundary (Sopeña et al., 1988). The greatest thickness of continental red bed sediment is found in centrally located areas of the basin, with the bed thickness pinching-out towards the south-western border (towards the Ateca High). It is at the marginal settings where sediments at Aranda de Moncayo and Calcena (see Fig. 5.1) retain a useful, but incomplete, record of the sediments.

Termed the Tierga Sandstones Formation (TS) and the Calcena Mudstones and Sandstones Formation (CMS) (Sopeña et al., 1988) these units, referring to Fig. 5.2 are the equivalent of the southern CIB margin Hoz de Gallo Formation, Rillo Gallo Sandstones Formation (Rueda de la Sierra), and Riba de Santiuste

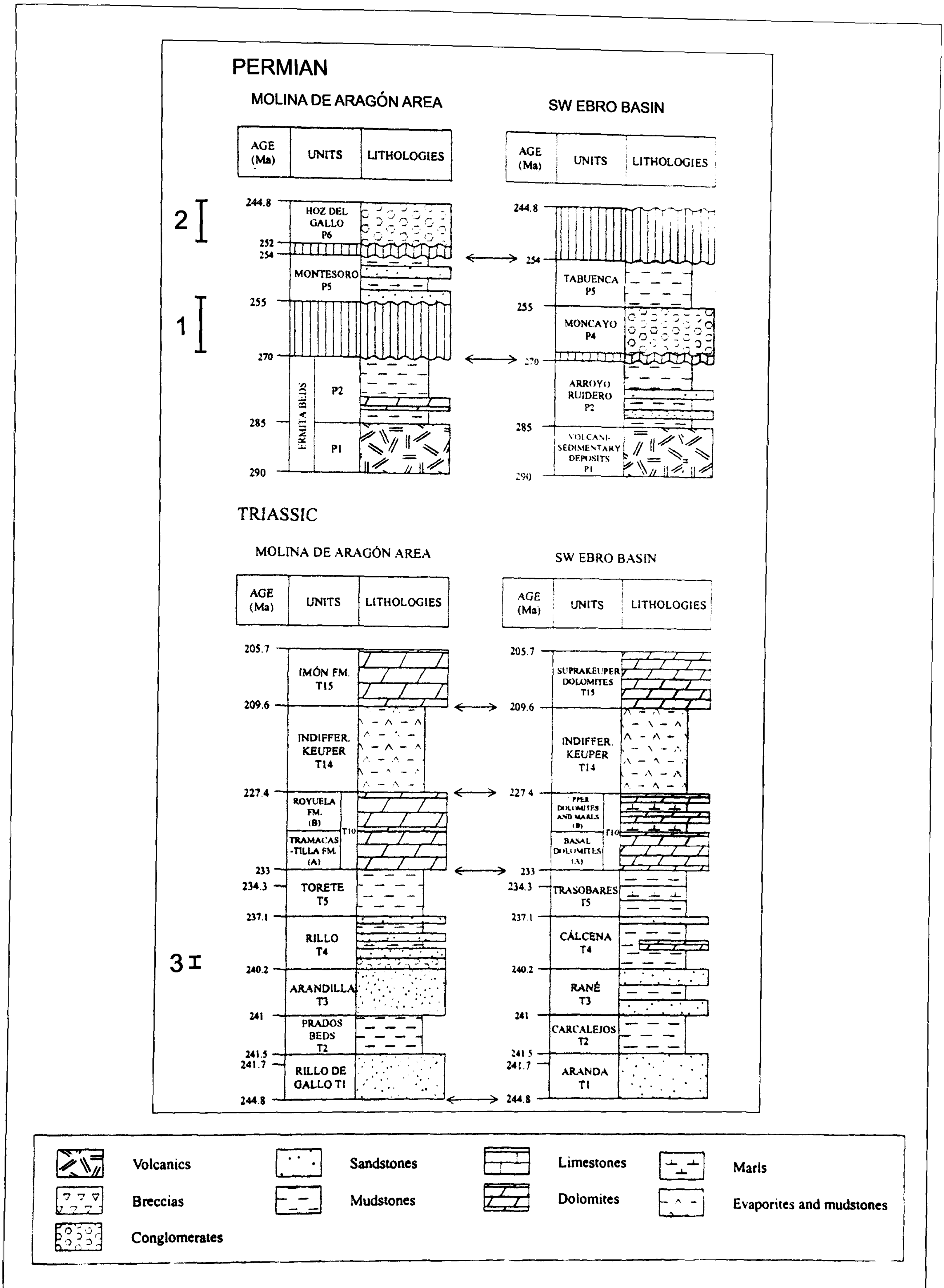


Fig. 5.3: Generalised logs from the Molina de Aragon area (CIB) and SW Ebro Basin highlighting three periods of drainage switching between the two basins (adapted from Vargas et al., In review).

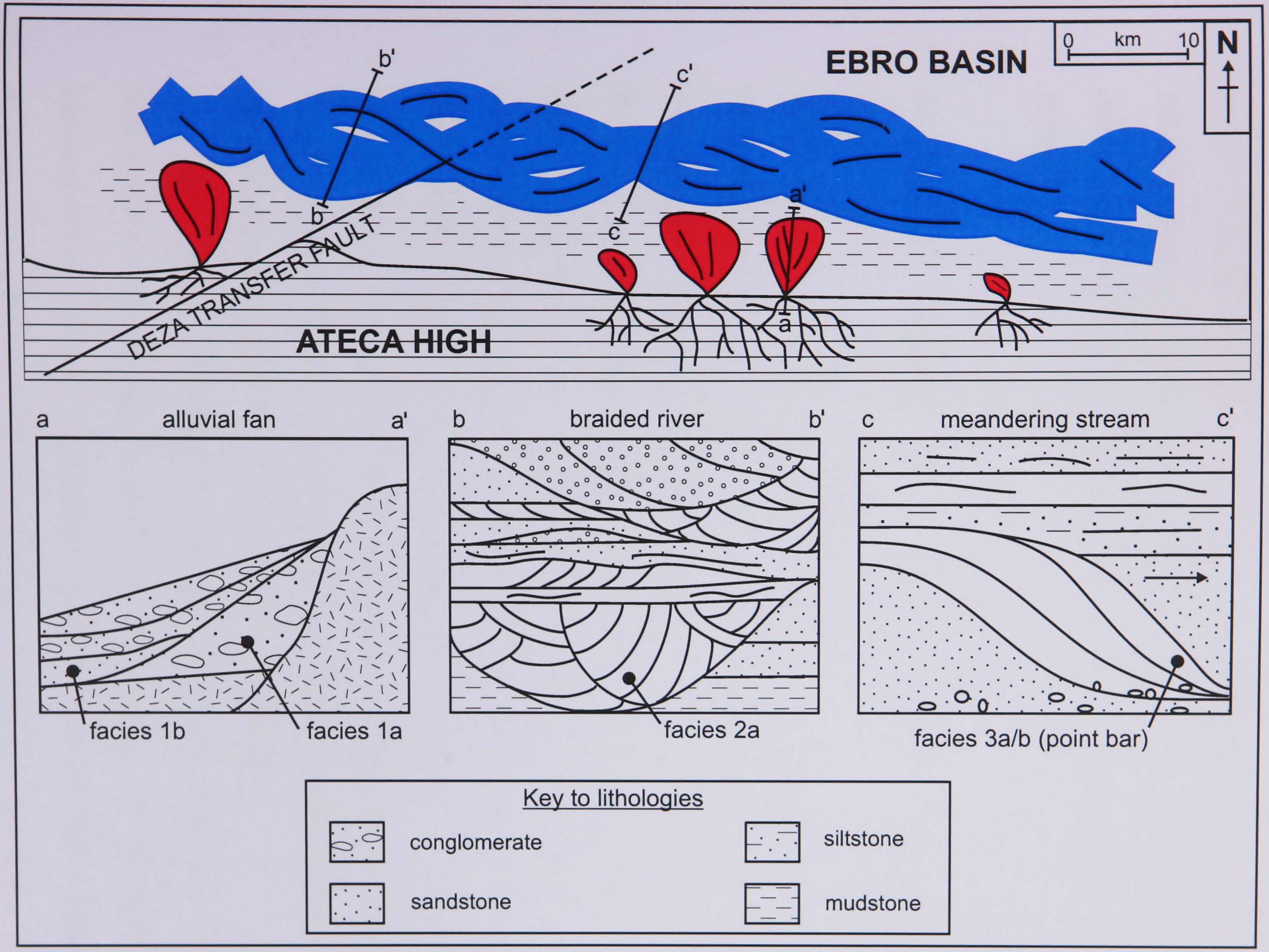


Fig. 5.4: Sketch map and facies diagram for the Permo-Triassic Ebro Basin

Conglomerates and Sandstones Formation (Riba de Santiuste). At the northern margin of the CIB the Monterde Formation, Nuevalos Formation and the lower portions of the Alhama Formation are the time-equivalent facies (Fig. 5.2). Palaeoflora associations found in the Moncayo region suggest the CMS Formation is Anisian in age (Lower-Middle Triassic) (Díez et al., 1996, López-Gómez et al., 2002).

5.3.3 Mid-Late Triassic (Buntsandstein Facies, Muschelkalk Facies, Keuper Facies)

By Anisian times (Middle Triassic), the Permo-Triassic Ebro Basin was starting to be filled with fluvial and alluvial systems and a marked increase in influence on the sedimentology of the westwards advancing Tethys Sea was observed. The CMS Formation first displays the transition in the form of pale, often pink, carbonate sandstones that appear in the uppermost beds of the formation. The mixing of carbonate and siliciclastic sandstones continues up section to the Basal Dolostones Formation (BD) (Figs. 5.2 and 5.3), representing sea level transgressions and development of a carbonate ramp environment associated with the onset of prevalent marine conditions. Though not present in the Aranda de Moncayo area, the BD Formation is exposed in other contemporaneous areas of the basin.

In the absence of the BD Formation in the Moncayo area, Middle-Late Triassic sediments can instead be seen as part of a 20 m thick section of dolomite limestone and marl. A switch from Buntsandstein facies deposits of fluvial origin at the base to Muschelkalk Facies dolomite limestone is observed and forms the remains of Tethys Sea transgressive deposits across the majority of the Permo-

Triassic Ebro Basin during the Ladinian (Mid-Late Triassic). Named the Trasobares Mudstones and Marls Formation (TMM) they form lateral equivalents to the Alhama Fm and Cañete Dolomites and Limestone (CDL) in the northern CIB, Torete Fm in the south CIB, and Mas Fm in the Castilian branch of the Iberian Ranges (López-Gómez et al., 2002), though fall outside the scope of this study hence their exclusion from Fig. 5.2).

By the Upper Triassic (Latest Ladinian), marine conditions dominated the Aragonese branch of the Iberian Ranges. Following flooding of the majority of low-lying land surfaces by the Tethys, marine sediments were deposition varied in thickness from <45 m at the western margin of the basin to 190 m near the Moncayo area (López-Gómez et al., 2002). Here, evaporite units are found intercalated with dolomite limestone units and occasional marls. These units represent the Keuper Facies, a period when sabkha conditions prevailed across parts of the Iberian Ranges and Buntsandstein and Muschelkalk Facies were no longer exposed at the surface

5.4 Alluvial Fan

5.4.1 Facies description

Exposures of alluvial fan facies across the northern face of the Iberian Ranges are scarce, though some can be observed in outcrop at Calcena (Fig. 5.1). In the exposures at Calcena, it is possible to determine three distinctive types of deposit: matrix and clast supported conglomerate, isolated medium grained sandstone units, and finer-grained sediments of siltstone and sandstone. Detailed study of the sediments was used to deduce the environment of deposition during the Late-Permian Ebro Basin from the Ateca High topography situated in the south of modern day Moncayo (Fig. 5.4). The likely formations they correlate with are the Araviana Conglomerate and Mudstone Formation (ACM) and Arroyo Riduero Conglomerate, Sandstones and Mudstones Formation (ARCSM) which in turn correlate to Late Permian formation in the CIB (Montesoro Beds Formation at Rueda de la Sierra, for example) (Fig. 5.2).

5.4.1.1 Facies 1a: Matrix- and clast-supported conglomerate

Units of conglomerate <0.5 m in thickness are observed at Calcena. The conglomerates are clast-supported to matrix-supported with a medium sandstone matrix containing sub-angular to sub rounded, predominantly quartzitic clasts, maximum clast size reaching 8 cm (Fig. 5.1). With an erosive, scoured base, these beds display some coarsening upwards in sections, though they show little or no internal sedimentary bedding structures other than occasional horizonation and sharp contacts. Clasts are imbricated in some cases and show a palaeocurrent direction to the northeast. Detailed study of the clasts reveals a grey and purple lustre over each pebble surface. Percussion marks, easily identified in clasts from the conglomerates of the Monterde Formation (Chapter 3, Photograph 3.2), are absent.

Photograph 5.1: alluvial conglomerate from exposures close to Moncayo (hammer is 40 cm in length).

5.4.1.2 Facies 1b: Massive medium-grained sandstone

These medium-grained sandstone units are laterally persistent (at least 200 m of exposure are observed in road cuttings) and range in thickness between 5 cm and 20 cm. The sandstones are red, micaceous and show a lack of internal structure, resulting in an absence of palaeocurrent indicators. Beds are observed pinching out in the restricted exposure and minor erosive surfaces are noticed on the base of many of the medium-grained sandstones. Hard, white evaporite nodules are also detected along irregular, eroded contacts, however they appear to have little effect on the sediments or associated macro-structure.

5.4.1.3 Facies 1c: Fine-grained sandstone and siltstone

These finer sediments show a similar lateral continuity to those of Facies 1b, and often mirror the bedding surfaces in the form of thin drapes. Maximum bed thickness of these pale yellow and red deposits is 3 cm, although coarse, overlying units cut into the sediment. Evidence of bioturbation or pedogenic development is absent in this facies.

5.4.2 Facies Interpretation

5.4.2.1 Facies 1a

The presence of matrix- to clast-supported conglomerates in laterally extensive (<200 m) bedding sheets, the presence of some imbrication and palaeocurrent indictors with a direction towards the northeast (perpendicular to the western basin boundary) suggest that these beds were the result of low frequency, high magnitude depositional events such as debris flows on an alluvial fan. This is supported by reference to Miall (1996) where the facies Gmm, Gmg, and Gh indicate debris flow of varying strengths and the possibility of longitudinal bedform development.

The sub-angularity of the clasts indicates that transportation of detritus was rapid and over short distances, possibly as episodic flash flood events depositing a range of coarse material juxtaposed to finer sediments of presumably distal fan localities. Sedimentation is thought to have occurred across the whole of the fan, as found with alluvial fans at Monterde and Nuevalos along the northern margin of the CIB, because beds are laterally continuous for hundreds of metres. Lack of complete sections prevents further investigation of this, and the presence of large fans of which these sediment form a small part of cannot be discounted. However, there is no evidence of bedding thinning or of radial palaeocurrent data, which is taken to mean continuous fan surfaces on a decimetre scale existed along the western margin of the Permo-Triassic Ebro Basin.

Sedimentological evidence from the deposits such as iron-staining of pebbles, oxidisation colour, and clast-shape can be interpreted as the deposition of sediment in a semi-arid to arid climate, supported by the presence of desert varnish on many of the clasts. This suggests that the climate was similar to that found across the whole of the CIB during this stage in the Permo-Triassic and that it can be deduced that climate possibly influenced sedimentation regionally, not just locally.

5.4.2.2 Facies 1b

A lack of fossiliferous material and the red nature of the strata suggest this facies was deposited sub-aerially in a continental setting. The beds are relatively thin (<20 cm thickness) and fairly laterally persistent indicating evenly distributed, low magnitude flux events which deposited sediment over a large area of the basin margin possibly on part of an alluvial fan.

The sediments in this facies represent the Sl facies code explained in Miall (1996; Table 4.1). Sandstone, ranging from graded from fine to very coarse with broad, shallow scours best explains this sedimentary unit and can be interpreted as scour fill on the surface of the alluvial fan. It is interpreted from sedimentological evidence that high-energy pulses in the water discharge enabling scours to form. The pinching-out of some of the beds in cross-section indicates that sedimentation across the whole fan was constrained and likely to have been controlled by fan surface topography.

The nodules provide some evidence of calcification on the top surface of the sandstone bed, though it is difficult to determine whether this is related to ancient pedogenic formation or modern groundwater alterations and weathering.

5.4.2.3 Facies 1c

According to Miall's facies classification (1996), fine-grained draped sandstones and siltstones with little or no internal structure are indicative of waning flood deposits or abandoned channel deposits, Fl and Fsm (Miall, 1996; Table 4.1). A lack of palaeosol development is likely to mean active and continual sedimentation, long periods of sediment exposure failing to occur, or a climate that was not conducive to soil formation. An absence of real structure to the fine sandstones and siltstones is the result of rapid deposition, allowing very little time for internal organisation of the bedding.

5.5 Braided Fluvial

5.5.1 Facies description

An excellent type locality for these fluvial facies, in the Ebro Basin, is at Calcena. East of the village of Calcena (Fig. 5.1), at least 22 m of section is accessible for architectural and sedimentological analysis. The main bulk of the deposits are made of coarse bedded sandstones which continue laterally for several tens of metres (Fig. 5.5) and display obvious channel features. These apparent channels cut into finer sediments and display sharp erosively cut bases. These units are representative of the Tierga Sandstones Formation (TS) and the Calcena Mudstones and Sandstones Formation (CMS), which can be correlated to the Nuevalos and Alhama Formations (Anisian) at the northern margin of the CIB (Fig. 5.2).

5.5.1.1 Facies 2a: Coarse- to medium-grained, pebbly sandstone

Units of red, coarse-grained sandstone ranging in thickness from metre to decimetre scale are observed with this facies. These sediments contain numerous examples of internal sedimentary structures such as tough cross bedding (1-2 m in length; Photograph 5.2), planar cross bedding (<1 m in length), ripples (<20 cm in length), extensive bioturbation picked out on top bedding surfaces, and large scale channel features (<5 m in width; Photograph 5.3). Palaeocurrent direction is obtained from all varieties of cross bedding and rippled bedding producing an overall direction of south-easterly, though the range is more like north-east through south-east to some southerly indicators. Thickness tends to vary laterally, and channelisation and cutting down into the underlying lithologies is common (see Fig. 5.5). Scoured basal surfaces are observed on the majority of the coarser sandstone beds and undulating

Photograph 5.2: Internal trough-cross bedding (1-2 m in scale) in the sandstones at Calcena.

top surfaces can also be seen. Throughout the coarser sandstone beds, isolated pebble clasts (<5 cm in size) occupy positions resting on a scoured base or within a trough cross bedded section, though imbrication of these clasts is not detected.

5.5.1.2 Facies 2b: Fine-grained sandstone and siltstone

Occasionally found dispersed between the large beds of Facies 2a, these fine-grained sandstones and siltstones are often horizontally laminated and a maximum thickness of 90 cm. The deposits are red in colour and contain a high mica content. Intense burrowing is common in many of the beds and rootlet traces are often identified. Although these beds are generally continuous along section, it is noticeable that they are frequently cut into by the overlying coarser sediment channel features (Photograph 5.4). Rip-up clasts (<1 cm in size) of the finer sediments are seen within the basal portion of the overlying units. There is an absence of any isolated gravel or pebble clasts throughout the units.

Photograph 5.3: Large scale channel features (<5 m width) in the fluvial sandstones at Calcena.

Photograph 5.4: Fine-grained sandstones and siltstones interbedded with coarser grained sandstones near Calcena (Facies 2b).

5.5.2 Facies interpretation

5.5.2.1 Facies 2a

The coarse- to medium-grained channel sediments seen at Calcena demonstrate that fluvial channels and some small-scale bar development occurred in this area of the Permo-Triassic Ebro Basin. The absence of gravel size debris within the beds displays similarities with the low sinuosity stream deposits of the Welsh Brownstones described in detail by Allen (1983). He suggests the importance of bedding hierarchy and continues to press the need for analysis of division of genetically related 'packets' of sediment to be given some internal order. Indeed, Miall (1996) and Jones et al. (2001) demonstrate the use of such a hierarchy in sandstone body architecture.

At Calcena the presence of easily identifiable Sp, St, Ss and Sr (Miall, 1996; Table 4.1) resembles the sand sheets (SS) described by Jones et al. (2001) along with channel fill complexes (CH) and lateral accretion macroforms (LA) as featured in Jones et al. (2001; Table 1). With reference to Fig. 5.5 it is noted that the range of hierarchal bedform bounding surfaces observed through these deposits is between *three* and *five*. According to Allen (1983), Miall (1996) and Jones et al. (2001) the process of depositing these macroforms is by channel fill complex with overbank deposits, complex bedforms and minor channels with accretionary geometry and by a succession of minor erosive bounding surfaces (Jones et al., 2001; Table 1).

Putting this information together, it is viable to interpret the fluvial system in the Permo-Triassic Ebro as a braided fluvial system with bar complexes, with laterally accreting surfaces, and overbank areas. Currents shaped these

Fig. 5.5 : Correlation panel resulting from fieldwork near the village of Calcena north of the Ateca High. Bedforms, sedimentary structures and fluvial architecture can be identified from the panel.

bars and simultaneously sculpted the erosional surfaces over which they flowed in a similar fashion to the Brownstones of Allen (1983). To lend weight to this fluvial scenario, the palaeocurrent indictors acquired from the sedimentary structures give a spread of north-east to south which would compare well with the multi directional flow experienced in a braided river.

5.5.2.2 Facies 2b

This fine-grained sandstone and siltstone facies was deposited within a fluvial system running along the southern basin margin of the Permo-Triassic Ebro Basin. The beds bear a close resemblance to Fl, finely laminated sandstone and siltstone, and Fr, siltstone with rootlets and bioturbation (Miall, 1996) (Photograph 5.4). The former is described as overbank, abandoned channel or waning flood deposits whilst the latter as an incipient soil or root bed. Given that there is evidence that these fluvial sediments were based in a semi-arid climate (red-colouration, palaeogeographic reconstruction), and rootlet horizons are common throughout the exposures, it can be assumed that vegetation grew on the banks of this river system, and it seems in the fine sediment flanking the water-course. The presence of bioturbation indicates that the environment had a ready supply of oxygen and food on which the burrowing organisms could survive. Collating this evidence and the absence of any sign of energetic water action, cross bedding for example, it is clear that this was a low energy, stable setting in a braided fluvial system. The deposits represent sedimentation on the surface of sub-aerial barforms within the braided system which were periodically flooded, causing burial and reinitiation of new vegetation and burrowing organisms.

5.6 Meandering Fluvial

5.6.1 Facies description

Evidence that a meandering fluvial system existed north of the Ateca High during Permo-Triassic times is found in sediments at Aranda de Moncayo (Fig. 5.1). Here, 100 m of coarse sandstone beds intercalated with interbedded units of thin red sandstones, siltstones, mudstones and weak palaeosol horizons. A transition is noted in the colour of the sediments upwards from the red characteristic of the Buntsandstein Facies to pinks and, in the upper 70 m, white coarse sandstones. Interpretations are offered to the architecture and sedimentology of the bedforms derived from this data, and it is believed that these units represent a top-end example of the Calcena Mudstones and Sandstones Formation (CMS) which was coeval with the deposits of the Alhama Formation at the northern margin of the CIB, and Torete Fm (Rueda de la Sierra) and Cercadillo Sandstones and Mudstones at Riba de Santiuste in the southerly areas of the CIB.

5.6.1.1 Facies 3a: Red and pink coarse-grained sandstone

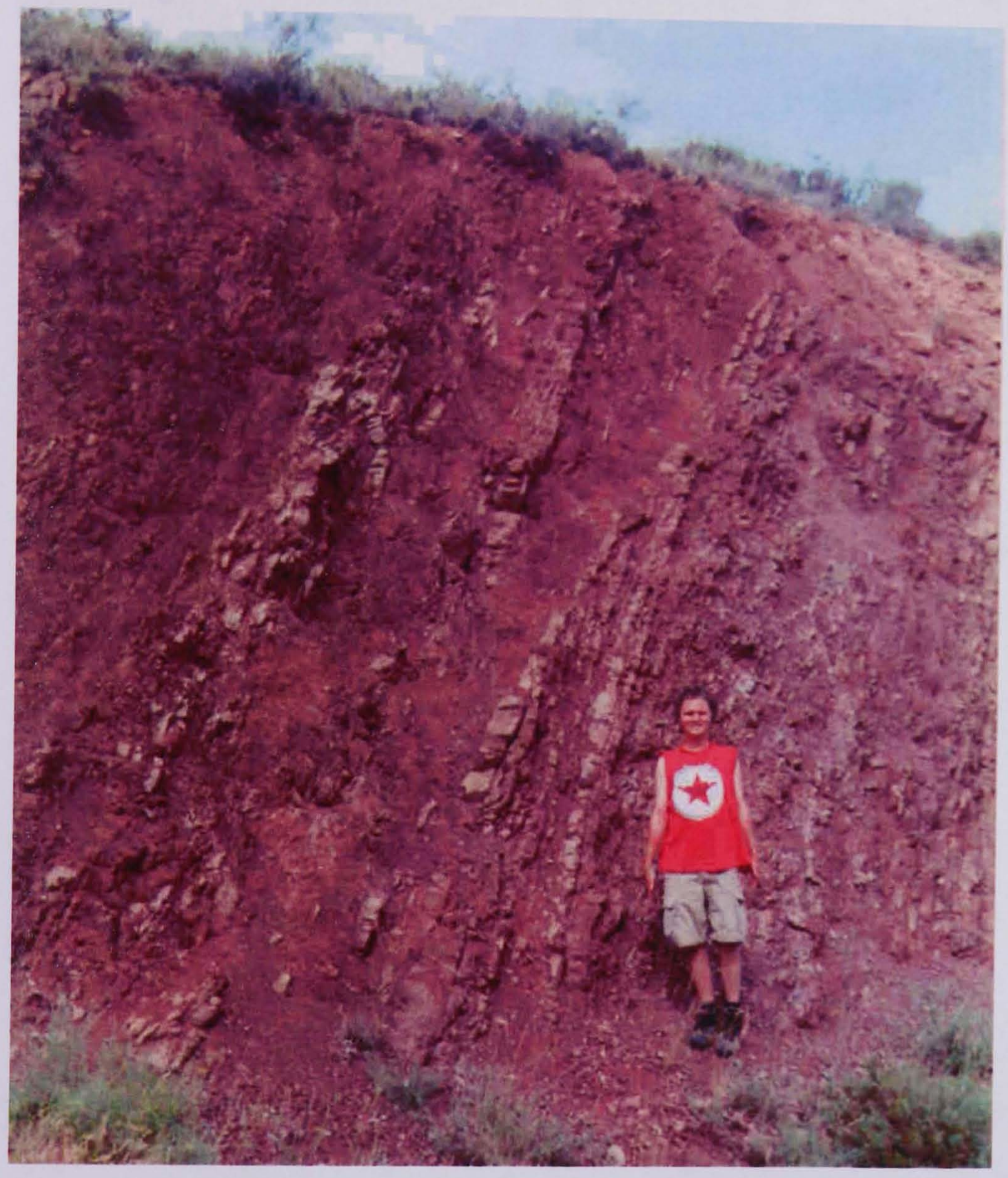
At the base of this section, beds of thick, red, coarse-grained sandstone (<2 m) can be clearly distinguished, separated by thick sequences of Facies 3b. These can be clearly seen repeating up section however, the colour of the sandstone changes markedly from red to pink up section. The entire coarse units display crude lateral accretion surfaces and an overall palaeocurrent direction that suggests an easterly palaeoflow. The true lateral extent of the beds is undeterminable due to restrictions of the extent of road-cutting, but from the exposure available the metre scale lateral accretion surfaces display high angle (15-20°) dips from the top of the bed to the base

(Photograph 5.5). The sandstone beds are rarely amalgamated, instead showing sharp contacts, and in some cases discordances between each bed filled with a thin layer (<2mm) of mudstone or siltstone. Often the beds have a slightly convex upper surface and scoured base.

Photograph 5.5: Observed pinching out of the sandstone beds (younging direction is to the left).

5.6.1.2 Facies 3b: Interbedded medium-grained sandstone, siltstone and mudstone

Thin beds of medium-grained red, micaceous sandstone are observed interbedded with pale yellow siltstones and red mudstones. Maximum thickness of the coarser interbeds is 5 cm, whilst a unit of the alternating horizons can stretch up to 5 m in thickness (Photograph 5.6). Interbedded portions of the section are sometimes cut into by overlying coarser sediment, but on the whole, bedding surfaces are concordant.



Photograph 5.6: Interbedded fine- to medium-grained sandstones at Aranda de Moncayo.

Vague rippled-bedding development (<2.5 cm; Photograph 5.7) occurs on the top surface of the medium grained sandstones, though it is impossible to identify indicators suitable for palaeocurrent analysis. Within the majority of the red, medium sand horizons root traces and abundant burrowing is identified. The yellow coloured siltstones are horizontally laminated towards their tops, though structure is less obvious below that.

Photograph 5.7: Rippled bedding with bioturbated surface seen at Aranda de Moncayo (space between ripples 2.5 cm)

5.6.1.3 Facies 3c: Bioturbated mudstone with pedogenesis

Beds, no thicker than 40 cm, composed of well-weathered mudstone occupy parts of deposits and tend to be succeeded by a coarse-grained sandstone unit, providing a sharp bedding contact with occasional overhangs. The mudstone lacks any internal structure and is strikingly discoloured in parts, changing from its deep red hue to a green pigment. Palaeosol formation, though considered immature pedogenic Entisol (after Retallack, 2001) because of visible laminations and only slight colour mottling and rootlet development, is identified at the top 5cm of some top surfaces of the mudstone beds. Bioturbation and rootlets (<4 cm in length) are also common.

5.6.1.4 Facies 3d: White, coarse-grained sandstone

Similar to Facies 3a, the only difference here is that these sandstone units have been separated from the others is that they are white in colour and possibly indicate a change in source provenance. These beds are thick, extending to 2m thickness in parts, and display similar wedge-shaped characteristics to their red and pink-coloured counterparts (Photograph 5.8). These beds, however, appear to weather more easily and therefore are found with eroded faces giving the impression that they are finer-grained than they actually are. Close sedimentological inspection confirms that they are coarse-grained and contain occasional isolated clasts. Palaeocurrents gleaned from the trough cross bedding within the sandstones suggests that palaeoflow headed in an easterly direction.

Photograph 5.8: Pink and white sandstones displaying truncated surfaces at Aranda de Moncayo (hand for scale).

5.6.2 Facies Interpretation

5.6.2.1 Facies 3a

Despite the relatively restricted lateral exposure of the sediments from which Facies 3a-d are determined, it has been possible to sufficiently analyse and interpret the sandstone bodies of Facies 3a. This channel facies appears as isolated composite units of several migrating stacked sandstone bodies. Miall (1996) suggests a model of such a fluvial setting where an unstable, meandering channel exists (Fig 8.34 in the book) and confirms the expected presence of channel deposits (CH), lateral accretion surfaces (LA) and crevasse splays (CS) with interbedded floodplain fines (OF) of facies 3b and 3c (Jones et al., 2001; Table 2). A lack of an expected wide range of palaeocurrent directions expected from deposits of a meandering system, this can be explained by the limited exposure. Of the palaeocurrent indictors identified, the easterly direction they suggest flow preferred agrees with the palaeodirection of the braided system of Facies 2.

This facies shows strong similarities with the Eocene Castissent fluvial sandstones of the Southern Pyrenees (Marzo et al., 1988) and sections of the Late Quaternary Colorado River (Blum & Valastro Jnr., 1994), the former example resulting from point bar deposition in a mixed-load meandering stream with the composite sandstones resembling the meander belt itself. St, Sl, and Ss typify these deposits whilst the thin horizons of finer material are the result of the fluvial system undergoing flood discharge fluctuations in this semi-arid climate, more than likely associated with seasonally-influenced variations (Marzo et al., 1988). Therefore, it can be assumed that the hierarchal bounding surfaces, though difficult to identify in the field, will rank between *three* and *five* due to the characteristic bedforms, accretionary units and fines of the depositional unit (Table 1; Jones et al., 2001).

5.6.2.2 Facies 3b

With the absence of palaeocurrent indictors it is impossible to determine the direction of flow from the ripples contained within the bedding. However, the medium-grained rippled beds were likely to have been deposited in the form of small flood events or crevasse splays (CS), flooding floodplains, represented by the rootlet- and burrow-rich mudstones (OF), similar to those described by Bridge (1984). These coarser-grained rippled beds match with Miall's (1996) facies classification Sr, interpreted as ripples from a lower flow regime, in this case within a crevasse splay or major overbank deposit. Several coarser rippled beds are identified in the exposed sections meaning that more than one flooding episode occurred during the history of this meandering fluvial system.

The finer-grained sediments of the siltstone and mudstone represent the floodplain deposits into which the crevasse splays enter. Their formal classification is Fr due to the presence of rootlets and abundant bioturbation horizons, though the yellow siltstones are likely to be Fl due to the pronounced lamination towards the top bedding surfaces. The absence of palaeosol formation of the mudstones in particular implies that periods of non-deposition and exposure was limited by episodic flood events, similar to that described in Jones et al. (2001; Table 2).

5.6.2.3 Facies 3c

These sediments are classic examples of poorly formed soil horizons – sediments that have been deposited and exposed during period of non-deposition at the flanks of this fluvial system. A period of non-deposition that would create this is, in this case, either a consequence of localised avulsion or a cessation in flood conditions. Since there is no evidence of syn-sedimentary tilting of the beds, and exposed sediments appear to rest relatively conformably on one another, it is assumed that these fine mudstones and palaeosol profiles are the result of waning flood conditions within the fluvial system. Classification of these deposits would be Fr and Fm (Miall, 1996) indicating a degree of incipient soil formation combined with overbank deposition. The presence of an abundance of rootlets suggests vegetation thrived at the margins of this fluvial system and that organisms capitalised on an ideal burrowing environment.

5.6.2.4 Facies 3d

This facies develops as higher energy channel version of facies 3a highlighted by the inclusion of isolated clasts within the sand bodies. Lithofacies St, Sl, and Ss are represented, interpreted by Miall (1996) as probable filling of scours and chutes across surface migration of intrachannel bars (Miall, 1996). These gravel-sand meandering systems area again seasonal and are formed of sheet-like composite beds deposited during flood stages as in the example of the Eocene Castissent fluvial sheet sandstones from the Southern Pyrenees (Marzo et al, 1988). The bounding surface hierarchies of the various composite beds ranges from *three*, of a macroform or minor channel/sheet deposit, to *five*, main channel/sheet deposit or a major flood unit (Jones et al, 2001).

However, these fluvial deposits differ from the other described because they are composed carbonate sandstone - as opposed to siliciclastic material observed in the other fluvial facies. The increase in carbonate within the sandstone is a direct result of the marine influence of the westwards advancing Tethys Sea during the mid-Triassic (López-Gómez *et al.*, 2002). There is no evidence to suggest the meandering system altered anatomically as it was periodically flooded by shallow marine Tethys waters, though, as with the Late Quaternary Colorado River and the manner in which it approaches the Gulf of Mexico (Blum & Valastro Jnr., 1994) and the fluvial system at Riba de Santiuste along the southern margin of the CIB (Chapter 4), a deltaic environment is thought likely to have formed.

Marine conditions prevail in this basin long before a true deltaic environment can establish along the southern margin of the Permo-Triassic Ebro. The carbonate sandstones from facies 3d quickly move into dolomite limestone up-section, representing another example of the onset of the true Muschelkalk facies across the Iberian Ranges.

5.7 Synthesis of depositional systems

Figure 5.4 summarises the depositional models for the succession based on the genetic relationships between the facies described in the preceding sections and cross-correlation with those of the CIB. Deposition occurred in a wide range of continental clastic environments associated with alluvial fans, meandering streams and braided streams.

Conglomerates, sandstone and mudstones (Facies 1a-c) were deposited in a continental depositional environment dominated by alluvial fans. The fans are interpreted, from the lateral extent of outcrop deposists, as being relatively small (<0.5-1 km in cross section) when compared with those of the CIB, but still dominated by high magnitude low frequency flood events with a mixture of debris and flood dominated processes. The development of transverse flux, represented by similar clast types within the coarse-grained alluvial fan deposits laid down at the margins of the Ebro basin, was strongly influenced by the regional tectonism (it is difficult to infer any climatic control with their poorer preservation) when compared to the CIB examples (see Chapter 3). The coarse clastic erosional detritus was derived from local input points along the Ateca high, as demonstrated by the sharing of clast lithology. It also seems likely that the distal fines of the fans supplied sediment and runoff to a playa lake in a similar way as the CIB (Chapter 3). The alluvial fans represent the early incipient drainage of the Ebro Basin.

Deposition of low-sinuosity braided stream deposits (Facies 2a-b), records the onset of a more permanent hinterland drainage system, supplied with a high volume of sediment. A lack of provenance data for this area means this is yet to be comprehensively tested, though field investigation suggests clasts lithology originates from the same region as the CIB. The braided system was dominated by channel-fill complexes containing well-sorted sands and a hierarchy of bedforms responding to waning flow from megadunes, dunes, megaripples and ripples (Facies 2a). The apparent lack of macroform bars with there distinctive accretionary units is interpreted to represent a more-or-less uniform flow, with the sole macroforms consisting of migratory dune complexes, similar to the sand shoals (e.g. Allen, 1983;

Jones et al., 2001) and stacked macroforms (e.g. Miall, 1994). The upper parts the braided stream facies (facies 2a) occupies is characterised by broad channel complexes, channel-fills, sand sheets and an important development, mid-channel bars. Several of the bars resemble simple cross-bedded bars in the form as described by Allen (1983) that are usually solitary with erosional tops and bases. Overbank fines are also present but form a lesser component of the facies.

The Braided fluvial deposits were superseded by meandering stream sediments. This transition records a lessening in sediment flux to the basin through a time period c. 8 Ma. (Fig. 5.2), but perhaps even over a much longer time period from the Permian. The sediments record fining-up successions (Facies 3a-c) with the main channel belt situated parallel to the western margin (Ateca high) of the Permo-Triassic Ebro rift basin according to the positioning of outcrops and basin reconstruction. The presence of meandering streams can suggest a stabilisation of the basin floor and a lowering of the regional gradient, in a similar way to that reported in many modern rift basins (e.g. Frostick, 1997). The nature of the field exposures makes it difficult to determine the actual size of the channel belts, but it seems likely that the channels wandered over a floodplain several kilometres wide. Such facies bear a close resemblance to the Riba de Santiuste area of the CIB (Fig. 5.2; Chapter 4).

5.8 Discussion

This section addresses several key points that have been overlooked in the current literature on rift basins (as explained in sections 5.1 & 5.2).

5.8.1 Drainage development: climatic control

The main climatic control on drainage development is through discharge variability. It is to be expected that lithofacies heterogeneities will increase with increasing seasonal or long-term variability in discharge, and that the frequency of the more minor bounding surfaces will increase (i.e. second and third order surfaces; Miall, 1996). The lithofacies and changing fluvial style for the Ebro basin during the Permo-Triassic, undoubtedly reflect changes in sediment flux and correspondingly discharge from waning flood events. The succession of facies described here is known to span the time of gradual continental break-up of Pangaea and a change from icehouse to greenhouse conditions with a trend towards more temperate-humid conditions. The gradual change in climate coincides with the changes in character of the fluvial systems from dominantly alluvial fans and coarse-grained braided rivers to meandering streams. However, rivers react to a number of stimuli, and it is difficult to determine whether a given change in character reflects tectonic or climatic influences, or both (Frostick & Reid, 1989; Frostick & Jones, 2002). Attempts to unravel causes are often thwarted by feedback among climate change and tectonism (Shanley & McCabe, 1994). Despite these difficulties, river character can be a valuable, and sometimes unique, guide to climate induced environmental conditions. Climate in the Ebro basin and the CIB, as determined from palaeogeographic reconstructions and analysis of the sediments, is likely to have altered sediment supply to the rivers. According to Doubinger et al. (1990) and Kutzbach et al. (1990) slowing of erosion rate is likely to result in the slow shift in climatic conditions through the Permo-Triassic endured throughout continued rifting and compartmentalisation of the basin.

Few studies dealing with fluvial facies have concluded that perennial flow influences the systems (Deluca & Eriksson, 1989; Luttrell, 1993). However, the braided river and meandering stream deposits (Facies 2 & 3) of the Tierga Sandstone and Calcena Mudstone Formations are interpreted as perennial flow deposits, with seasonal discharge variations and perhaps even some flashiness. The basis for such an interpretation is that in large perennial to intermittent rivers, channel macroform assemblages dominate the architecture. Under sustained discharge conditions the well-developed macroforms show a vertical decrease in grain size and overall scale of the bedding. Additionally large dune fields, well-defined channels, with deep scours and the development of bars are typical of perennial rivers interspersed with seasonal flow stage fluctuations. The range of comparable modern analogues with similar lithofacies varies and includes the Platte- and south Saskatchewan-type profiles of Miall (1978), the Yellow River, China (Chein, 1961) and the Brahmaputra, Bangladesh (Bristow, 1993). All are perennial braided rivers with substantial seasonal flow fluctuations.

5.8.2 Drainage evolution: tectonic controls

The Permo-Triassic synrift phase of the Ebro basin is not as well preserved as seen in the CIB and does provide limitations to the structural interpretations. However, as in all rift basins faulting exerts an important control upon drainage development and will thus determine the architecture and inlet positioning of sediment flux to a synrift basin. In the Ebro basin the diversity of facies and corresponding erosional processes that arise due to variations in spacing, orientations and interactions of faults illustrate the important tectonic controls on drainage development (Figs. 5.4 and 5.6).

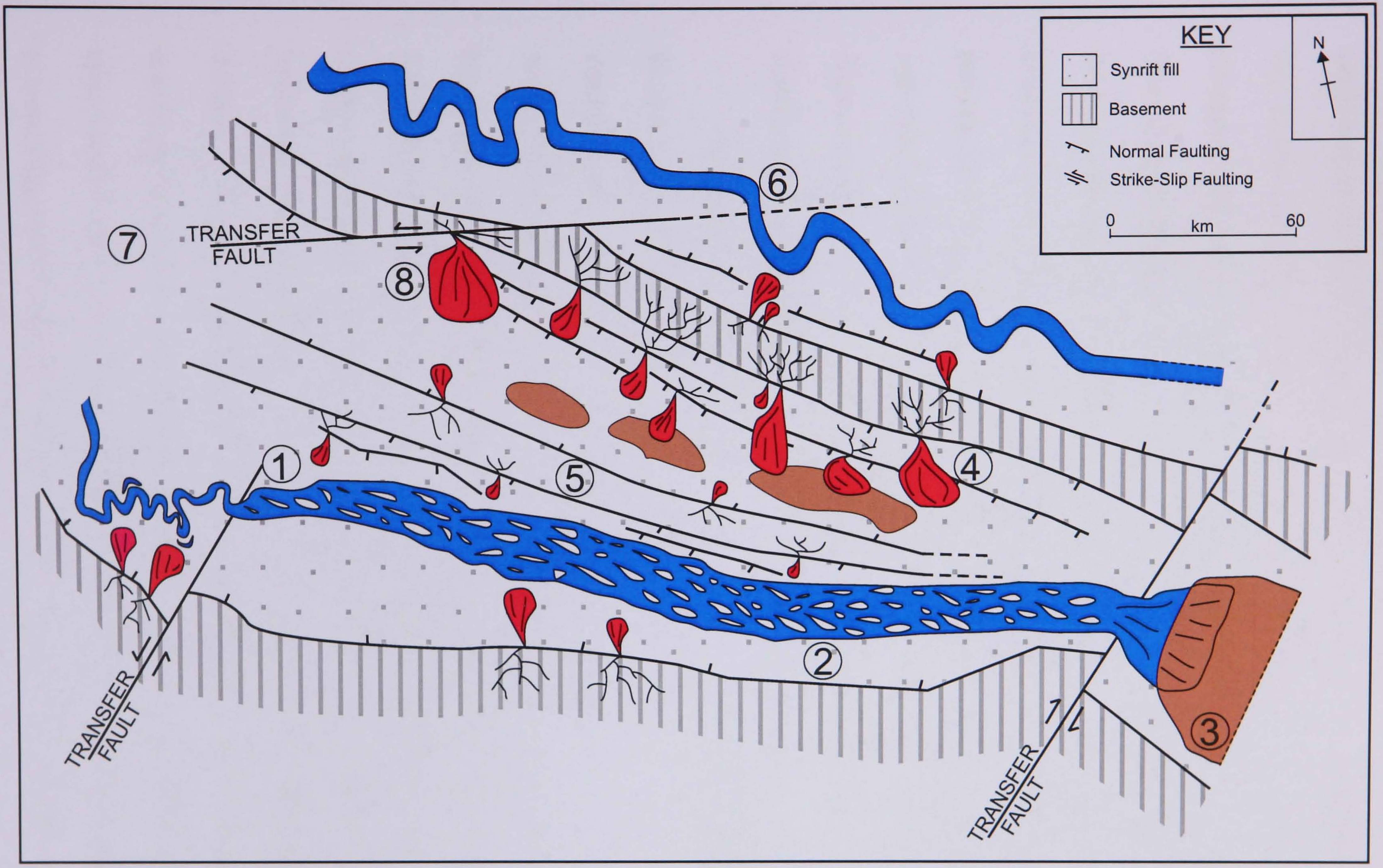


Fig. 5.6: Stylised cartoon map of drainage in a rift basin. Key to circled numbers: 1) Change in basin floor gradient across a transfer fault; 2) Dominance of axial fluvial systems; 3) Along basin influence of transfer faults; 4) Relay zone controls of sediment flux; 5) Intrabasinal structural partitioningand subdivision of depositional systems; 6) Axial fluvial dominance, breaching transverse structure; 7) Hinterland drainage control and uplift; 8) Transverse faults allowing drainage development.

It is widely recognised that where basement lithologies are similar, footwall catchments are generally smaller, shorter and steeper than those of the hangingwall (e.g. Leeder & Jackson, 1993). Along the Ateca high, separating the CIB and Ebro rift basins, alluvial fans developed in the hanging wall of normal faults (see Chapter 3) and it seems that more sediment ended up in the CIB than the Ebro Basin during the Permo-Triassic. The fans along the western margin of the Ebro basin are likely to be starved of sediment at certain times as flux to the CIB dominated coevally. This presents a new finding that when alluvial fans are evolving back to back, one margin will dominate and control all ensuing drainage pathways. This has a major implication for interpreting subsurface synrift sediments where small alluvial fans could wrongly be interpreted as having developed in the footwall of a fault system.

As mentioned in chapter 4 the development of axial drainage depends upon the ability to breach transverse bedrock ridges and transfer faults, by headward stream erosion or stream diversion. It is less obvious in the Ebro basin, but the Deza transfer fault (Fig. 5.1) cuts across the Ateca High and propagates into both the Ebro Basin and the northern CIB. The fault possibly influenced the drainage pattern of the Ateca High and could be the reason why axial drainage is diverted away from the northern areas of the CIB. However, many studies have identified that once breaching occurs the direction of axial stream flow differs between two basins of different widths (e.g. Leeder & Jackson, 1993; Gawthorpe & Leeder, 2000). This may be the case in many modern rifts, but tectonic uplift in the hinterland drainage system to the north of the CIB and Ebro basin is likely to have played a leading role in controlling the behaviour of the axial rivers, through differential uplift, supply of sediment, control on gradients and resulting stream power of the axial rivers. The differential uplift of the hinterland may also be accountable for the switching of axial drainage and sediment flux during the early stages of infill in both basins (Fig. 5.6). The sharing and competition between two neighbouring rift basins for sediment flux is an important new finding and identifies the need for large-scale regional studies (see chapter 7).

To further complicate issues, the direction of flow by axial rivers is dependant upon the relative elevation of the basin floor. Drainage will tend to flow from narrow to wide basins (Leeder & Jackson, 1993), with the result of sediment deposition to raise the level of the basin floor. Although, such processes may result in switching of axial rivers, it seems unlikely that increased sediment flux would be able to override the tectonic control, let alone switch channels over a distance of nearly 100 km.

5.8.3 Relevance to basin analysis

The comparison between two ancient synrift fills identifies the importance of axial drainage systems in controlling not only the sediment supply but also the efflux of basins. Frequently the drainage patterns are neglected in many basin analysis studies and only the depositional packages form the main focus of attention. It can be determined from this study (and previous chapters) that the drainage patterns play a key role in controlling the depositional patterns within the rift basin.

The presence of axial drainage systems is an important economic component of continental synrift basins, because the relatively well-sorted channel belt deposits left by axial channels may be good hydrocarbon reservoirs or water reservoirs, in contrast to the poorly sorted deposits of the transverse alluvial fans.

Through the use of facies patterns and palaeocurrent trends indicate that in order to correctly interpret basin geometries and drainage patterns, then observations need to be made on a length scale of 10-20 km, comparable to that of the largest fault segments. This is particularly relevant to subsurface exploration since this length scale is similar to that of many exploration blocks.

5.9 Conclusions

Several important conclusions can be drawn from the architectural study of the Ebro Basin that has implications not only for understanding synrift fills, but also for the development of drainage networks in rift basins.

1) The synrift succession, younger than ~250 Ma and deposited less than 39 Myrs after rift initiation (Ermita Formation, volcaniclastics) comprises of alluvial fan, low-sinuosity braided river and meandering stream sediments.
2) An important axial drainage system evolved that through a period of c. 8Ma of the late Permian to early Triassic and become established as one of the important sediment supply routes.
3) The depositional model comprises of alluvial fans that are eventually superseded by low sinuosity braided and then meandering perennial rivers, similar to that seen in the southern CIB.
4) The architecture of the braided fluvial deposits are dominated by channel-fill complexes, sheet sands, and associated simple and more complex bar types. The meandering stream sediments record several fining-up successions, interpreted as point bars.

5) A seasonal climate with marked discharge variations transporting erosional detritus from the hinterland to the basin is envisaged, the longevity of which allow axial fluvial systems to become established and provide the main sediment flux and efflux for the basin.

6) The alluvial fans along the western margin of the Ebro basin became starved of clastic sediment supply through drainage capture and possibly renewed tectonic activity on the CIB side of the Ateca structural lineament.

7) The development of axial drainage depends upon the breaching of transverse bedrock ridges and transfer faults (e.g. Deza fault). However, the tectonic uplift in the hinterland drainage system in-between the CIB and Ebro basin is likely to have played an important leading role in controlling the behaviour of the axial rivers, through differential uplift, supply of sediment, control on gradients and resulting stream power of the axial rivers.

8) The differential uplift of the hinterland may be accountable for the switching of axial drainage and sediment flux during the early stages of infill in both the CIB and Ebro basin (Fig. 5.6). The competition between two neighbouring rift basins for sediment flux is an important new finding and identifies the need for large-scale regional studies.

9) Facies and palaeocurrent trends may only be correctly interpreted when observations are made on a length scale of 10-20 km, comparable to that of the largest boundary fault segments. This is repeatedly identified along the length of the axial fluvial system flowing parallel to the Ateca High.

The ideas developed in this chapter will be further discussed in Chapter 7 to provide an overall synthesis of controls acting upon drainage systems during synrift episodes *of rift basins. However, before this is discussed an overview of modern rift basins is presented in Chapter 6 to compare and contrast with the CIB and Ebro basin.*

Chapter 6

Rift Basin Case Studies

Key findings/discussions:

· Three different modern day extensional rift basin settings; the East African Rift, Rio Grande Rift; Red Sea Rift) are examined and compared to the CIB

· In all basin examples, basin topography and positioning of drainage is influenced by fault activity

· Structurally-controlled sediment conduits along basin margins play an important role in delivering sediment flux from source to sink in all basins

· Synrift intrabasinal and marginal depositional systems differ in the comparative basins depending on climate and tectonics and variations in basin linkage

· Cross sections across the basins reveal that the CIB shares geometrical features of all three examples, suggesting that purely 'fixist' rift basin models are inaccurate

· Examples used are all recent rift systems and widely used in the literature as analogues for many ancient basins. The CIB identifies that the overall rift concepts are correct but the details are wrong.

6.1 Aim of the chapter

The absence of regular cross-referencing between examples can lead to a lack of understanding about extensional settings both locally and globally. This is seen regularly in the literature where studies and models focus on a single area or basin rather than comparing the structural and sedimentary features of a range of rift basins.

Having analysed and interpreted the synrift sedimentary fill of the Permo-Triassic CIB (Chapters 3, 4 and 5) the aim of this chapter is to compare and contrast with other rift basins to provide a wider context to the study. Three examples shall be discussed: the East African Rift, the Gulf of Suez/Red Sea Rift and the Rio Grande Rift (Fig 6.1). Of particular importance is the preservation of synrift deposits recording the transition from a wholly continental environment to that of a wholly marine setting along the margins of an extensional rift basin and the influence basin structure, and in turn tectonism, has on the placement of drainage.

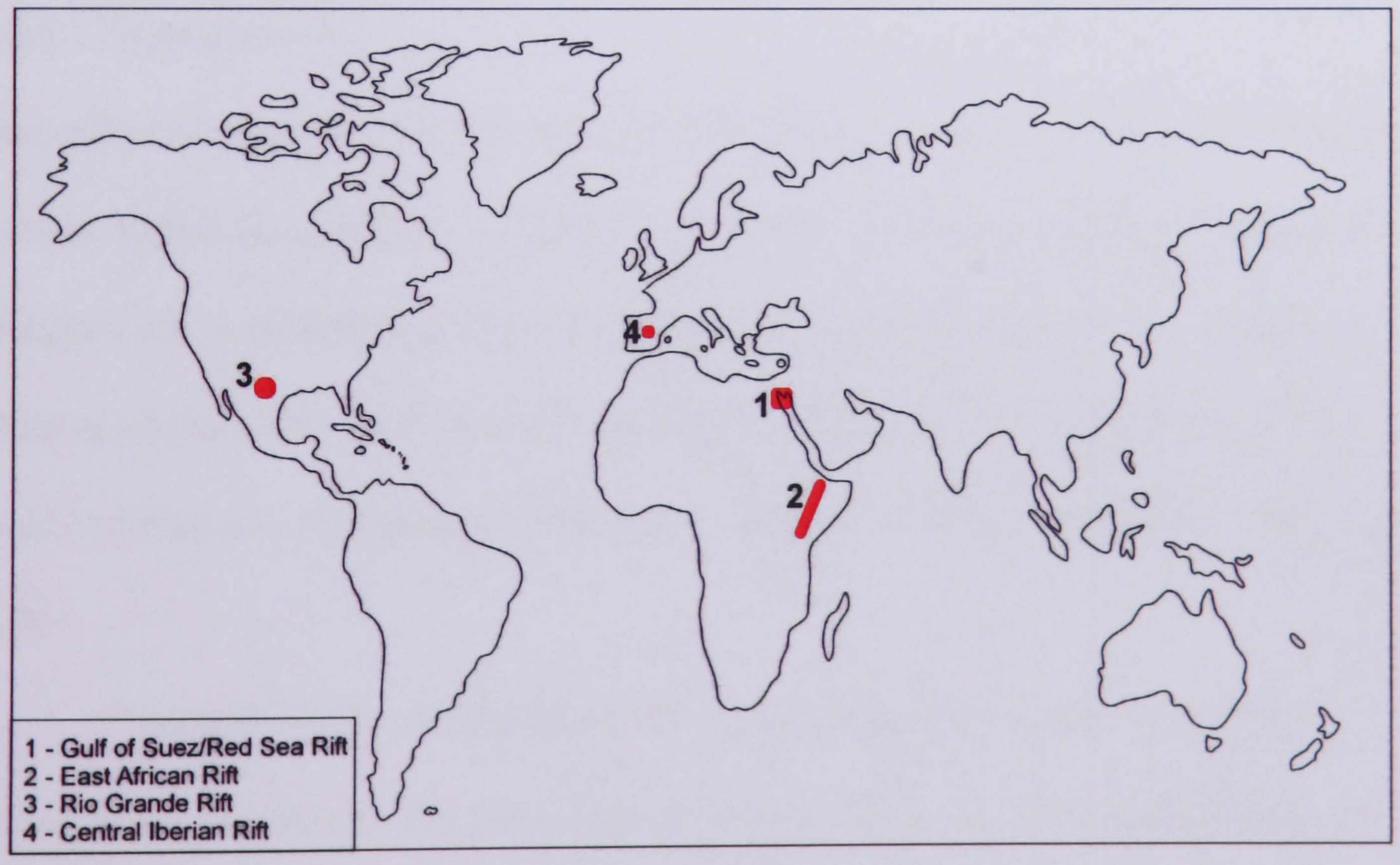


Fig. 6.1: World map showing the locations of the four rift basins chosen for comparison in this chapter.

6.2 Rift basins of the world

The three rift zones, the East African Rift basin, the Gulf of Suez/Red Sea Rift, and the Rio Grande Rift, have been chosen for this comparative study as each contain differences in synrift fill, structural style and basin development that contrast or show similarities with the CIB. Examination of the variation in characteristics leads to new observations and interpretations about the CIB and helps reconstruct the evolution of this large rift basin in the centre of the Iberian Microplate during the break-up of the supercontinent Pangaea. Figure 6.2 compiles information about these basins and allows comparisons to be drawn between them. Though the implications of these comparisons are discussed later, reference to the table is advantageous throughout this chapter.

6.2.1 The East African Rift

6.2.1.1 Introduction

One of the most prominent and frequently described modern-day rift zones, the East African Rift is an example of a region of tripartite crustal extension culminating in a complex series of differing rift basins with associated sedimentary fills. It forms a striking geomorphological feature running from Afar, in northern Ethiopia, to the southern areas of Lake Malawi a distance of almost 35,000 km (Frostick, 1997; Fig 6.3).

Undoubtedly the East African Rift is one of the best examples of active rifting that exists today. The plate tectonic setting, basin structure, sedimentary fill and detailed microflora and fauna are used as analogues for interpretation of ancient, arid to semi-arid subsurface basins worldwide (Frostick, 1997).

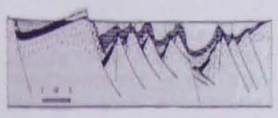
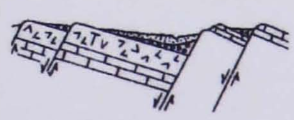
	Gulf of Suez/ Red Sea Rift	East African Rift	Rio Grande Rift	Central Iberian Rift Basin
Size	300 km long 50-90 km wide	35,000 km long 30-200 km wide	400 km long <100 km wide	100 km long <50 km wide
Spreading rate	105 km since Miocene	10-35 km since Miocene	-	-
Typical fault displacement	1-50 m	<12 m	25 m	-
Climate	arid to semi-arid	Varies: arid, dry to tropical, wet. Microclimates exist.	semi-arid, warm with seasonal precipitation	semi-arid, dry with occasional flood events
Marginal depositional facies	Continental (alluvial fans, lacustrine) to shallow marine (fan deltas)	Continental (minor alluvial fans <1km diameter, lacustrine)	Continental (streamflow dominated alluvial fans)	Continental (alluvial fans, lacustrine) to shallow marine (delta lobes, algal lagoons)
Intrabasinal depositional facies	Deep marine (distal marls) and evaporites	Continental (lacustrine, fluvial systems - though most are diverted away, lacustrine deltas).	Continental (braided fluvial sheetfloods and floodplains)	Continental (lacustrine, braided and meandering fluvial) to shallow marine (deltas).
Volcanic deposition	Non volcanic (minor late prerift to early synrift basin dykes only)	Intensive volcanism in rift axis. Commenced during early rift development	Ash deposits linked to reversal magnetostratigraphic timescales	Volcanic activity during early development. Ashfalls create alkali lakes.
Structure of the basin margin	Normal faulted. Strongly segmented, with relay ramps breached by transfer faults. Act as sediment supply routes Hangingwall synclines.	Normal faults 'interlock' forming assymmetric half graben geometry. Uplifted, titled fault blocks. Relay ramps common at breached normal fault tips.	Normal faulted forming tilted half graben fault blocks.	Normal faulted tilted fault blocks. Relay ramps form at breached fault tips creating sediment supply routes.
Rift basin in cross section				
Basin linkage	Major connectivity of basins to Mediterranaen Sea and Indian Ocean during marine flooding.	Yes, though between some basins, barriers of varying height exist and block drainage. Transform faults often form at transition between basins.	Ancestral Rio Grande links all basins and flows freely between them	Linkage between CIB and Iberian Basin. Transform fault marks the transition.
Basin compartment -alisation	Yes. Whole rift system divided into smaller extensional basins 50 km long and 10 km wide.	Yes. Forms a series of sub-basins	None	Yes. CIB divided into two sections. Absence of interaction between depositional systems
Key recent references	Bosworth & McClay (2001) Kahlil & McClay (2001) Jackson et al. (2002)	Frostick (1997) Lærdal & Talbot (2002)	Leeder et al. (1996) Perez-Arlucea et al. (2000) Mack et al. (2002)	This study

Fig. 6.2: Table showing the characteristics of each of the four rift examples areas.

6.2.1.2 Geological History

The main grabens that make up the East African rift basin are divided into three (western, eastern and southern) branches; they are all as symmetrical and bordered by a major normal fault on one side, and faulted flexures on the opposing side (Chorowicz, 1990). The rift zone crosses a variety of geology and its setting is within a major craton, resulting in a largely crystalline basement. The pre-rift geology centres on Precambrian rocks associated with Palaeozoic metasediments and marine Mesozoic rocks (Frostick, 1997) and can be seen clearly in Ethiopia. Much of these

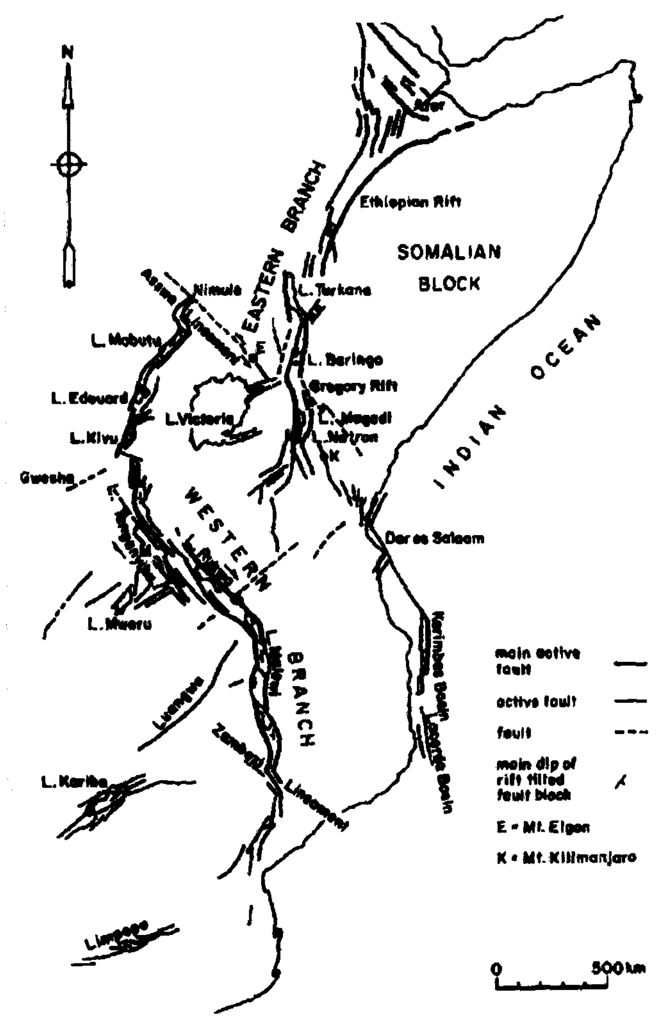


Fig. 6.3: Map of the East African Rift Zone (adapted from Frostick, 1997).

deposits are absent further south of Ethiopia, where the rift zone cuts through only Precambrian metasediments. Only in the most southerly areas, around Lake Malawi, do Palaeozoic/Mesozoic sediments appear again as part of the pre-rift basement geology.

The East African Rift zone is thought to have formed and evolved as one arm of a trilete system of rifts with the Red Sea and Gulf of Aden, meeting in a triple junction around Afar in Ethiopia (Frostick & Reid, 1989). The majority of the rift is thought to be a good example of an active rift, where volcanic activity occurred along its length in varying degrees of intensity at an early stage of basin development. However, the western branch of the rift is considered to be passive rather than active indicating a degree of lithospheric flexure. Frostick (1997) suggests that difficulties arise when applying labels of 'active' (a continental margin that is seismically and volcanically active) and 'passive' (a continental margin that is seismically and volcanically inactive) to the East African Rift and that the rift basins in this area result directly from lithospheric extension.

Rifting in the East African system began in early Miocene time and continues today with extension generally orientated NW-SE, varying from this trend to N-S, NW-SE, and NE-SW in other circumstances (Fig 6.3). Half-graben geometries of each individual rift basin in this zone are bordered along the margins by normal faults resulting in a series of titled fault blocks, such as in Lake Malawi (Fig. 6.4). Basin width varies between 30 and 200 km, with the widest basin occupying a location in northern Ethiopia (Frostick, 1997).

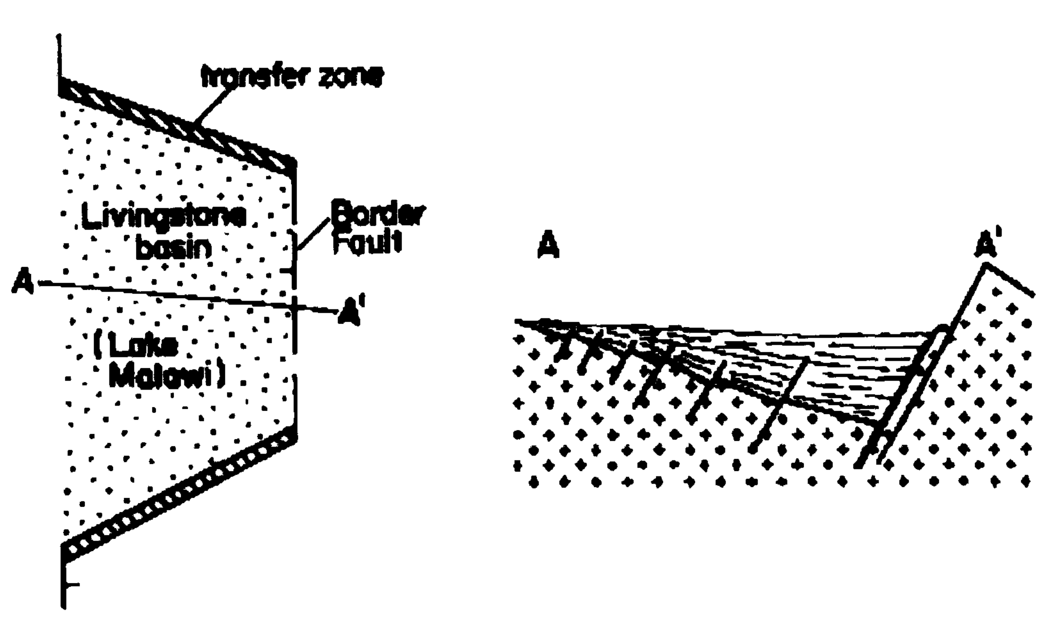


Fig. 6.4: Cross section through Lake Malawi (Livingstone Basin, East African Rift) showing well-developed half graben geometry (adapted from Frostick, 1997).

Segmentation of the rift zone into basins occurs due, in part, to topographical barriers of contrasting heights formed within a series of arcuate half-grabens switching sides of the rift zone, a product of which is a sequence of hydrologically isolated drainage basins. Structurally-controlled relay ramps and transfer zones occur along the fault-controlled margins of these basins (Baker, 1986; Chorowicz, 1990; Gawthorpe & Hurst, 1993; Frostick, 1997) and have a marked influence on the basin drainage patterns.

Figure 6.5 highlights the importance of the interplay between three very different rift basins within the East African Rift zone; the Lake Turkana Basin, the Lake Tanganyika Basin, and the Baringo-Naivasha-Magadi Basins. Each shows relationships between basin-fill, structure, and crustal thickness, as well as rates of strain and volcanism. It is this latter geological control that has had a distinct influence of basin geometry having been closely associated with the domed areas of the rift zone, through which the basins cut. Volcanism as basin fill is limited in the western branches, slightly more developed in the northern Ethiopian areas, whereas widespread extrusive volcanics have been linked with the area from the Oligocene through all subsequent stages of rifting.

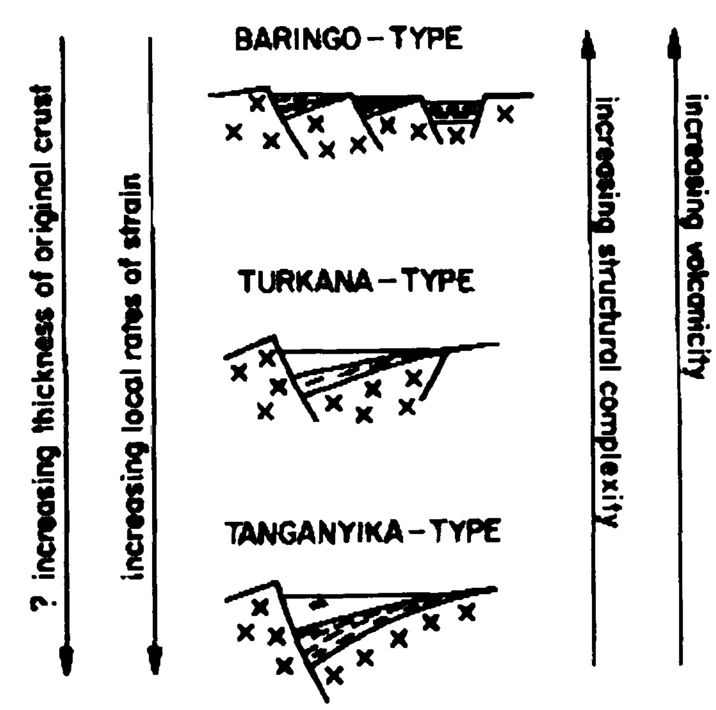


Fig. 6.5: Schematic diagram showing the variety of structural style of basin found in the East African Rift (adapted from Frostick, 1997).

Other than the volcanics, basin fill in the East African rift zone comprises clastic sedimentary facies and depositional systems responding to local and regional differences in tectonism, volcanism and climate (Baker, 1986; Tiercelin, 1990; Frostick & Steel, 1993; Frostick, 1997). These systems include examples of fluvial, alluvial and lacustrine sedimentation. In the Lake Tanganyika Basin, lacustrine deposits occupy a narrow faulted trough 50-80 km wide, divided up into smaller sub-basins each 100 km long. Sedimentary basin fill in this basin is wedge-shaped and thins towards the flexured margin. Uplift along this margin allows only small rivers to cross, with the exception of the large fluvial system running through the basin, and deflects drainage away from the faulted boundary. The crystalline nature of the

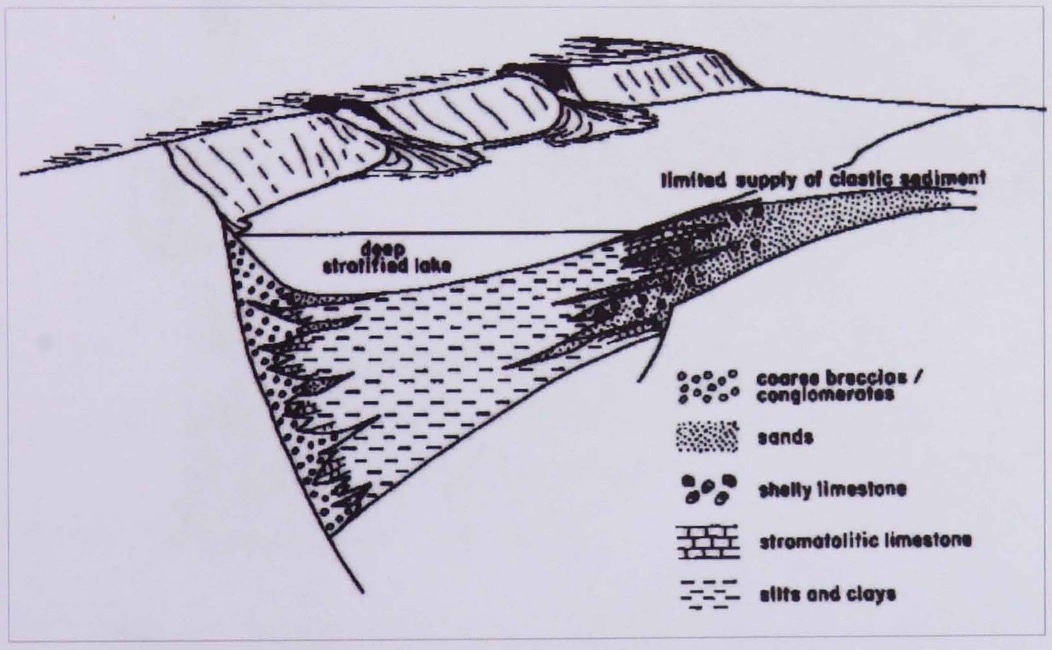


Fig. 6.6: Stratigraphy of the Lake Tanganyika Rift (taken from Frostick, 1997).

basement rock, which fails to easily erode, restricts clastic sediment supply resulting in reduced sedimentation rates in the lake (Fig. 6.6). Only in the northernmost portions of this basin is there an increase in sediment supply, directly related to the influence of adjoining river systems in that part of the rift zone.

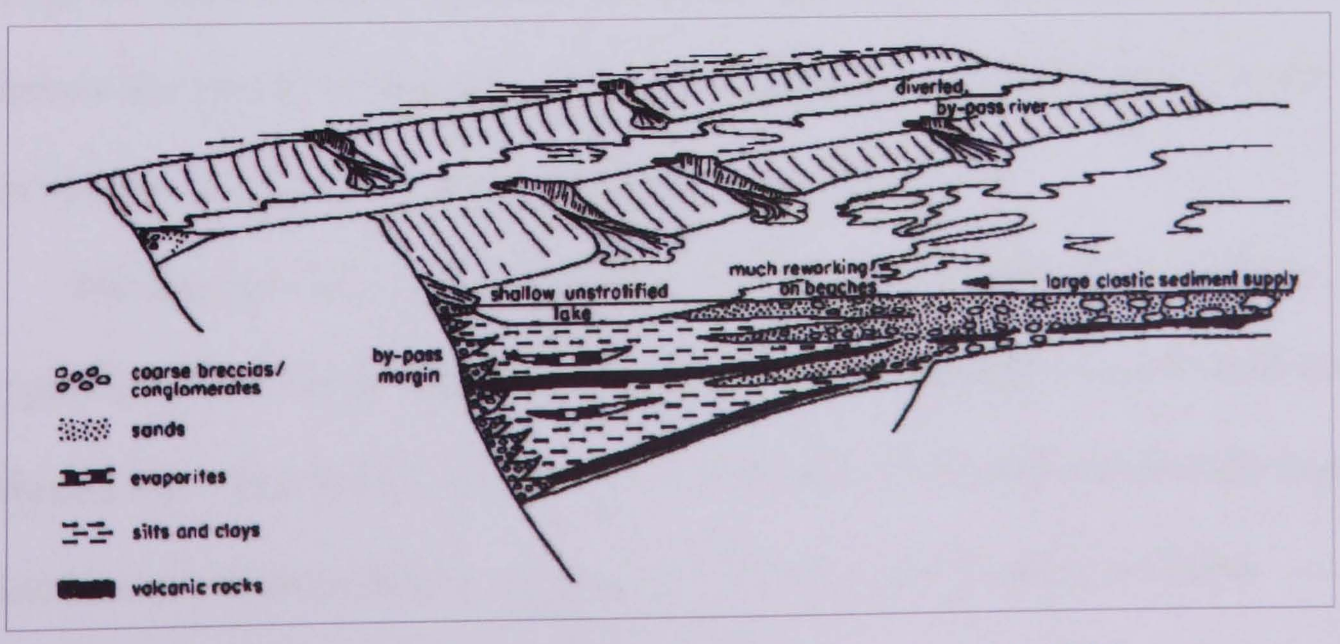


Fig. 6.7: Stratigraphy of the Lake Turkana Basin (taken from Frostick, 1997).

The Lake Turkana Basin is a shallow lake basin, which is generally unstratified and highly saline (Fig 6.7). Basin width and length have both been influenced by successive episodes of doming associated with local volcanism, and volcaniclastic deposits occur throughout the basin fill sequences acting as chronostratigraphic markers. The Tertiary and Quaternary sedimentation within this basin is dominated by clastic sedimentary sequences, debris for the depositional systems being sourced from the easily weathered volcaniclastic rocks.

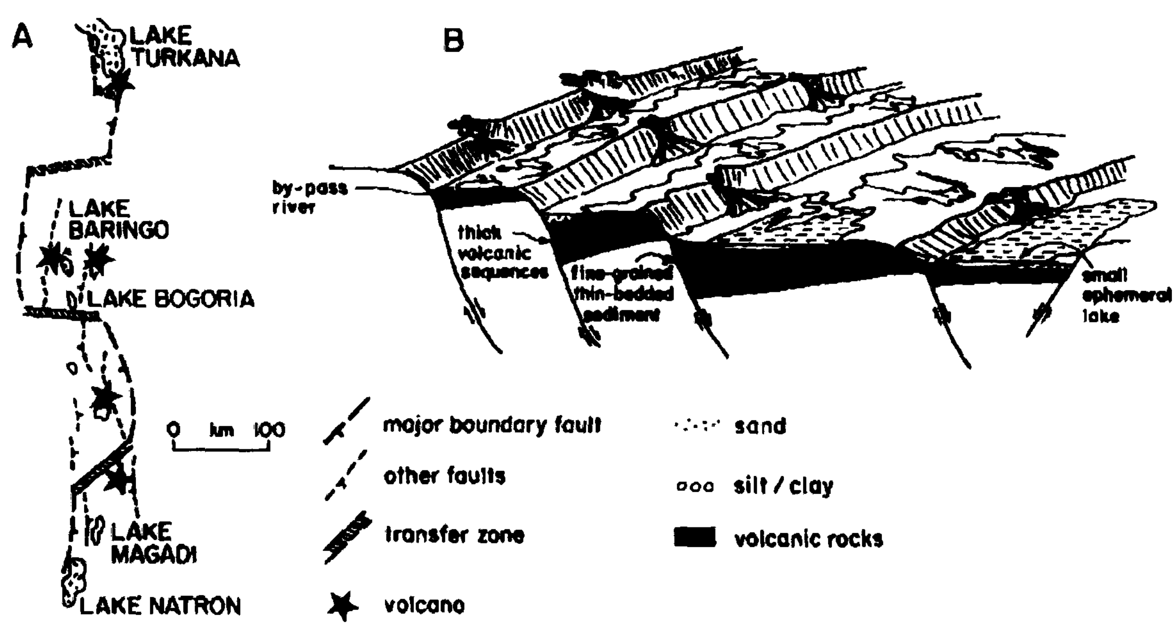


Fig. 6.8: The Baringo-Naivasha-Magadi Basin A) Structure and B) stratigraphy and depositional systems (taken from Frostick, 1997)

Interbedding of fluvial, deltaic and littoral deposits occurs, as do small alluvial fans situated on the fault scraps, however footwall uplift and tilting prevents drainage of smaller rivers to intrabasinal areas (Frostick, 1997). Intercalation of fan sediments and lacustrine deposits does occur during period of fault activity at the basin margin, the lake as a result is dominated by clastic fines.

The Baringo-Naivasha-Magadi Basin (Frostick, 1997) occupies a 400 km long portion of the eastern rift and is covered by small lake deposits in relation to the previously described basins (Fig. 6.8 A, B). The lakes are stratified and shallow and tend to be compartmentalised away from the normal faults forming the basin boundary by antithetic and synthetic faulting. Intrabasinal structures also control the pattern of river drainage across tilted fault blocks, structures which in turn limit the transfer of sediment perpendicular to rift axis orientation, encouraging individuality of the depositional systems in each segmented area. Lœrdal & Talbot (2002) recognised lineaments of structural highs and low relief located in the centre of the Edward-George Basin that appeared to dictate the pattern of drainage. Antithetic faults (relative to the main boundary faulting) determine lake morphologies and river courses as well as separating lake floor sediments.

Within the Baringo-Naivasha-Magadi Basin finer fluvial sediments are found, due to the localised shallow basin floor gradients and limited-size drainage networks. In addition, volcaniclastics, which form kilometre thick sequences in the basin, often fill the accommodation space available for sedimentary infill, the latter settling for reduced thicknesses in the basin stratigraphy. This pattern of sedimentation is observed in the smaller rift basins of Ethiopia where main variations depend on the volcanism, internal basin structure in terms of the abundance of antithetic and synthetic faults, and the longevity and composition of the lacustrine environment (Fig. 6.8 B).

6.2.1.3 Key Findings

The East African Rift Zone can tell us a lot about the processes acting upon a half-graben rift basin not only in a modern context, but also as an analogue for the ancient. Key studies have addressed the need to further our understanding of the basins within this rift zone and a number of important findings have been established that help us understand the development of the CIB:

i) The continental-scale structure of the East African Rift provides several examples of rift basin geometry as applied to ancient sub-surface deposits

ii) There is striking evidence in many of the East African Rift basins that sedimentation is related to tectonics, volcanism and climate, the latter in the form of rainfall fluctuations. Sedimentary facies and depositional systems are clearly controlled by water balance (and lake level) whilst drainage pattern, basin morphology and their positioning is influenced by active tectonics. Smaller basins that collectively comprise a branch of the rift zone tend to be ephemeral, with the larger, broader rift basins situated in the northern and southern extremities, remaining active for relatively prolonged periods of time

iii) The structure and linkage of the basin margin boundary faults dictates the positioning of drainage and in the case of the Baringo-Naivasha-Magadi Basin, it directly influences the orientation pattern so that drainage flows normal to the basin axis. Intrabasinal structures such as antithetic and synthetic faults are the main architects behind lake morphology and influence the meandering and braided river courses within the basins (Lœrdal & Talbot, 2002) a feature seen in the CIB (see Chapter 4)

iv) Relay ramps and transfer zones exist along the basin margins that allow restricted flow of small rivers between basins and have the potential to position the path of sediment flux from drainage areas to the basin depocentre as seen at the northern margin of the CIB (Chapter 3)

v) The amount of volcanicity appears to correlate with the complexity of faulting within a basin. Greater amounts of volcaniclastics accumulating into a basin also reduces the amount of accommodation space available for clastic sedimentation fill

vi) Filling of the rift basin in East Africa is asymmetric, the thickest sequences lying adjacent to the faulted margin, thinning towards the flexure. Accommodation space increases during a period of tectonic activity (subsidence and uplift) and decreases as sediments fill the void

vii) The East African Rift Basins contain a variety of interacting clastic depositional systems which differ to that seen in the CIB deposits (Fig. 6.2). Some are dominated by deep lakes that occupy the majority of the basin depocentre, others contain lakes and fluvial systems the positioning of which are influenced by extrinsic factors. Other rift basins hold small, shallow lacustrine environments, which interfinger with minor alluvial fans situated at the faulted basin margins. This latter situation shows similarities with the playa/alluvial fan interactions at the northern margin of the CIB (Chapter 3)

viii) Frostick & Reid (1990) stated that the African rift basins offer a potential for the accumulation of strata-bound economic resources that have not been fully investigated. From further understanding of the depositional models within these rift basins, it will be possible to model and locate potential sites containing heavy minerals and evaporate deposits as well as useful reservoir rocks.

6.2.2 The Rio Grande Rift

6.2.2.1 Introduction

The Rio Grande Rift is a major rift zone in Western USA starting in the central Colorado Rocky Mountains and running southwards through the states of Colorado and New Mexico, finishing in Mexico. It is a modern rift zone which is normally divided into three for research purposes; northern, central and southern regions (Chapin, 1979). Each region is composed of a number of small rift basins that as a whole make up the rift zone 400 km in length and <100 km wide (Fig. 6.2), with the Rio Grande River flowing axially through the rift zone.

This rift zone is used as a comparison because it enables us to observe modern day processes and depositional environments interacting in half-graben rift basins contrasting to the CIB, East African Rift and the Gulf of Suez/Red Sea Rift. Among the differences are the synrift fill, basin linkage and size of the rift system itself (Fig. 6.2).

6.2.2.2 Geological History

The size and nature of the Rio Grande Rift Basin, despite being smaller than the East African Rift, means a description of the geological history would be on epic proportions. Instead, for the purpose of this case study, it is necessary to study one area in detail – the area of southern New Mexico in the USA (Fig 6.9).

Crustal extension in this area of the Rio Grande Rift initiated in early Oligocene time, continuing to the present day (Mack et al., 1994; Mack et al., 2002). Uplift of the granitic and metamorphic Caballo Mountains and Black Range in the latest Oligocene produced a small rift basin by the name of the Palomas Basin. After readjustment by pulses of tectonism during the latest Miocene and early Pliocene, fault blocks uplifted and created raised topographic mountain landscapes. It is these areas of high relief that flank the modern day Palomas rift basin.

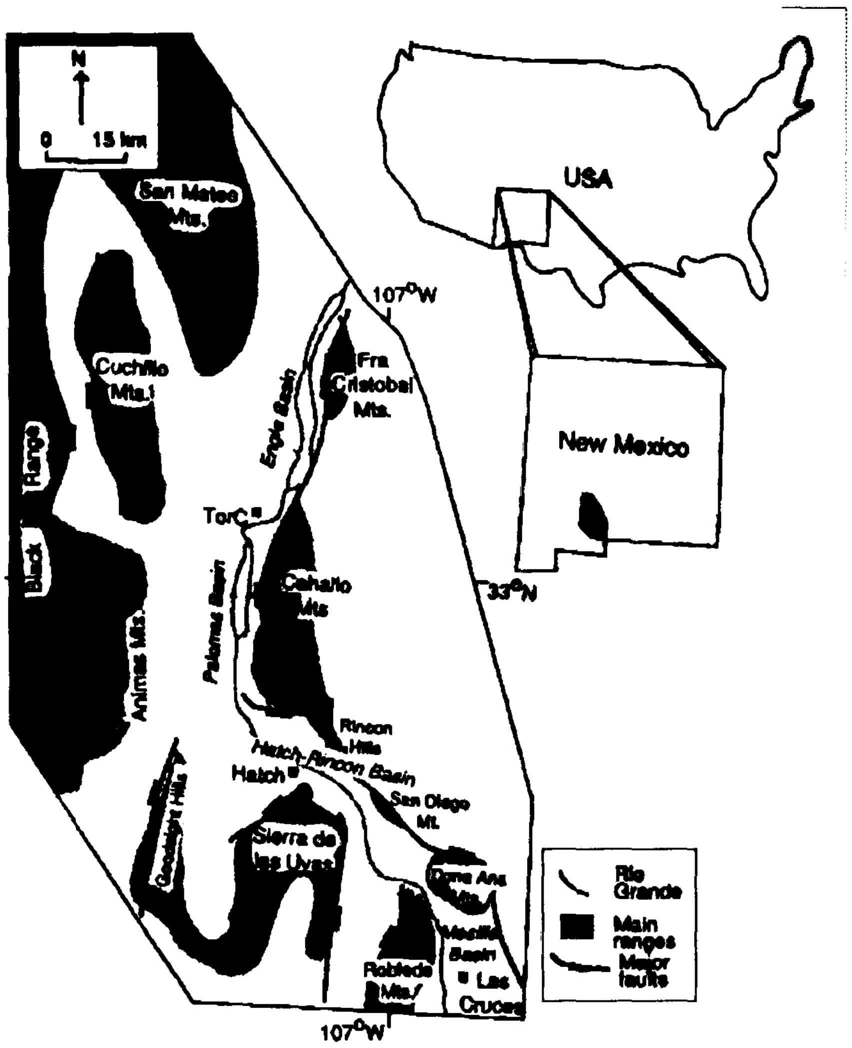


Fig. 6.9: Location map of the Palomas Basin within the Rio Grande Rift, USA (after Leeder et al. 1996).

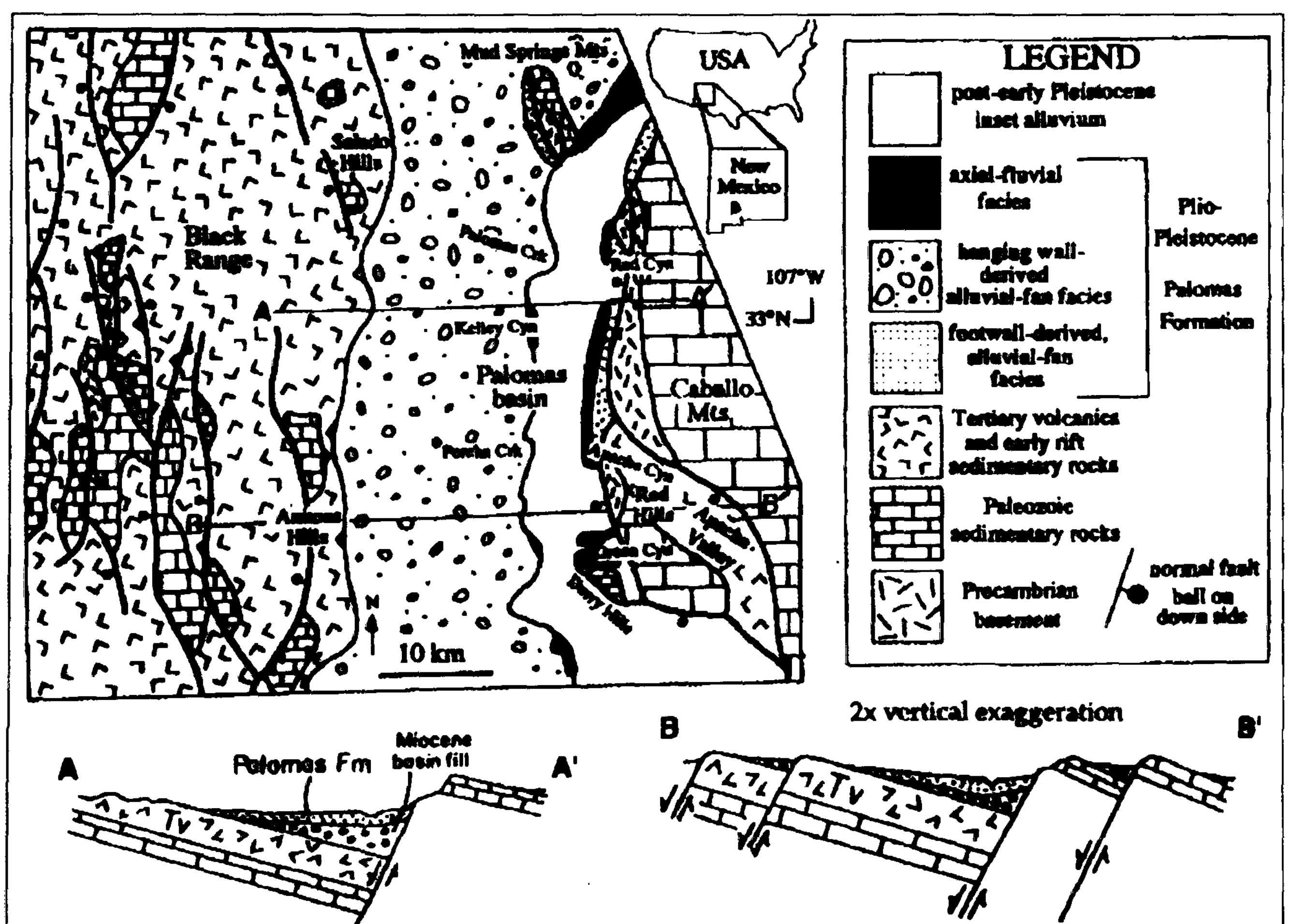


Fig. 6.10: Plan view map of the stratigraphy and structure of the Palomas Basin (after Mack et al., 2002).

The Palomas Basin is an east tilted half graben, 40 km long and 25 km wide, with a basement composed of Proterozoic granites and metamorphic rocks as well as Palaeozoic carbonate and redbed sediments and volcaniclastics (Fig. 6.10). Formign the margins of the Palomas Basin are a series of normal faults, with what Chapin (1979) termed 'domino-style' normal faulting similar to margins of the Edward-George Basin in the East African Rift (Lœrdal & Talbot, 2002). These are active and have experienced 30m of post-early Pleistocene displacement and several metres of Holocene offset (Mack et al. 2002). The basin margins are composed of a series of normal faults that link to form lineated footwall fault zones and well established relay ramp structures influencing drainage to the hangingwall block of the basin.

Deposited within this basin is hundreds of metres of basin fill which has been dated as Pliocene-early Pleistocene by vertebrate biostratigraphy, radioisotopic dating of interbedded volcanic rocks and reversal magnetostratigraphy (Mack & Leeder, 1999). This basin fill consists of alluvial fans, fluvial deposists, aeolian deposits and palaeosols, as well as sediments from the ancestral Rio Grande River running through the rift zone. The faulted margins were active during deposition and have a strong influence on the footwall and hangingwall derived fans, but less so on the axial fluvial systems which occupy basin depocentre positions. An asymmetrical distribution of the fluvial and alluvial systems in the basin is consistent with models of tectonic control on half graben rift basins in the literature (e.g. Frostick & Steel, 1993; Gawthorpe & Leeder, 2000). It is the interaction of these systems, and the constraints acting upon them, which provides interesting information on the style and nature of recent sedimentation within a rift basin.

6.2.2.3 Key Findings

A selection of studies (Chapin, 1979; Leeder & Jackson, 1993; Mack et al. 1994; Leeder et al. 1996a; Leeder et al. 1996b; Mack & Leeder, 1999; Perez-Arlucea et al. 2000; Leeder & Mack, 2001; Mack et al. 2002) has addressed the implications derived from the Rio Grande rift and, in particular, the Palomas Basin which is just one small half graben basin in the rift zone. Similarities with the research carried out on the CIB have been tabulated (Fig. 6.2) and are summarised as follows.

i) The Palomas half graben rift basin, has an asymmetrical pattern of sedimentary fill dominated by footwall-derived alluvial fan and axial fluvial sediment, and a broad belt of hangingwall-derived alluvial fan sediment (Fig. 6.11)

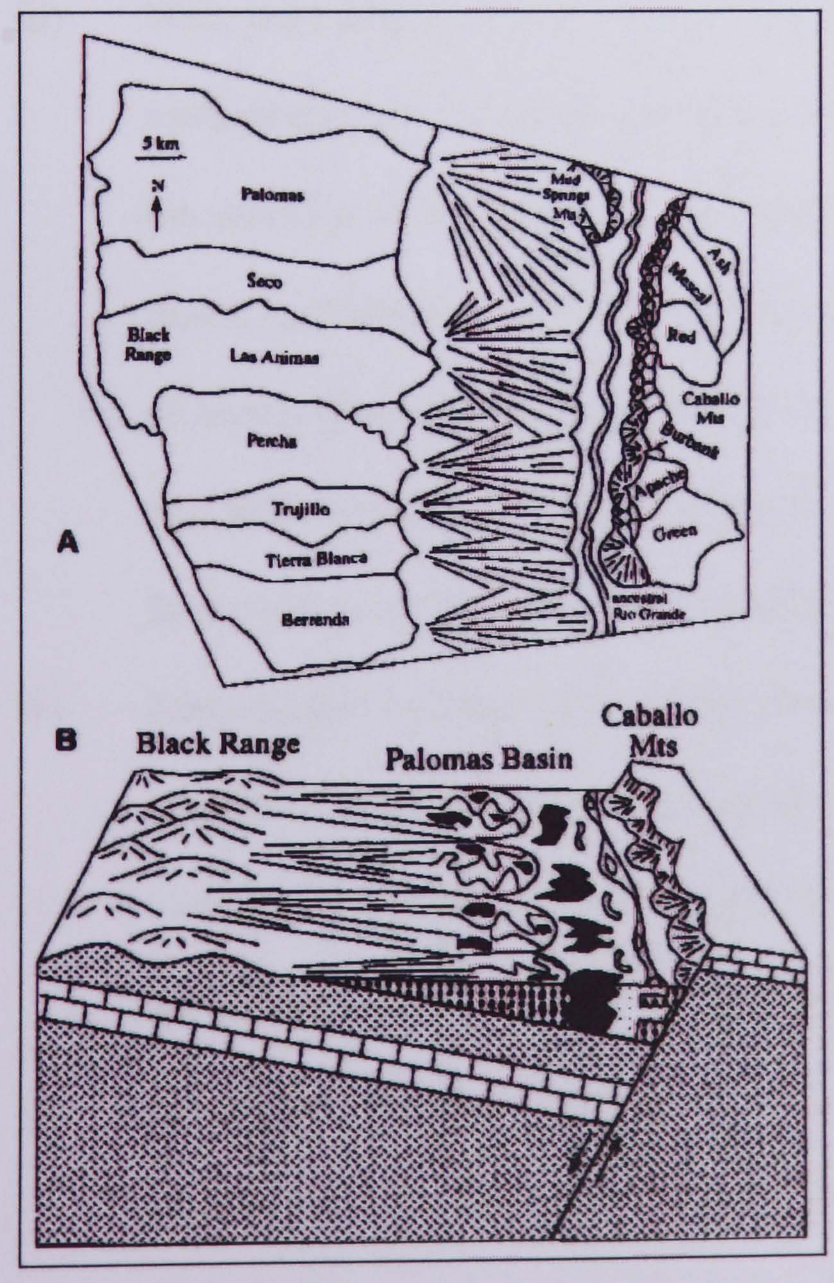


Fig. 6.11: A) Plan view geomorphological map of the depositional systems in the Palomas Basin. B) Cross section through the Palomas Basin showing the asymmetric geometry of the basin (after Mack et al., 2002)

ii) Northern areas of the Palomas Basin show signs of basinward propagation of both footwall and hangingwall alluvial fan deposits (Mack et al., 2002). Fault migration and propagation lead to uplift, erosion and resedimentation of the previous sedimentary infill, outward flux from structurally controlled catchments influenced by lithology and runoff. Tilting of the basin floor exacts a major influence on the drainage systems throughout the basin and in many cases dictates movement and pathways of depositional systems. A similar reaction to basin floor tilting occurs in the CIB, described in Chapter 4, where the fluvial system running axial along the basin switched its form between braided and meandering according to the gradient of the basin floor.

iii) Wide fault offsets in the footwall blocks encourage large drainage catchments from which flux initiates. It is this drainage that determines the synrift architecture of the sedimentary infill, such as in the Palomas Basin. In particular, axial drainage from a basin can alter once tip zones of normal faults breach and form a transfer zone or relay ramp which acts as a guide for the axial fluvial system to follow (Fig 6.12) comparing favourably with the CIB internal drainage patterns (Chapter 4 and Fig. 6.2)

iv) Footwall derived alluvial fan facies resemble the product of gravely bed streams deposited primarily in channels rather than by debris flows and or sheetfloods. Cyclothems are recognised within the fan sediments which are envisaged to be a result of 150 ka palaeoclimatic cycles

v) Axial fluvial sediments occur as channelised pebbly sandstones with local clast provenance. Detailed sandbody architecture is multi-storey and indicates low sinuosity braided channel-belts which traversed into well-established floodplains. An abundance of scoured surfaces on these sandstones implies frequent lateral combings and avulsions by the channel belt.

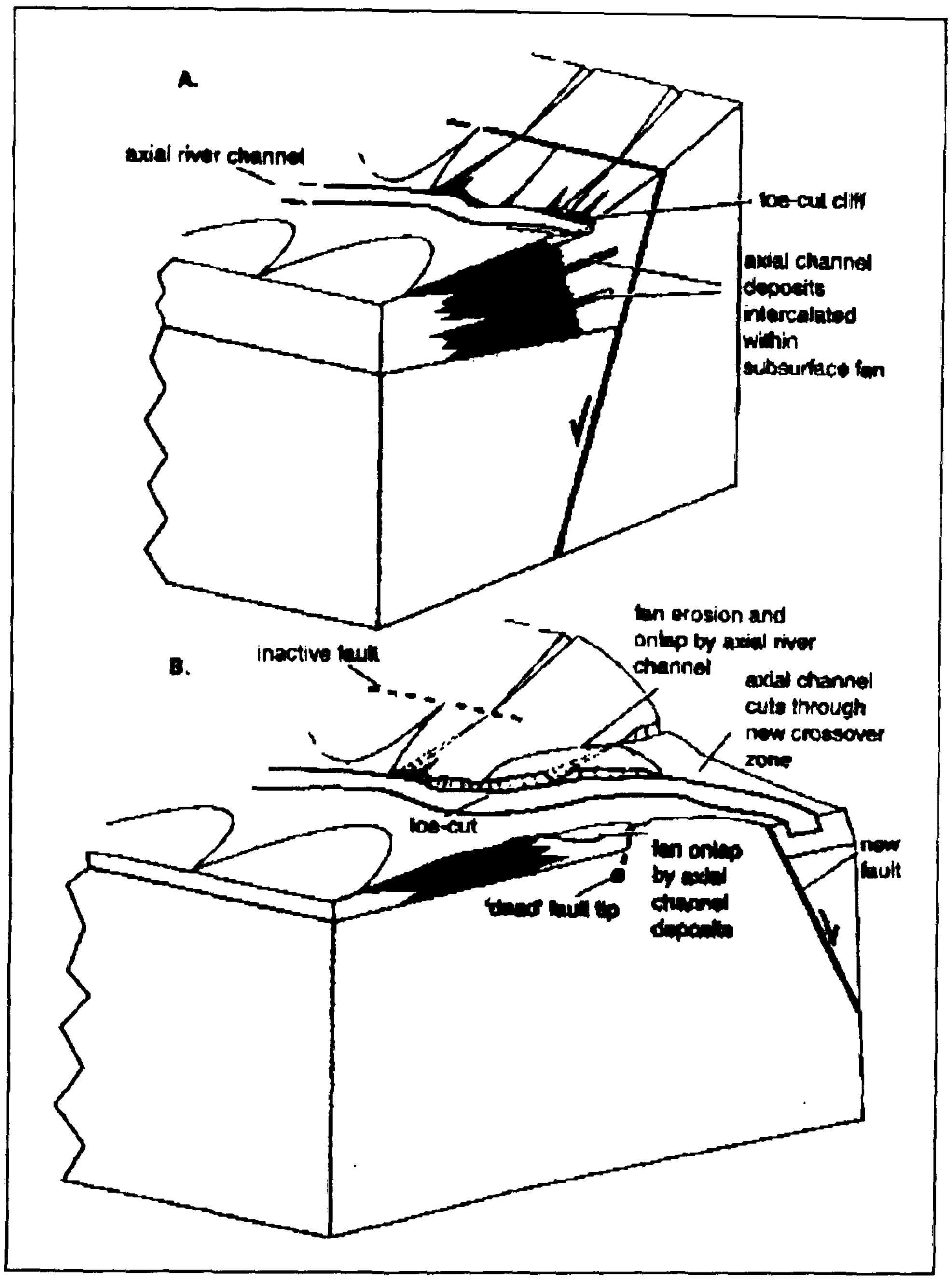


Fig. 6.12: Block diagram showing the development of an active rift basin margin (A) and the result (B) after the death of boundary fault systems (After Leeder & Mack, 2001).

vi) Lateral shifting of the fluvial depositional system occurred due to periodic fault movement and tilting of the basin floor in the direction of the footwall block, whilst restricting the amount of sediment transferred towards the distal portions of the basin margin-hugging alluvial fans. Toe-cutting of the distal fan areas (Fig. 6.12) occurred as a result of river channel migration towards the footwall block, rather than avulsion of the channel belt onto a horizontal basin floor surface

vii) Whereas tectonism has controlled the positioning and overall directional evolution of the sedimentary fill, climate is the overriding factor that influences internal sedimentology. The southern Rio Grande climate is semi-arid, as was the CIB climate, and fluctuations in sediment flux are potentially associated with climatic oscillations. In particular, the presence of calcic palaeosols across abandoned fan surfaces suggests periods of non-deposition and exposure followed by a flooding. Similar flood events and periods of non-deposition across fan surfaces occurred at the northern margin of the CIB (Chapter 3)

viii) Interaction between axial and transverse depositional systems occurs in the Palomas Basin reflecting allocyclic controls of climate and tectonics (in the form of basin floor tilting and fault propagation).

6.2.3 The Red Sea Rift

6.2.3.1 Introduction

The Red Sea Rift is an important rift zone formed as a result of north-eastwards separation of the Arabian Plate and the African Plate during the Palaeogene-early Neogene (McKenzie et al., 1970). In the north west of this zone lies the Gulf of Suez (Fig. 6.13), a rift setting displaying interaction between extensional tectonics and continental and marine sedimentation similar to the CIB. In comparison to the previous two case studies from the East African Rift and the Rio Grande Rift, the formation of this rift zone is associated with minor amounts of volcanic activity (Khalil & McClay, 2001) and styles of synrift fill comparable with the CIB (Fig. 6.2).

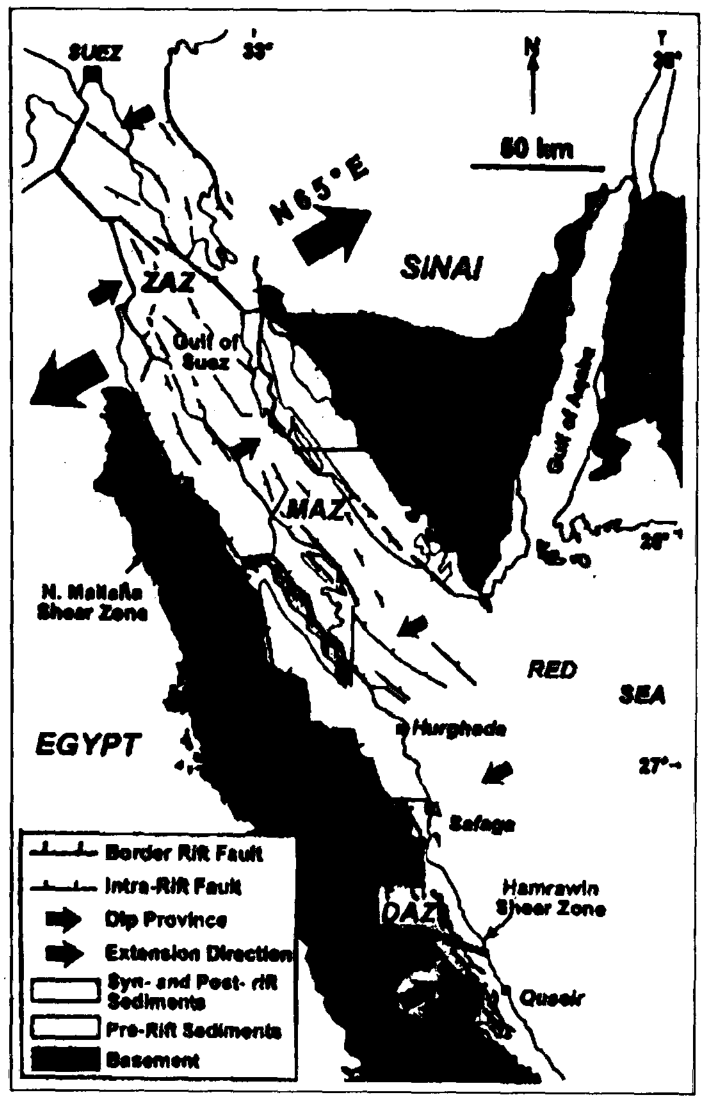


Fig. 6.13: Location map of the Red Sea Rift/Gulf of Suez (taken from Khalil & McClay, 2001).

6.2.3.2 Geological History

Up to 300 km in length and 80 km wide, the Gulf of Suez Rift is located in the NW-SE trending arm of the Cenozoic Red Sea rift system. It formed as a result of late Oligocene-early Miocene crustal extension in an ENE-WSW direction. Dominant extensional faulting trends are NW and WNW which, in part, reflects the pre-existing basement fabrics and also the effect of Pan-African shear zones. The margins of the rift basin are made up of several large-scale, normal fault systems which delineate classic half-graben style tilted fault blocks, up to 20 km wide (Bosworth, 1995; Bosworth & McClay, 2001; Kahlil & McClay, 2001; Jackson et al. 2002). Faulted blocks throughout the basin, and the associated normal faults, change polarity along axis of the rift and segment the rift into different dip provinces, of which one example is the Hammam Faraun fault block, existing in the central dip province. Occupying a position in the footwall of the west of this fault block, a structure known as the Hammam Faraun fault, sits the East Tanka Fault Zone (ETFZ)

(Fig. 6.14) (Sharp et al. 2000; Jackson et al. 2002). The ETFZ is a 3.5 km long normal fault zone composed of NW-SE trending normal fault segments and

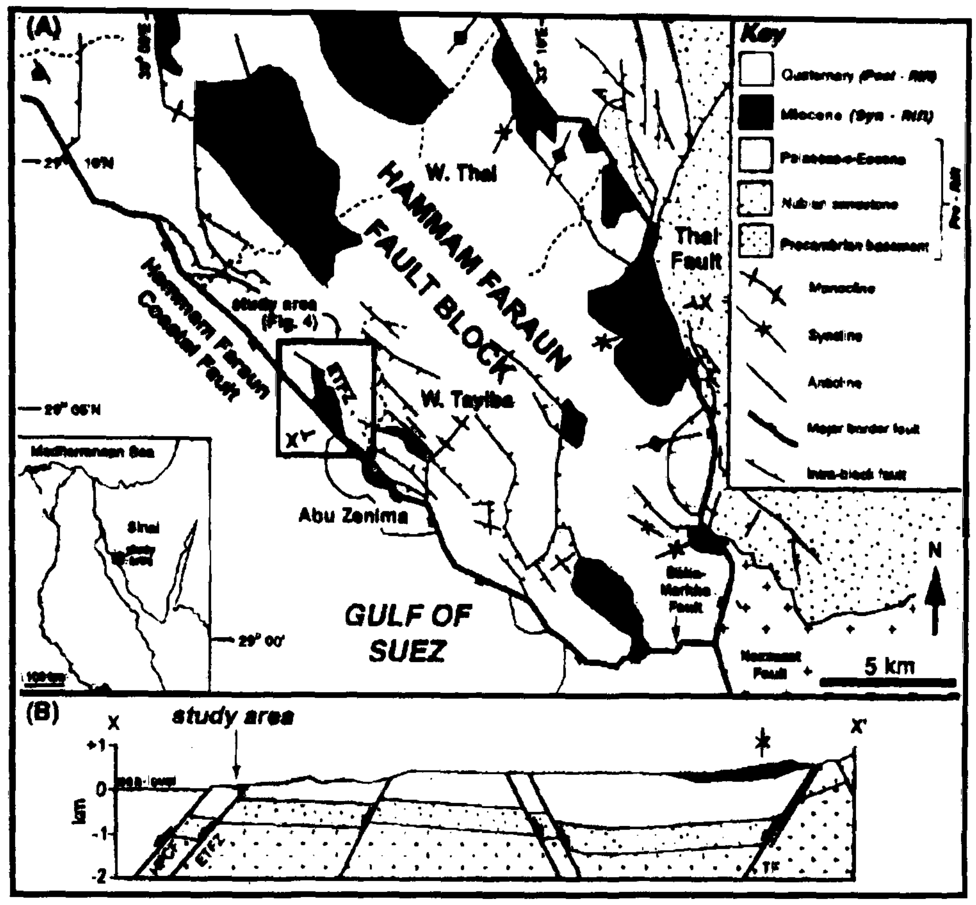


Fig. 6.14: Structural map (A) and cross section (B) of the Hammam Faraun Fault Block in the Gulf of Suez (taken from Jackson et al. 2001).

N-S trending alternative segments. Along strike the fault segments branch, link up or tip out, and folding in the hangingwall and footwall of the fault zone is common. The hangingwall is also dissected by a series of antithetic faults displaying displacement up to 5 m, and on larger-scale (<1.5 km) antithetic faults in the fault zone itself show up to 50 m displacement. It is this dissection and structural alteration of the stratigraphy and basin margin make-up that produces fault-parallel folding in response to lateral and vertical fault tip propagation, transverse folding due to along strike displacement variations and relay ramps (Fig. 6.15). Evidence of comparable intrabasinal and marginal structures exists in the CIB and can be related to this example (Fig. 6.2).

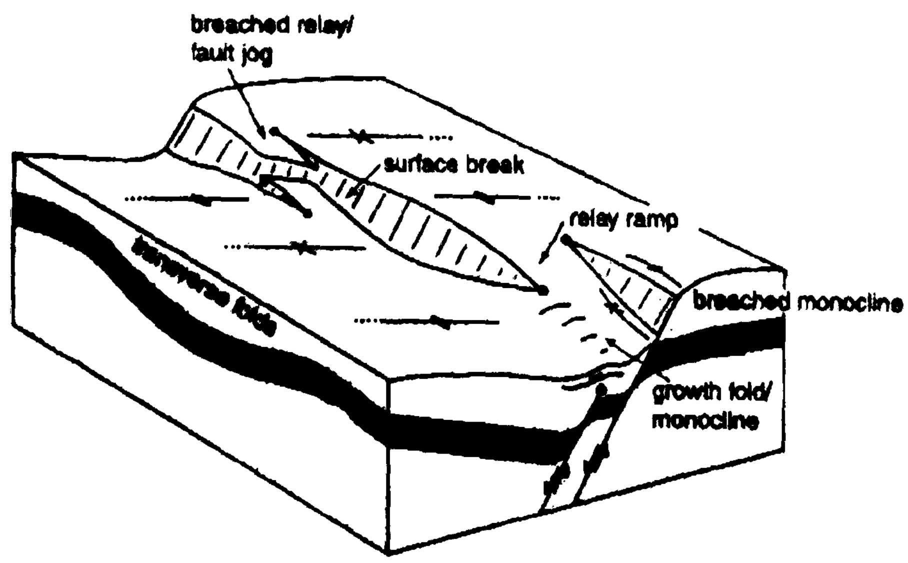


Fig. 6.15: Schematic diagram showing the structure and tectonic features of a relay ramp and breached normal faults (after Jackson et al. 2001).

The basement rock of the Gulf of Suez rift, in the area of the ETFZ is composed of Eocene-Oligocene prerift strata of carbonates and sandstones. Unconformably overlying this is a synrift succession that can be divided into three main depositional units according to flooding surfaces and sequence boundaries; continental deposits, tidally influenced sediments and shallow marine sandstones. The thickest successions are found close to the hangingwall fault, with thinning of the succession as it moves away parallel to strike.

The continental deposits are made up of red siltstones, discontinuous calcrete horizons, channelised sandstones and rippled sandstones interpreted as a broad, shallow, braided fluvial system within a semi-arid, poorly vegetated floodplain (Jackson et al. 2002). The fluvial deposits pass up into proximal alluvial fan facies composed of trough cross-bedded conglomerates. In total, there were two fluvial depocentres located in the hangingwalls of the normal fault segments, one axially along the faulted basin and one perpendicular to the fault zone.

A transgressive surface defines the boundary between the underlying continental deposits and the overlying succession of bi-directional rippled and planar cross-bedded sandstones, green mudstones, oyster debris and bioturbated beds. The lithofacies represents a tidally-influenced depositional system, with tidal flats and channels. Stratal thinning is observed and accommodated by low angle onlap surfaces, intraformational onlap, truncation surfaces and overstepping of the underlying continental deposits.

Mudstones and laterally persistent sandstone bodies represent the third depositional unit within the synrift fill and overlie a marine flooding surface sequence boundary. This interval is also thickest in the hangingwall areas of the fault zone and thins away from the margin. The mudstone is generally green and bioturbated and indicates deposition in an offshore marine environment. The sandstone bodies within the succession are trough cross bedded and contain an ichnofabric of *Ophiomorpha* and *Thalassinoides* indicting a lower shoreface environment during deposition with some high energy tidal action that affected the sediments periodically (Jackson et al. 2002). This is very similar to the CIB where trace fossil of *Thalassinoides* are found on the base of many sandstone units.

6.2.3.3 Key Findings

The Gulf of Suez Rift in the NW Red Sea Rift zone provides superbly preserved examples of the interaction between sedimentation and tectonics. A number of key discoveries have been made regarding the nature of tectono-sedimentary deposition along the Gulf of Suez Rift, in particular the East Tanka Fault Zone (ETFZ):

i) The NW Red Sea area incorporating the Gulf of Suez is an example of a non-volcanic rift, with only a few insignificant late pre-rift to early synrift basinal dykes and basaltic flows

ii) Initial rifting in the Gulf of Suez acted under the influence of strong basement fabrics disguised underneath pre-rift successions of sedimentary fill. Extension of the rift basin was directed ENE-WSW resulting in fault orientation running approximately NW-SE in the form of segments and titled blocks. With further extension, rifting focused on the areas towards the centre of the basin

iii) Individual normal faults delineated the fault blocks and often showed strong segmentation and soft linkage in the form of relay ramps. These zones of soft linkage developed into hard-linked transfer faults giving rise to a strong rhomboidal fault arrangement to the rift, a structural pattern mirrored in the CIB

iv) Thickness and facies variations within the syn-tectonic strata allow insight into the spatial evolution of the fault zone at particular stages of its development. Overlying deposits reveal that following rift initiation hard linkage of the ETFZ occurred as a result of influential transfer faults traversing the fault zone, forming a larger fault

v) The entry points of sediment flux to the basin, especially during continental deposition are controlled by the spatial and temporal physiography of the rift basin. A link between basin physiography and fault-related subsidence and uplift can be made as the latter two are thought to be first order controls on topography around normal faults and encourage growth and propagation of individual faults. Transfer zones and relay ramps created along basin margin fault arrays are considered important flux pathways to a rift basin, a point further highlighted along the northern margin of the CIB (see Chapter 3). However, the structure of the ETFZ linked and diverted drainage away from the transfer zones ensuring starvation of the hangingwall depositional areas and an absence of long-lived sediment routing systems

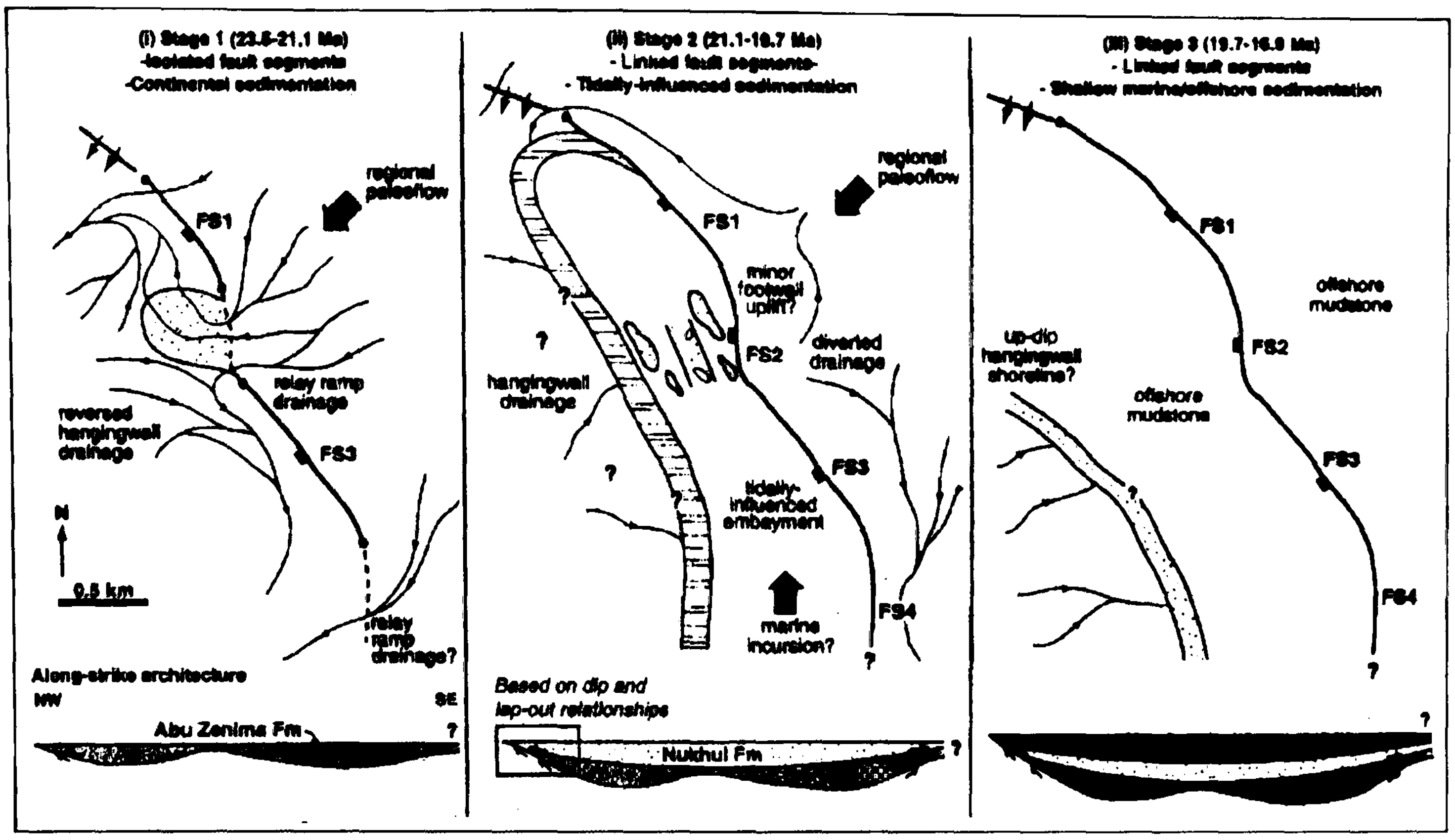


Fig. 6.16: Evolution of depositional systems along a faulted margin in the Gulf of Suez (taken from Jackson et al. 2001).

vi) As observed in Fig 6.16, drainage in both continental and marine settings within the rift basin is influenced by the structure of the fault zone and has repercussions on the geometry of fill in the basin. A clear thinning on the synrift fill is observed away from the hanging wall faults, parallel to strike, before the whole surface is flooded in a compete marine transgression. Variations are also observed along strike of a fault zone where observations from authors such as Gawthorpe et al. (1997) suggest stratal surfaces and facies stacking patterns, in depositional sequences located along normal fault zones, show disparity.

6.3 Conclusions and key findings

Examination and comparison of the three modern day rift settings with the CIB has revealed a series of similarities that can help us interpret the ancient synrift deposits. Characteristics of basin geometry, size and structure, sedimentary depositional systems, volcanic activity and interconnectivity all correspond at varying levels of with the CIB (Fig. 6.2). For instance, the East African Rift, and its composite basins, is larger than the CIB, but fails to show abundant alluvial fan sedimentation along the faulted margins, forming a series of intrabasinal lakes and river systems instead.

Asymmetric basin fill is a common factor in all the rift basin examples as is the marked influence of normal faulting, especially along the extensional margins (Fig. 6.2). Basin boundaries are often composed of normal fault zones and these regularly influence the complexity of topography and nature of sedimentation. Depositional systems occupying the areas created by these faulted zones differ depending on climate and tectonics in addition to sea level and basement lithology. In many cases the occurrence of volcaniclastics, except in the Gulf of Suez/Red Sea Rift, is common along active rift margins, though this is less pronounced along the southern margin of the CIB. The resultant volcaniclastic basement strata provide an ideal source of debris and detritus for alluvial fan and fluvial systems.

Faulting in the rift basins significantly influenced drainage in the basin. Drainage in the East African Rift, for example, originates from adjacent basins through large-scale transfer zones. Marginal relay ramps, such as in the Red Sea/Gulf of Suez Rift, position flux according to the resultant tectonic topography (Fig. 6.15). Active tectonism is the cause of a migration of depositional systems around relief created in the Rio Grande Rift basins. All of these examples play a role in governing depositional style and drainage pattern, and it is possible to use our understanding of these settings to infer similar structures in the CIB. In particular, small marginal relay ramps existed during Permo-Triassic extension in the CIB and acted as 'sediment corridors' for clastic flux from uplifted catchments areas, analogous to Gulf of Suez/Red Sea Rift margins.

In terms of accommodation space and sediment supply, the three subject basins and the CIB show similarities in as much as accommodation space is available for the accumulation of sediments. However, there are different controls on the creation of accommodation, which vary according to the setting. A steady supply of deep marine sediments of the Gulf of Suez/Red Sea rift are deposited in space controlled by sea level and tectonically-controlled base level alterations. Therefore overfilling of the basin hasn't yet occurred. The East African Rift and Rio Grande Rift meanwhile both create less accommodation space despite sediment supply continuing at constant rates. This is seen as fluvial sediment aggrades in the basins as it keeps up with base level fall (though there is evidence for basin floor tilting in the Rio Grande fro toe-cutting of fans which shifts the pattern of deposition across basin).

The CIB experiences base level fall during the early stage of its evolution allowing the accumulation of alluvial fan and playa sediments, though later stages of basin evolution result in a decrease in accommodation space as the rate of base level fall slows. Longevity of sediment routing systems at the basin margin (see Chapters 3 and 7) ensured sediment supply continued into the Triassic, though rising sea level and a constant rate of deposition meant the basin was choked by the Mid-Late Triassic.

The three rift examples show the dynamic relationships tectonics and climate have in extensional rift basins and the tectono-stratigraphic signatures that should be investigated to understand complete basin evolution. Cyclic sedimentation observed in modern-day Rio Grande Rift deposits are identified in CIB alluvial fan sediments and have led to the formation of an orbital forcing theory.

6.3.1 What the published literature does not demonstrate

Of the three rift basin examples (used in this chapter and summarised in Fig. 6.2) that are extensively documented in the research literature, very little is available on their direct comparisons. This is further reflected in the current models (e.g. Gawthorpe and Leeder, 2000) that tend to be selective rather than representative of understanding controls on sedimentation during active rift phases. This includes:

(i) A lack of detail about intrabasinal structures (see Chapter 4)

(ii) The impact of transfer faults on synrift sedimentation (Chapter 4)

(iii) The importance of climate in controlling sedimentation in rift basins (Chapters 4, 5 and 6)

(iv) Compartmentalisation and its impact on drainage and depositional systems, an important factor seen in the CIB (Chapter 4 and 5)

(v) Volcaniclatsics do not always have a marked affect on influencing post-sedimentation

(vi) Importance of catchment histories on determining basin fills.

Chapter 7

Discussion of climatic and tectono-sedimentary evolution of the Central Iberian Rift basin

7.1 Introduction and rationale

It is worthwhile at this stage to reconfirm why rift basins are important to study. The sedimentary fills and bounding tectonic structures of rift basins provide sinks with high preservation potential for sedimentary and fossil records of past changes in climate, sea/lake level and sediment/water supply. They also provide information on the growth, activity, decay and death of normal faults, vast economic reserves of hydrocarbons (as well as water and minerals), a record of early plate tectonic break-up, and a record of back-arc extension during cycles of plate convergence.

It is the purpose of this chapter to provide a comprehensive overview of the key aspects of the tectono-stratigraphic evolution of the Permo-Triassic Central Iberian Basin (CIB). In recent years the many studies documenting modern rift evolution has shed light on many key important processes and the effects of allocyclic controls on rift basin sedimentation. However, major gaps still exist in providing fully documented stratigraphic and structural studies of ancient rift basins and it is hoped that this study will allow further focus and highlight important key findings from the CIB.

The influence of tectonics and climate on depositional systems forming in the CIB is profound. Structurally-controlled marginal and intrabasinal areas are found to have a marked effect on the distribution of sediment supply. Climate acts as the overriding allocyclic control on sedimentation, especially at the margins where alluvial fans form, along which periods of quiescence correlate with timescales of orbital forcing. Whilst small-scale background signals, throughout the deposits, suggest tintinnabulation of geomorphological controls and morphometric parameters, complicating climatic and tectonic signatures within the CIB (Humphrey & Heller, 1995). The architecture of the CIB and especially the synrift fills was controlled by an ever interacting combination of allocyclic and autocyclic processes, as stated above. The fortuitous preservation of the synrift Permo-Triassic sediments in the CIB has enabled the detailed investigation of the important controlling processes on the drainage and depositional systems during a time of major continental break-up and global changes in climate. Implications can be drawn from the CIB and applied to similar, sub-surface, sequences (e.g. preserved North Sea synrift sediments) and serve to compliment and improve existing models of rift basins within the literature.

7.1.1 Current literature models on rift basin sedimentation

The most recent models dealing with rift basin sedimentation was produced in a seminal paper by Gawthorpe & Leeder (2000). It discussed the up-to-date thinking on sedimentation in continental and marine rift basins, also suggested stylistic models of the development in a series of depositional environments (Figs. 7.1 and 7.2). In addition to the tectono-sedimentary evolution of the basins in both marine and non-marine phase, the importance of basin linkage between faulted segments and the effect that has on controlling drainage within and between basins, has been widely documented.

Later stage development of a basin under marine conditions, such as that seen in the CIB is shown to result in a reduction in boundary fault activity, increase in baselevel and associated restrictions on drainage and depositional sedimentation. Figure 7.3 (see also Chapter 5) shows a basin model styled on the CIB to highlight the important features of this particular ancient rift basin. Whilst the Gawthorpe & Leeder models are comprehensive and raise some important issues regarding rift basin sedimentation, they cannot be applied to all rift basins especially in the ancient where we find evidence for contrasting controls on drainage, such as intrabasinal highs, tintinnabulation (Humphrey & Heller, 1995) and transfer faults. It has been one of the purposes of this study to illustrate that the CIB reveals that these current literature models are very 'fixist' and can not wholly be applied to ancient synrift basin settings.

7.2 Allocyclic Controls on synrift sedimentation

The most obvious and easily accessible setting for appreciating the effect of sediment supply, tectonism and basin geometry of synrift sediments is through the detailed evaluation of alluvial fans, fluvial systems and associated depositional systems that once occupied the CIB. These sedimentary systems clearly display the difficulties in differentiating between tectonic and climatic sedimentary signatures. Depositional style and architecture of sedimentary systems relies on the complex interaction of several controlling factors within a rift basin (cf. Frostick & Steel, 1993; Gawthorpe & Leeder, 2000), two of which, tectonics and climate, exert an important influence on the depositional systems of the CIB. The influence of a third allocyclic control is baselevel/sealevel change that will be briefly discussed later to provide a complete picture.

7.2.1 Climatic controls

The importance of climate on rates of sedimentation has been discussed throughout this study (Chapters 3, 4, 5, 6) and has provided evidence to suggest that episodes of

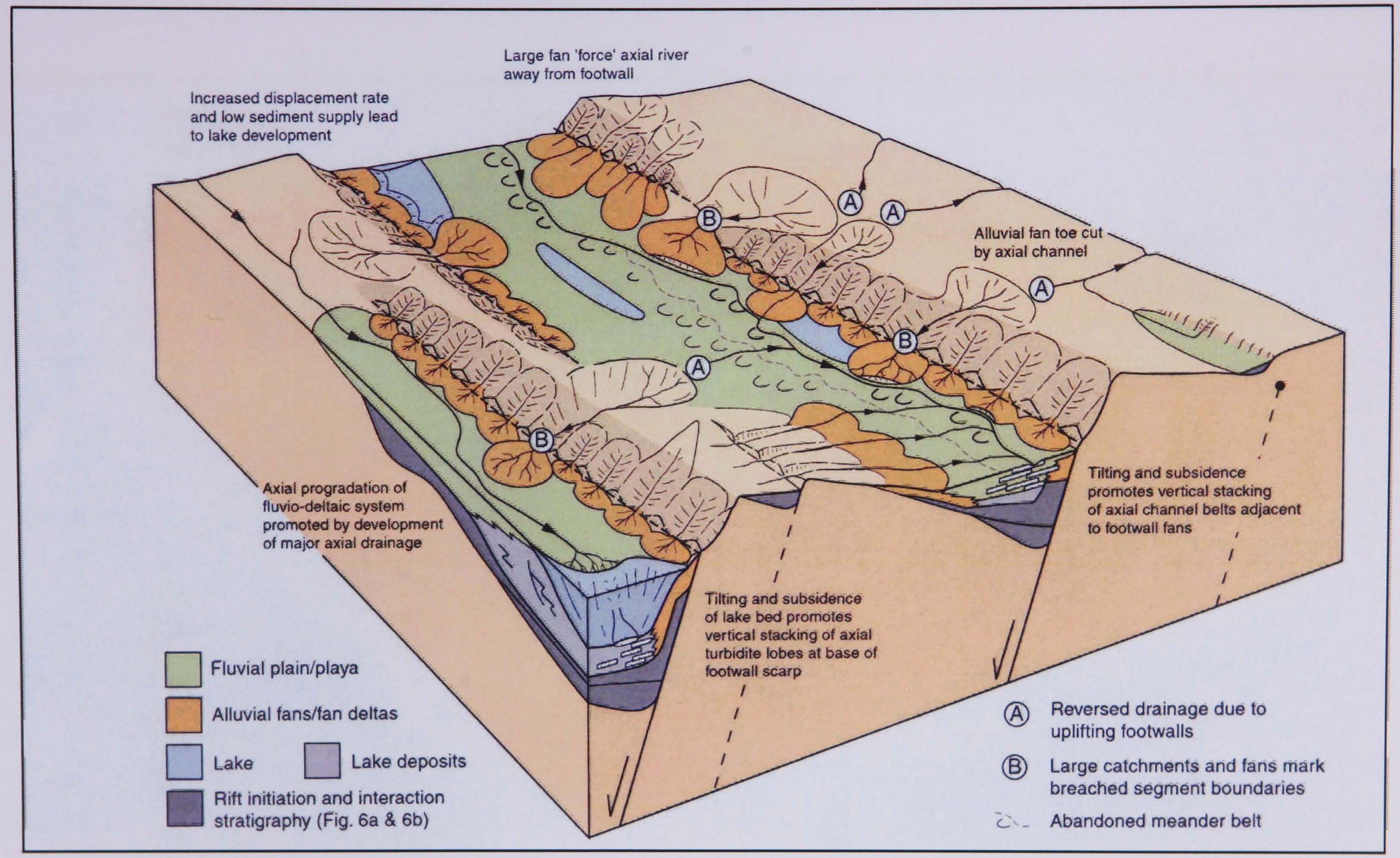


Fig. 7.1: Model of non-marine, continental synrift sedimentation (After Gawthorpe & Leeder, 2000)

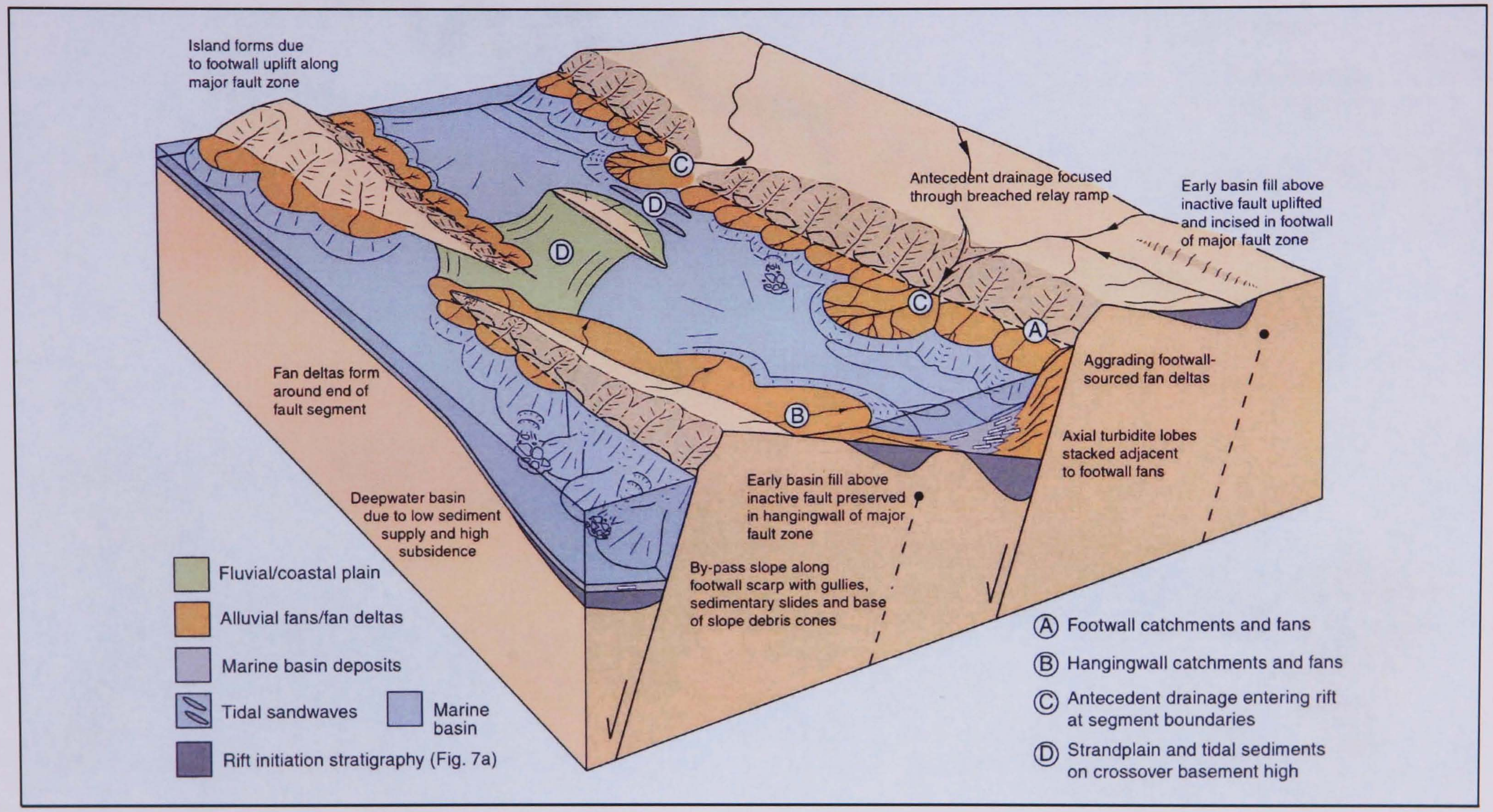


Fig. 7.2: Model of marine, continental synrift sedimentation (After Gawthorpe & Leeder, 2000)

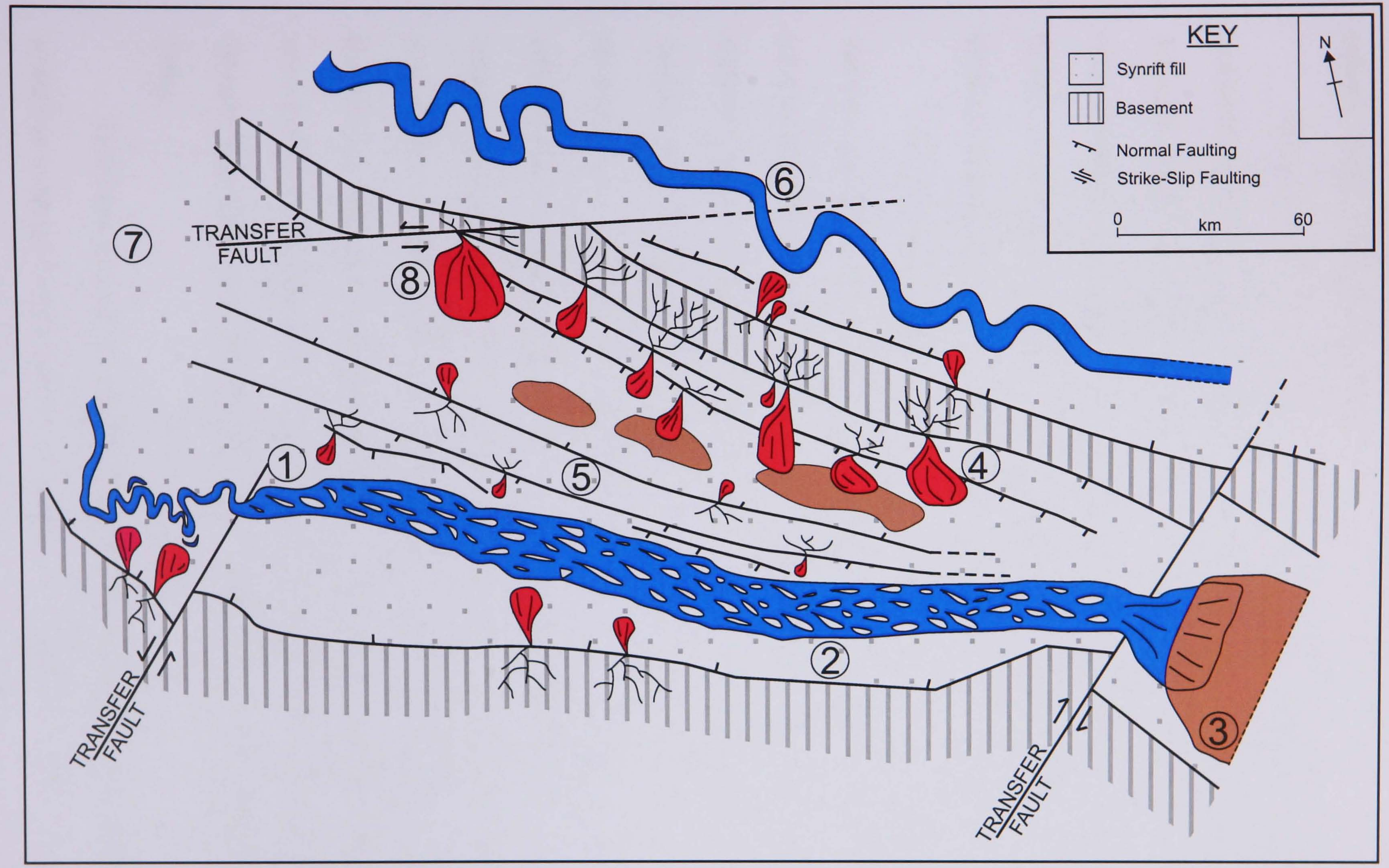


Fig. 7.3: Stylised cartoon map of drainage in a rift basin. Key to circled numbers: 1) Change in basin floor gradient across a transfer fault; 2) Dominance of axial fluvial systems; 3) Along basin influence of transfer faults; 4) Relay zone controls of sediment flux; 5) Intrabasinal structural partitioningand subdivision of depositional systems; 6) Axial fluvial dominance, breaching transverse structure; 7) Hinterland drainage control and uplift; 8) Transverse faults allowing drainage development.

sediment flux are related to climatic forcing, namely flood events in uplifted, external catchment areas entering the basin.

Reconciling the role of climate control on synrift sedimentation has featured previously in the literature (e.g. Humphrey & Heller, 1995; Leeder, 1997; Gawthorpe & Leeder, 2000) though these ideas are rarely applied to the ancient. Detailed study of the Buntsandstein and Muschelkalk facies deposits in the CIB allows us to reconstruct the fill history and analyse the effects of climate on marginal and intrabasinal depositional systems, as well as in basins adjacent to the CIB.

The CIB was located approximately 35° N of the Equator during the Permo-Triassic according to palaeomagnetic and palaeogeographic data (Ziegler, 1988), and palynological studies (Doubinger et al., 1990) elsewhere along the Iberian Ranges show the CIB was a warmer, drier environment during the Late Permian-Early Triassic. Dry and rainy seasons in a semi-arid environment alternated during the development of depositional systems along the basin margin and Permo-Triassic palaeowind circulation, proposed by Kutzbach et al. (1990) detailed the presence of westward equatorial flow, Tethyan boundary currents and eastward winds (though it is not determined at what latitude). Under eastward, low latitude winds, a substantial level of orographic rainfall would occur on upwind slopes and rain shadows on the areas downwind of high relief and vegetation in the drainage areas and basin substrate would have been minimal during the dry season (Arche & López-Gómez, 1999).

Tectonic activity is commonly held responsible for abrupt coarsening and control on sediment flux for alluvial fan sequences, with the role of climate often neglected. Permo-Triassic alluvial fans along the northern margin of the CIB indicate clearly the problems of differentiating the sedimentary signatures of climatic and tectonic adjustments.

The dominant seasonal character of the CIB and lack of vegetative cover on the catchment areas during arid phases increased sediment yield and resulted in flashy runoff episodes, similar to that experienced in the Gulf of Suez/Red Sea region and the East African Rift (Chapter 6). Sediment flux to the basin occurred as large flows and floods of pebble-sized clastic material forming alluvial fans. The boundaries of each facies are sharp, laterally extensive, illustrate little or no reworking, and in turn, poorly developed palaeosols can be found draping over the coarse fan sediments. These characteristics cannot be easily explained by tectonic readjustment of the fan or drainage basin. It is clear that the coarse sediments were deposited by high magnitude, low frequency flood events controlled by climate and not by tectonism as indicated with other similar depositional systems, the Boniches Fm in the Iberian Basin for example (López-Gómez & Arche, 1997).

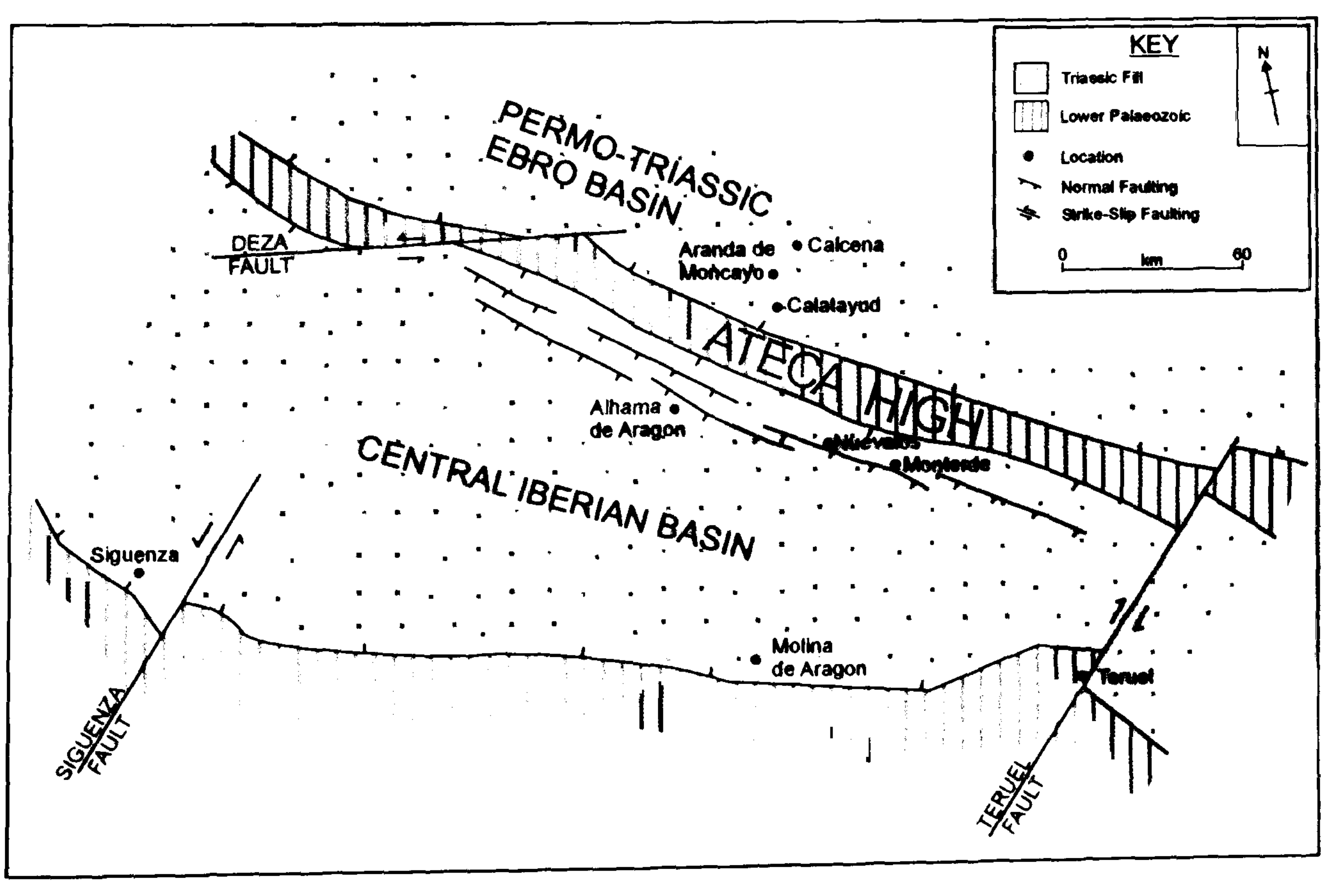


Fig. 7.4: Map of the CIB and Permo-Triassic Ebro Basin showing major faults and outcrop locations.

The coarse sediments originated from a source in the Ateca High flowing, according to palaeocurrent evidence, as southwards-directed transverse drainage across the basin margin (Fig. 7.4). An example of this is seen in the Monterde Fm (Chapter 3).

These thick units of high magnitude, low frequency coarse flux events were punctuated by periods of non-deposition when sedimentation across the alluvial fans was non-existent. Consistent with models of soil formation in semi-arid environments (Retallack, 2001), immature palaeosols formed. Field evidence in the Buntsandstein facies indicates the palaeosols were draped over the whole alluvial fan surface, suggesting prolonged intervals of quiescence on the fan surface occurred, during which deposition ceased, or 'switched-off' completely.

This sequence of repetitive coarse flux events interrupted by palaeosols in the alluvial fans can be used to identify periods of relatively 'wet' and 'dry' climate on the fans, a 'wet' period represented by a coarse conglomerate or sandstone unit and 'dry' by a soil horizon (Fig. 7.5). The palaeosols can also be used to infer Milankovitch timescales events (see section 7.2.2).

Evidence from outcrop suggests transverse clastic flux to the basin continued into the Anisian (Middle-Triassic) a period of at least five million years. The presence of climatically-controlled, delta lobe sandbodies and the longevity of such systems suggests sediment supply persisted throughout the Permo-Triassic. Periodic switching of prolonged events of non-deposition sustained during the formation of playa lake systems, occasionally experiencing interaction with distal fan facies.

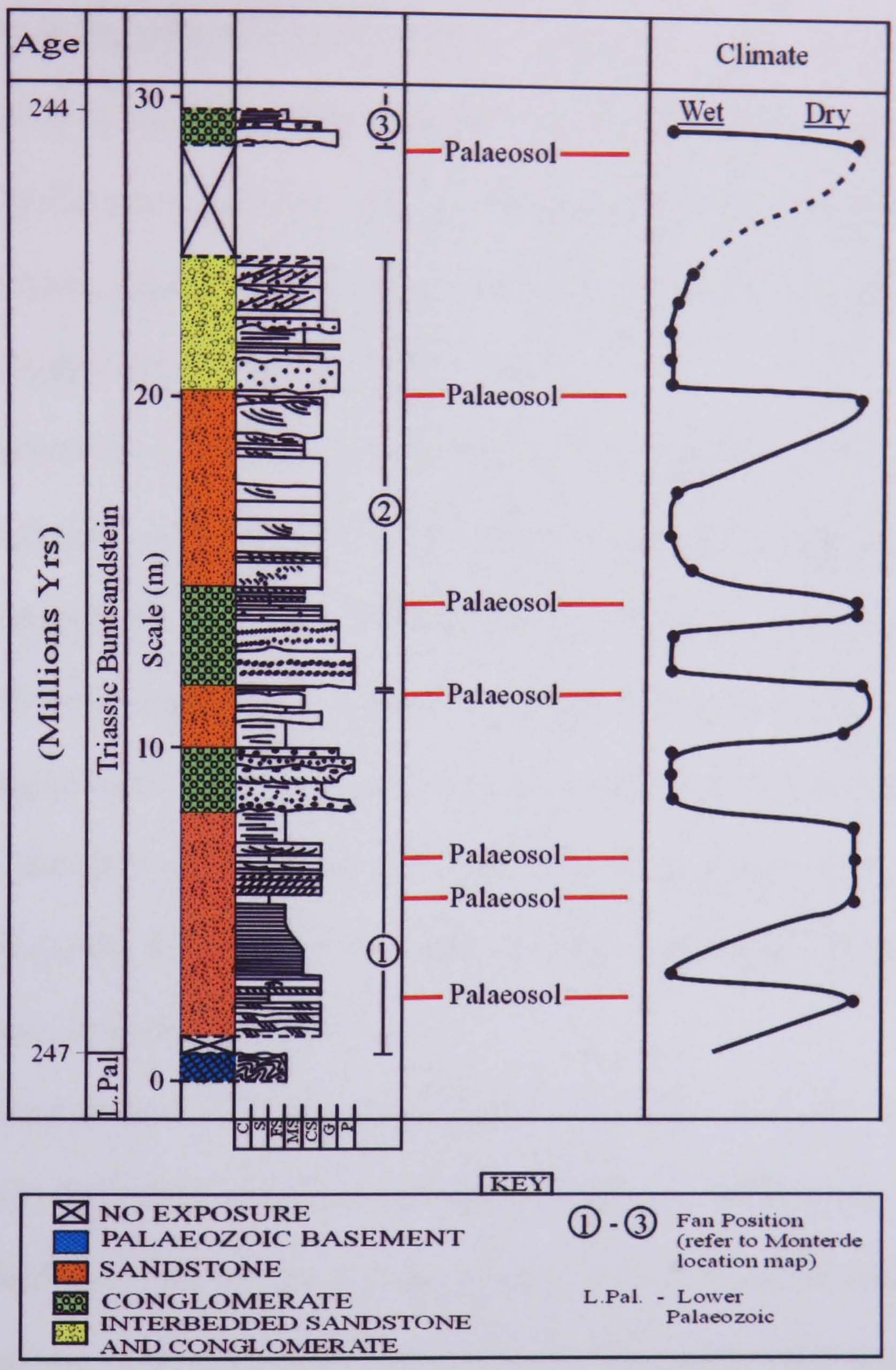


Fig. 7.5: Graphic log of the alluvial fan sediments of the Monterde Formation showing inferred relative climate during deposition and tentative Milankovitch timescales during non-deposition and corresponding palaeosol development.

Reconciling the role of climate on Buntsandstein sedimentation is essential to understand the process acting upon deposition and offers and insight into the control on sediment supply to the basin. The palaeoclimate experienced a warming and increased dryness from late-Permian to late-Triassic in the Iberian Ranges (Doubinger et al. 1990) resulting in red bed oxidation conditions characteristic of a semi-arid environment. During the Autunian (Upper Permian), sedimentation of the

Boniches Fm in the adjacent Iberian Basin to the SE acted under a humid climate with high levels of precipitation and non-calcic soil formation (López-Gómez & Arche, 1997). Gordon and Heller (1993) cite an increasing aridity of the climate as a function of increasing availability of coarse material to be incorporated into sediment supply, rather than tectonism-induced subsidence.

Sediment flux to the basin, transversely and axially, can be described as flashy, though Buntsandstein fluvial deposits show a degree of stability compared to the high magnitude fan sediments. Fluvial styles are attributed to tectonism (see section 7.2.3) but sediment yield is linked to seasonal character which runoff in a semi-arid region would be flashy and less competent (Arche & López-Gómez, 1999). Vegetation, though scarce and unknown in species, still existed and was often washed away by flood episodes to be preserved in the channels, confirmed by plant material discovered at Rueda de la Sierra.

The occurrence of halite pseudomorphs on the upper surface of Upper Buntsandstein facies beds within the Cercadillo Sandstones and Mudstones Formation and the Torete Fm, as well as the Alhama Fm in the northern margin fan systems suggests, in the opinion of Muñoz et al. (1992), an influx of saltwater and concentration of Halite crystals, with increasing evaporation. Therefore, evaporation presumably exceeded rates of precipitation as the presence of marine conditions and a form of coastal plain evolved. A meandering river system continued to flow into the westward advancing Tethys Sea meaning that drainage sourced from the west of the basin continued until complete marine flooding of all land surfaces.

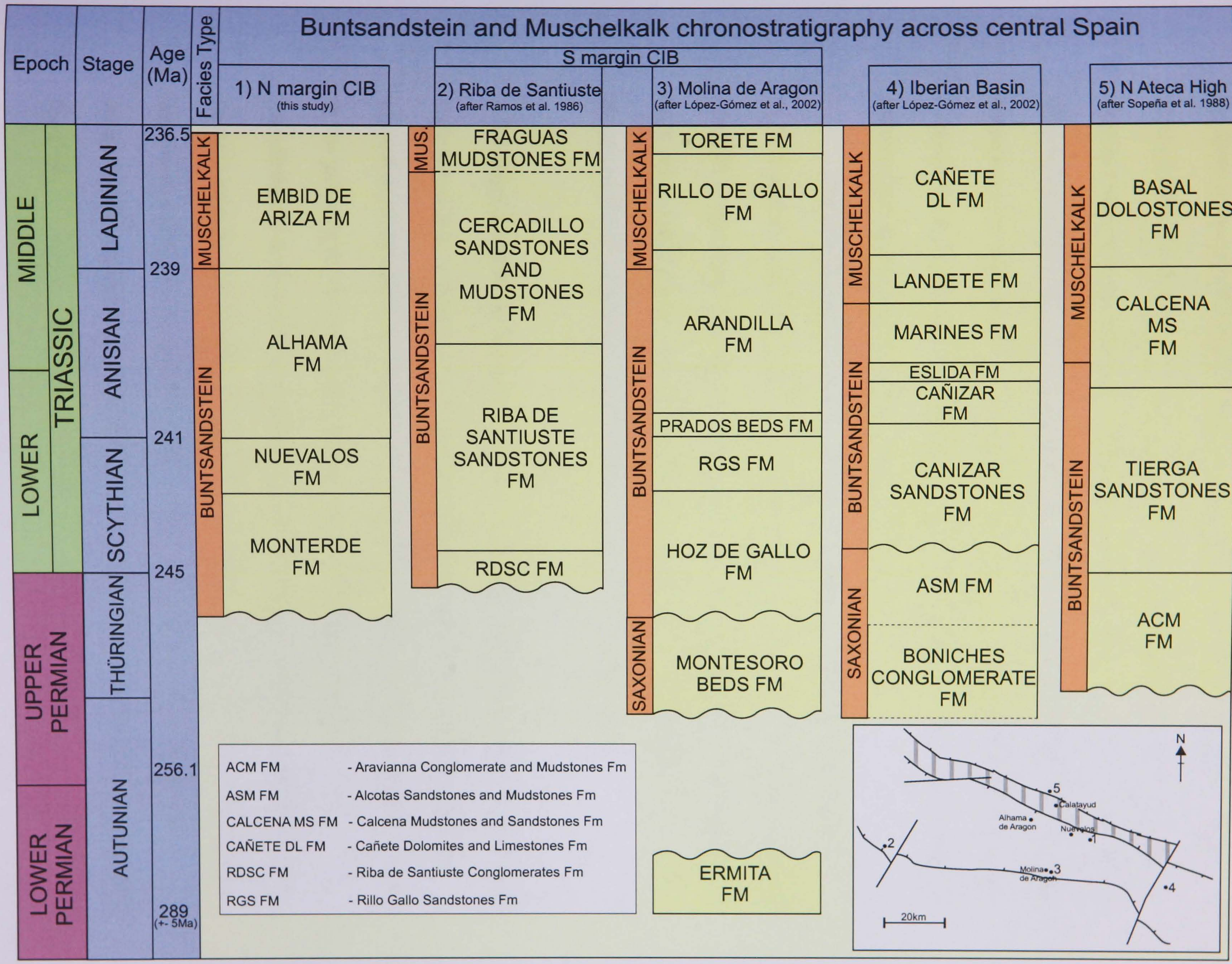


Fig. 7.6: Stratigraphic correlation table across the whole of the CIB, Iberian Basin and the Permo-Triassic Ebro Basin.

In keeping with the interpretation of increased aridity of the palaeoclimate in the Iberian Ranges during the Late-Permian and Early-Triassic, the Ebro-Basin showed little difference in climate. The sediments underwent deposition in a well-oxidised environment and slight varnishing of larger pebble-sized clasts occurred on alluvial fan sediments, a process presumably linked to wetting and drying of the fan surface during flash floods. A lack of sections available for detailed logging ensures analysis using Fischer plots is virtually redundant, offering very little in the way of information about accommodation space for example.

The fluvial system running axially along this basin originated from the W/NW and showed little difference sedimentologically than the fluvial sediments of the CIB, suggesting the drainage source was over similar basement catchments or both originated from the same area to the NW (now covered in postrift fill), somehow diverting around the Iberian Ranges into separate rift basins.

7.2.2 High-resolution terrestrial record of orbital climate forcing in alluvial fans

Astronomically calibrated pre-Quaternary terrestrial records of climate, with the exception of lacustrine proxies (e.g. Olsen & Kent, 1999), are not generally present in the geologically record. This omission results in a significant gap in our knowledge of ancient climate systems. Holocene high-resolution terrestrial climatic records have been obtained from fluvial sediments of the Maas valley, Netherlands. However, a tentative approach is applied of using cyclicty in alluvial fans to determine the climatic record for the early Triassic along the north eastern margin of the CIB.

The application of orbital forcing timescales, namely as Milankovitch cyclicity, in continental alluvial fan sediments relies on a number of assumptions. De Boer & Smith (1994) and House (1995) identified periodicities on Milankovitch scale and provided evidence that sediment flux and the climate controlling it was linked to orbital forcing. In the case of the CIB it is palaeosol horizons that are being used as marker horizons in a tentative theoretical experiment. The palaeosols must be laterally persistent and stratigraphically correlated across the whole fan surface and assurances need to be made that they record abandonment of deposition on the fan surface rather than switching. Only then can the application of orbitally-forced periodicity of fan sediments be applied and used as a high-resolution climate record.

The Monterde alluvial fan complex along the northern of the Iberian basin developed at the site of a long-lived sediment conduit, supplying sediment to the rift basin. The conduit was controlled structurally by the evolution of a relay-ramp. Within this conduit three phases of fan progradation have been identified. The bounds of each facies within the fans are sharp; stream dominated deposits are superimposed on finer grained flood plain sediments with little evidence of either reworking or loading and in turn, palaeosols, often with rhizoliths, can be found draping over much of the conglomerates and sandstones. These characteristics cannot be easily explained by tectonic adjustment of the drainage basin as it has already been shown that fault movement affects accommodation space and positioning of sediment pathways. So what did control flux to the basin and was there a reason for the periods of quiescence during which soils formed across the whole of the fan surface?

It appears the best explanation is that coarse sediment was deposited by discrete high magnitude flash floods controlled by the climate in this semi-arid environment. The intervening periods of non-deposition and exposure led to palaeosol development, which may or may not have been controlled on orbital-forced timescales. Further work is needed to determine the accuracy or indeed the validity of such analysis.

The margin of error on innovative methods such as this are high considering there is no absolute constraint on the upper and lower age dates of the sequence due to destruction of pollen and spores in red beds which would have been used for this purpose. However, palaeosol formation occurs as a continuous, traceable horizon across the whole surface of the fan and therefore switching of channels across the fan substrate cannot be used as an explanation for periods of non-deposition. Instead, there is clearly a climatic influence on sediment flux from source to sink, which can be interpreted from the resulting sedimentation, or lack of it.

The sedimentology of the lower 30 m alluvial fan sediments of the Monterde Formation was examined in detail though sedimentation rates were difficult to ascertain from outcrop studies. Age dates obtained from previous studies on the underlying basement rocks and upper contemporaneous sequences from the Triassic (López-Gómez et al. 2002) provide a timeframe in which the alluvial fan sediments were deposited. By counting the number of palaeosol horizons between these two age dates it could be possible to infer the number of times there was a period of quiescence at this particular location along the basin margin during this timeframe. The frequency assessment of a set number of palaeosols applied to the age range over a certain number of million years to deposit the sequence, results in periodicities that could potentially lie in the Milankovitch Band. It is suggested that these frequencies represent the stratigraphic expression of climatic perturbations related to orbital forcing and link to the length of time taken for the palaeosols to mature. This suggests the time taken for full soil maturity within continental alluvial fan deposits is at least the time length of the corresponding Milankovitch cycle (Fig. 7.2).

7.2.3 Tectonic controls

Despite the relatively large amount of literature on the role tectonism plays in shaping rift basins (e.g. Frostick & Steel, 1993, Gawthorpe & Leeder, 2000) there is still paucity when dealing with inferred tectonics in the ancient. Changes in overall accommodation space, basin floor tilting (internally and marginally), placement and size of depocentres, basin margin character and orientation, drainage and sediment supply are all influenced by tectonism during and after crustal extension. Many of these features are observed in modern analogues in the East African Rift, Rio Grande Rift and Red Sea locations and can be applied to the Permo-Triassic CIB to help understand synrift deposition and basin evolution (see Chapter 6). From these comparisons it is possible to analyse fully the effect tectonics has on depositional facies, in this case the Buntsandstein and Muschelkalk, in the CIB.

Hard and soft linkage of NW-SE orientated normal faults at the northern margin of the CIB, following breaching of the fault tips, occurred resulting in relay ramps and minor transfer zones. The geometry of the margin combines similar elements of the East African Rift basins (Gawthorpe & Hurst, 1993; Frostick, 1997) and the Rio Grande Rift Basin (Mack & Leeder, 1999; Leeder & Mack, 2001). In the

CIB we can observe the role structure plays on the positioning of sediment conduits along the basin margin.

The Buntsandstein and Muschelkalk deposits of the CIB situated up to 40 km along the palaeomargin, allow us to examine the switch from continental to shallow marine deposits in a half-graben rift basin setting. This is ideal for assessing the evolution of basin margin structures over the period of synrift sedimentation. It is clear that the high magnitude, low frequency alluvial fan flood events that exploited tectonically controlled conduits at the basin margin, continued to operate during sea level rise associated with the Tethyan transgression. Evidence from the sediments elucidates towards a gradual rise in sea level that drowned the alluvial fans and playa lakes, but failed to flood the hinterland drainage areas. This enabled climatically driven episodic flux of sediment to the basin to continue through the established conduits, forming shallow-marine delta lobe systems prograding towards the SE, before succumbing to eventual marine flooding of the hinterland. This demonstrates how sediment routing systems established along the northern margin of the CIB rift are persevered during a change in depositional environment.

Detailed study of the northern margin illustrates that a conduit providing sediment to an alluvial fan will continue to feed fluvial style delta lobe systems during sea level rise and will also influence the direction of drainage into the basin. This highlights the importance of longevity in routing systems at a rift basin margin and indicates that sediment corridors formed along relay ramp structures were maintained throughout the basin development during the Permo-Triassic and provided routing for the continued flux of sediment from the hinterland.

The CIB existed as a wedge-shaped half-graben rift basin undergoing active extension during the Permo-Triassic. The northern margin constituted a normal-fault zone, however major structural influences existed in many other regions of the basin. Mapped sediments across the 50 km wide basin reveals that alluvial fans and playa systems in the north failed to interact with fluvial systems running axially through the CIB simultaneously. There is not one exposure that suggests this interaction occurred despite field investigations and analysis of the thick sequences of post-rift fill. However, the lack of interaction and the proposed presence of an intrabasinal high, mean it can be elucidated that compartmentalisation caused the facies of the northern CIB and southern CIB to remain isolated from each other. An area of high relief was positioned normal to the basin margins in the centre of the basin - an intrabasinal high. This structure is related to uplift and internal faulting linked to structural rotation, natural topographic features or minor displacement from intrabasinal faulting. A barrier between depositional systems of the northern area and the southern areas, influenced by NW-SE faulting, existed in the CIB (Figs. 7.3 and 7.4) mirroring modern day examples such as the Newark Basin in the Basin and Range province (Anders & Schlische, 1994) and Edward Basin in the East African Rift (Lærdal & Talbot, 2002).

From extensive facies investigation it appears that drainage forming an axial fluvial system in the southern segment of the CIB entered the basin from an undefined north-westerly source area (NW of Sigüenza) and finished at an undefined location in the south east of the basin (SE of Molina de Aragon). Arche & López-Gómez (1999) describe "a narrow corridor" to the SE of Molina de Aragon connecting the CIB to the Iberian Basin, and aerial satellite mapping of the modern-day reactivated fault lineaments can identify this thinning of the basin towards the SE. Connectivity between basins is dictated by an important transfer fault, with dextral strike-slip movement, that runs N-S through the city of Teruel (Fig. 7.4). Development of the facies within these structures is linked to localised as well as regional climate change and explains the presence of perennial or even seasonal axial drainage and more episodic transverse drainage.

Synchronous N-S faults occurred along the southern basin margin to the immediate SE of Molina de Aragon and Sigüenza, but were discrete, resulting in relatively minor drainage barriers. They failed to span the whole width of the basin and it is likely base level altered in relief. This localised alteration in basement gradient, in response to transfer fault offset, is consistent with models of rift basin development from the East African Rift Basins (Chorowicz, 1990; Gawthorpe & Hurst, 1993; Frostick, 1997) where isolated basins, such as the Turkana Basin display connectivity with adjacent, but equally independent rift basins.

Having established that tilting of the basin floor occurs lengthways in the CIB, it is important to consider the expected tilt towards the southern margin also. Asymmetry of the fault block, linked to subsidence close to the footwall fault zone, accommodates thick units of Buntsandstein and Muschelkalk sediment due, in part, to margin-wards avulsion of the axial system where 'toe-cutting' of alluvial fans took place (Bridge & Leeder, 1979; Alexander & Leeder, 1987, 1990; Leeder & Mack, 2001). Transverse clastic flux to the basin in the form of small alluvial fans will have acted in the same manner as those at the northern margin, where structure was the primary control on positioning of sediment supply routes and climate on the internal sedimentology of the fans, and to avoid repetition will refer to the explanation s in this chapter.

However, axial tilt of the CIB has important implications, because it affects the depositional facies. Miall (1996) highlights the dynamic relationship between base level gradient and fluvial facies and sinuosity (Fig. 7.7), with low gradients

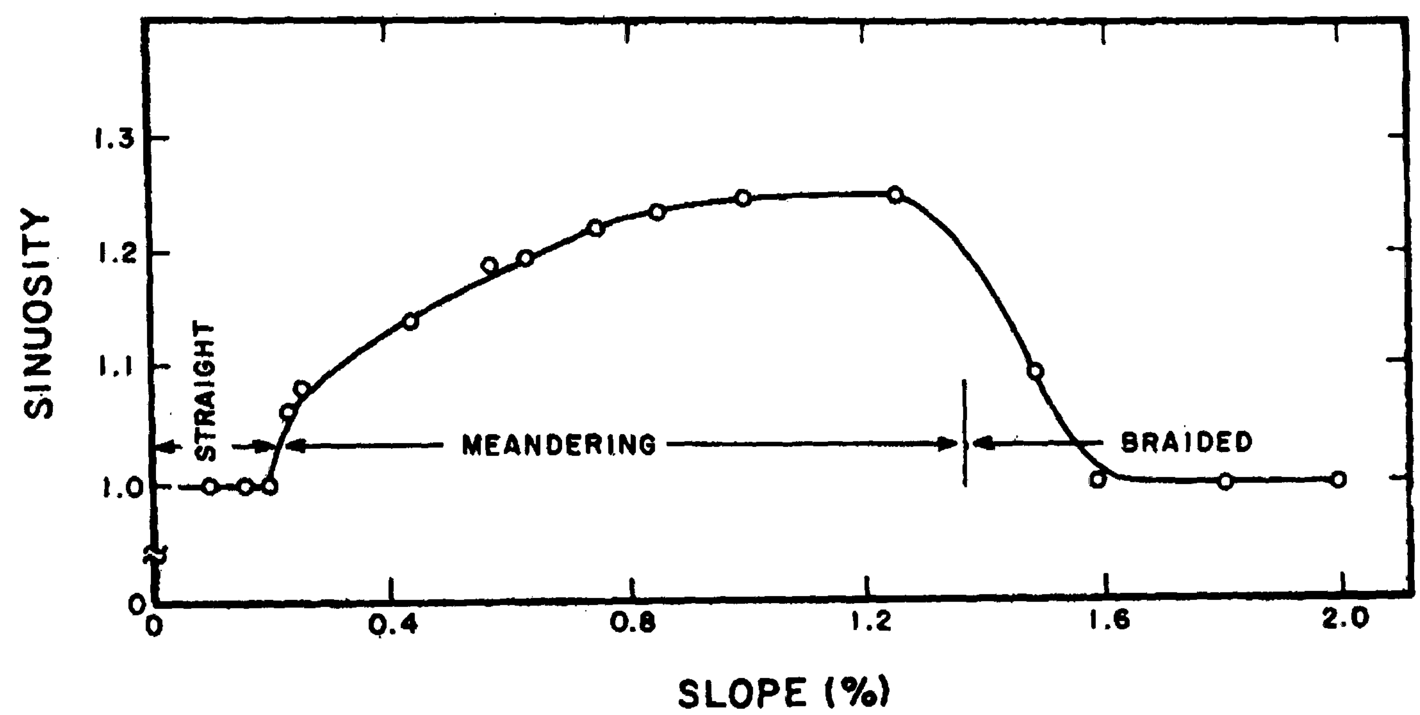


Fig. 7.7: Graph showing the relationship between slope and sinuosity at constant discharge (taken from Miall 1996).

encouraging braided systems. Chapter four describes the evolution of meandering to braided depositional fluvial facies from NW-SE along the basin. Sediments of meandering facies at Riba de Santiuste (Sigüenza) are contemporaneous with braided facies at Rueda de la Sierra (Molina de Aragon) suggesting that for this change in facies to occur there must have been an abrupt change in basin floor gradient northwestwards altering the fluvial profile axially. The increase in basin floor slope is related to high relief on the NW (dextral-slip side) of the transfer fault running through Sigüenza and explains the sudden change in braided fluvial style beyond this juncture (Fig. 7.11b, c and d), consistent with Miall's (1996) interpretations. Thick successions of red beds at Riba de Santiuste can be accounted for due to a focused depocentre at this location SE of the transfer fault in which sediment-choking occurred at regular intervals ensuring continued sediment supply to the rest of the axial system down stream. This discovery suggests the interplay of bi-directional vertical basin floor tilt had a lateral and longitudinal effect on axial fluvial rift systems.

In the Ebro Rift Basin, the three major Buntsandstein and Muschelkalk sedimentation stages, namely early Buntsandstein facies, established Buntsandstein facies, transitory Buntsandstein to Muschelkalk facies were laid down in a half graben rift basin setting similar to that seen at the northern margin of CIB. A normal- and antithetic-faulted margin with tri-directional lineaments stretching NW-SE, E-W and NE-SW formed the structure of the margin. Active faulting during the Permo-Triassic occurred along the margin and accommodated several 'tecto-sedimentary cycles' related to progressive stages of structural evolution. This occurred due the formation of faulted blocks and compartmentalisation, producing basin depocentres in which sediment collected. The idea of compartmentalisation better explains the style and position of the facies systems and was first suggested by Arche & López-Gómez (1996) and fits well with the interpretation here.

In much the same way as the CIB (this study) and Rio Grande Rift (Mack & Leeder, 1999), relay ramps and transfer zones occupied locations along the margin. It is these that routed sediment into the basin from the Ateca High, according to palaeocurrent indicators and descriptive province study of alluvial fan deposits. The Ateca High drainage areas therefore provided the source for the CIB and Permo-Triassic Ebro fan systems and took advantage of structural patterns to supply clastics to the basin. What is not know is the longevity of these margin structures, since the exposure of fan sediments of this age are so heavily displaced by modern day thrusting.

In the areas off-margin, the segmentation of the basin and creation of depocentres occurred. The braided fluvial deposits and subsequent remains of a meandering fluvial system used these areas of accommodation space to accumulate in relatively thick units. Prolonged tectonic activity existed within the basin according to Puigdefábregas & Souquet (1986) but there is no evidence for any significant landscape barriers to divert the fluvial drainage. Instead, it can be assumed that the interaction of the braided system with the alluvial fans resulted from migration of the fluvial system towards the hangingwall margin of the basin (Fig 7.11b, c and d), controlled by uplift of the intrabasinal areas. Assuming consistent seasonal discharge, this alteration in the gradient of the basin floor also affected the fluvial architecture, a consequence of which was the evolution from braided (with steep gradient) to meandering (with an increasingly shallow gradient) as highlighted by Miall (1996).

Further extension during the late-Mesozoic initiated basin widening and the development of a shallow water platform which played host to fluvial systems and, later on, shallow marine, lagoonal sediments associated with the opening of the Tethys to the East. Flooding of the major basin boundary structures occurred and resulted in their drowning during the mid-Triassic (López-Gómez et al., 1998).

7.2.4 Local versus extrabasinal controls

It is necessary to consider all controls operating on the CIB during syn-rift sedimentation, and these include those controls influencing sedimentation from outside the CIB and on a smaller scale within the depositional systems themselves. Tectonics has an affect on the basin fill both on a local scale and outside the CIB. It controlled topography of the substrate within the basin and determined positioning and compartmentalisation of depositional systems (see Chapter 4 and 5), as well as influencing base level and therefore accommodation space. However, outside the CIB faulting is thought to have influenced drainage pathways and the shape and size of the CIB itself.

Climate also operated both on a local scale and extrabasinally as explained in this chapter. On a local scale, the overriding climate will influence the presence of vegetation, local erosion rates and indirectly the amount of suspended sediment carried from hinterland areas. The amounts of rainfall in a catchment area will also have downstream or intrabasinal affects on the amount of water in the fluvial and alluvial flux. Flood stages are related to this.

7.2.5 Use of Fischer Plots with alluvial fan sediments

It is possible to pick up the signature left from climatic and tectonic influences in sedimentary deposits and use them to predict or interpret factors such as accommodation space and subsidence, as well as cyclicity and sealevel. The use of Fischer Plots was first suggested by Fischer (1964) as a valuable tool for determining the relationship between cycles of sediment deposition and the rate of subsidence in a given area, from which information about accommodation space and sea level could be extracted (Chapter 1). They are often utilised for marine sequences and changes in basement rather than sea level, for carbonates in many cases (Read & Goldhammer, 1988; Boss & Rasmussen, 1995), but there is no evidence to suggest they should not be used on non-marine sequences, a point highlighted by the only other known study into non-marine Fischer plots (Turner, 1999).

Fischer plots are a new technique to be applied to the CIB continental sediments and prove useful for identifying cycles of stacking patterns in the successions, where sedimentary systems and sediment cyclicity implicitly respond to an increase or decrease in accommodation space or sediment input. As a preliminary experiment, the Fischer method has been applied to the alluvial fan sediment of the northern margin of the CIB, with the intention of testing its usefulness on ancient non-marine sediments. The method yields some very interesting results indicating accommodation space and sediment flux at the basin margin interact dynamically.

There are several errors to consider before applying any Fischer Plot analysis. It is necessary to assume that erosion and compaction are negligible on the succession, all cycles are accounted for in the sequence, and a constant rate of sediment flux occurred coevally along the basin margin. The number of cycles required for a sequence to at least start to be statistically accurate is fifty (Sadler et al., 1993), which regrettably does not occur with the CIB margin sediments of the Monterde Fm. Also, a lack of exposure within a succession renders a plot untrustworthy after that point as seen at Nuevalos in Figure 7.8. These Fischer plots, and the new use for them, are created on the presumption that they provide a basis for further work and in-depth analysis of sediment cyclicity on the CIB alluvial depositional facies.

The Monterde Fm of the northern margin of the CIB provides sequences of alluvial fan deposits for analysis. Figure 7.8 displays the results of seven Fischer plots plotted for the alluvial sediments along the basin margin of the CIB. Despite the variability in thickness of fan deposits, it is clear that there is cyclicity of the sediments throughout each of the logged sections, though it is hard to say if this is periodic. The Fischer plots are constructed using logged sequences from the northern margin of the CIB and plotting individual cycle thickness against overall average thickness. The result is a saw-edge plot providing a crude indication of cyclicity within a sedimentary sequence. Many factors have to be taken into consideration when interpreting the plots, and even more so for continental facies.

Fig. 7.8 (location 6) is located at Nuevalos where 115 m of alluvial sediments are preserved in 49 cycles of sediment packages. The majority of cycles are thin and show a fluctuating trend below the zero 'cumulative departure from mean cycle thickness' or 'cycle thickness'. Any negative value on this scale indicates a decrease in the available accommodation space, or a change in the sediment supply, and a positive value an increase. Trends therein represent an increase or decrease in the amount of space available.

Sedimentation at the location of Nuevalos had little accommodation space to fill. The plot in Fig. 7.8 (location 6) shows an apparent decrease in accommodation space followed by a small relative increase in accommodation space before decreasing again and finally showing a massive increase to a positive value. Is this

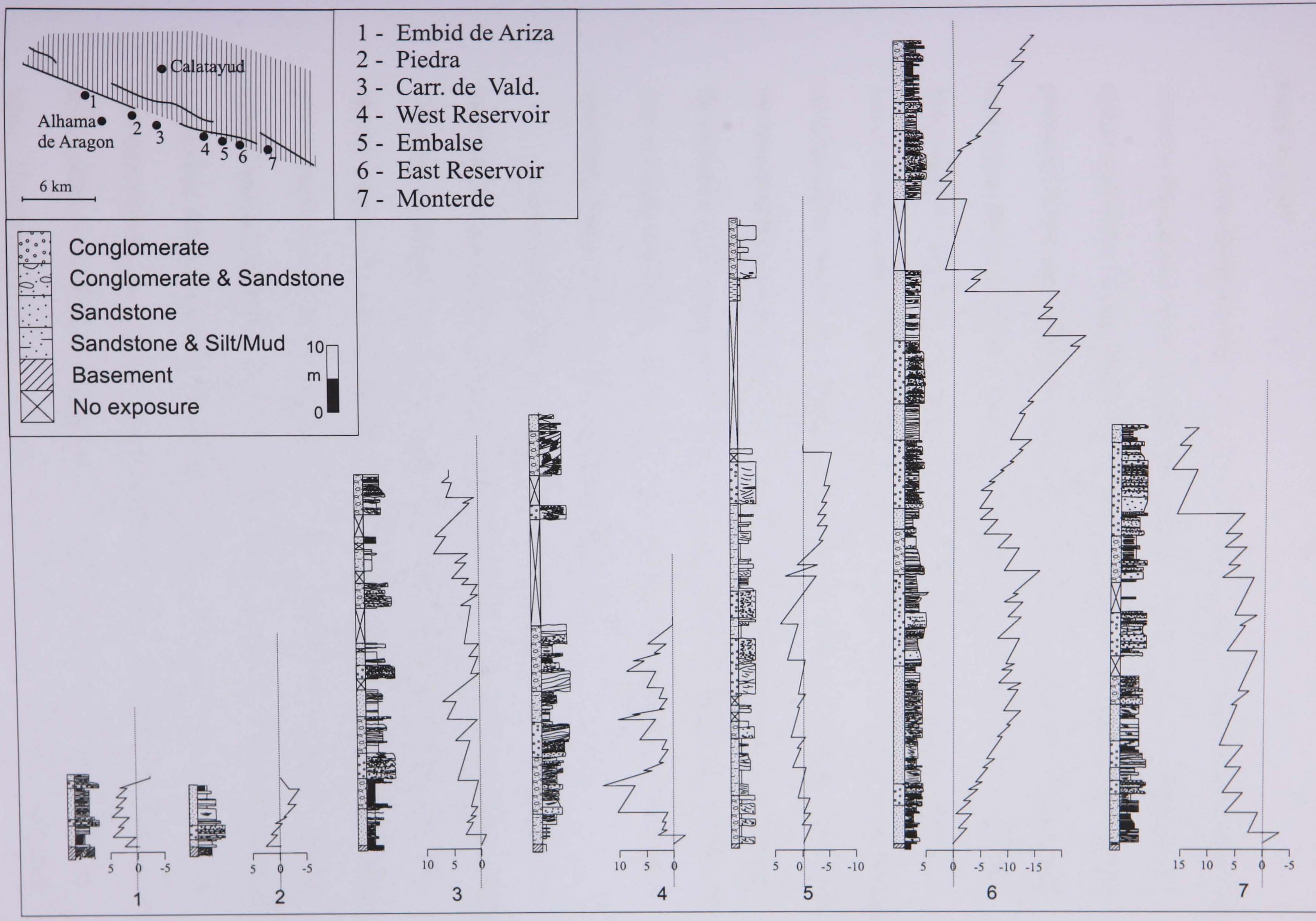


Fig. 7.8 1-6: Graphic logs and Fischer Plots of alluvial sediments along the northern margin of the CIB; Location Key: 1) Embid de Ariza, 2) Piedra, 3) Carr. de Vald., 4) West Reservoir, 5) Mid Reservoir, 6) Nuevalos/East Reservoir, 7) Monterde.

evidence to support the presence of a sediment conduit at this location along the basin margin?

Accommodation space was low at Nuevalos due to the sediment routing relay structure and prevented the accumulation of sediment and encouraged the flux of clastic material to bypass further into the basin. However, the amount of sediment preserved at this site indicates that a large amount of flux entered the basin at this point along the margin indicating the presence of room for sediment to mount up. The reason for this is the low-lying topography of the depositional area enabled increased storage space for the sediment rather than it being moved on by the lack of accommodation space. As a further issue, towards the top of the alluvial succession, the accommodation space climbs to zero before decreasing again which is linked to the initiation of interdigitating fan and lacustrine sediments. This raises doubts over how accurate data can be when traversing a facies change in the succession and is something that needs to be addressed in further work.

This scenario shows an opposing trend to that at Monterde (Fig. 7.8) where available accommodation space increases as does the basement surface relief (see Fig. 7.9) have combined to store a thick sequence of sediment. Fig 7.8 (location 7) is a smaller logged exposure of alluvial sediments from Monterde subjected to Fischer plot analysis. It is clear that there are fewer cycles in this case, due to the reduced section length, plus these 18 cycles are thicker than those at Nuevalos and this leads to question the usefulness of Fischer plots to interpret alluvial fan sediments. The plot demonstrates an increase in accommodation space, or increased sediment input, followed by a small relative decrease in accommodation space before increasing again. Therefore, accommodation at varying high levels at this location along the basin margin during the Thüringian-Scythian resulted in some storage of sediment, in thickly-stacked cycles.

The sediments at Carranco de Valdaroque and West Reservoir (Fig 7.8 location 3 and 4) show an interesting relationship between sedimentation and accommodation space. In both examples low rates of accommodation, around zero, are observed for finer sediments, but then a marked increase occurs with the onset of coarse conglomeratic alluvial fan deposits. This would suggest that local tectonism, triggering localised basin margin subsidence, accommodated the increase in flux rather than encouraging bypass into the basin. However, further up the succession, accommodation space decreases even when another coarse clastic depositional episode occurs. In this situation, it is likely that the structurally controlled sediment conduit, in the form of a relay ramp, would have transported the sediment further into the basin.

Whilst climatic controls dictated the magnitude and nature of the sedimentation, it is localised tectonic subsidence and associated uplift, along the normal faulted margin that not only created the positioning of entry points to the basin, but also the space in which to accommodate or divert flux. From the Fischer plots in Fig. 7.8 it can be inferred that subsidence and the creation of accommodation space along the basin margin was localised and had a direct effect on the depositional system. However, the size of the fans, fan topography, grain size of the sediment need to be considered in all interpretations, something which is difficult with the CIB fans and is likely to lead to inaccuracy in interpretations.

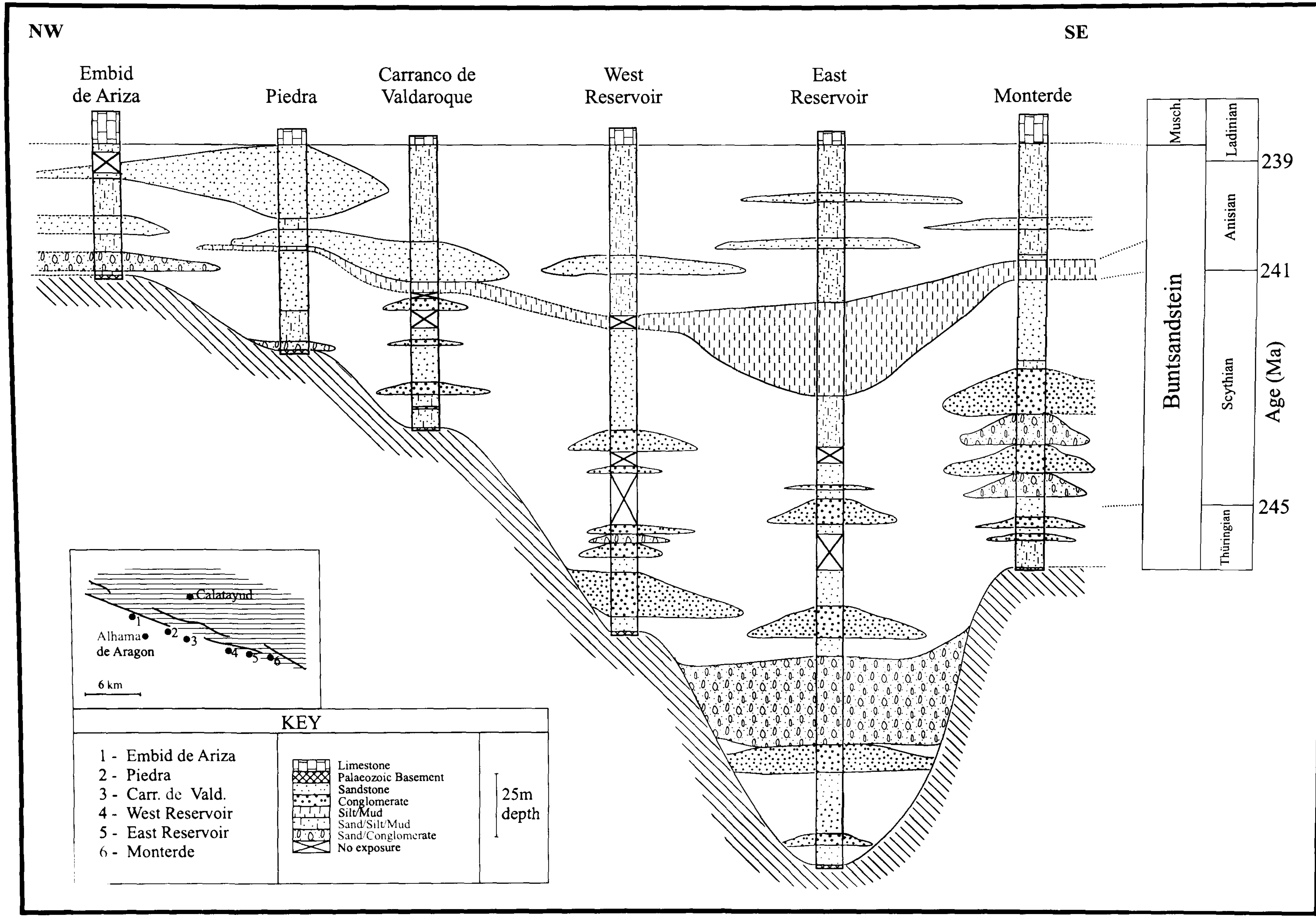


Fig. 7.9: Lithological correlation panel along strike of the northern margin of the CIB resulting from in-depth field investigations and graphic log construction. Time equivalent lines have been added against the age dates to hint at contemperaneous depositional episodes.

7.2.6 Sealevel and relative baselevel changes

Baselevel (sea level and lake level) change, together with tectonic subsidence or uplift as described above, control a large portion of the accommodation space in which marine and/or lacustrine sediments can be deposited. Furthermore, the rate of change of accommodation development (relative baselevel change) is one of the major controls influencing stratal geometries of stacking patterns in shallow marine sediments, as widely discussed in the sequence stratigraphic literature (e.g. Van Wagoner et al., 1990). Of importance to the study of rift basins are the general relative rates of base level change compared to the rates of vertical movement and uplift, and the rates of cyclical processes such as climatic controls on sediment flux.

High-resolution global sea level curves are nothing new, and well document the Late Quaternary glacial-interglacial changes (e.g. Shackleton, 1987). The cycles have a dominant 4^{th} order frequency of c. 100 kyr, a magnitude of ~130 m, and are markedly asymmetric, with post-glacial sea level rise occupying only 20% of the time in anyone cycle. Rates of glacio-eustatic sea level change are rapid with average 4^{th} order fall of 1.5 m kyr^{-1}, although higher rates of fall are associated with 5^{th} order glacio-eustatic falls. In contrast, average rates of post-glacial sea level rise are ~10 m kyr^{-1} and during the last deglaciation, around 12 ka, sea level rose at ~ 20 m kyr^{-1} with a peak of 4 m per 100 yrs (Fairbanks, 1989). Such high rates of change can easily account for the rapid marine transgression (TST) seen at the transition from the Buntsandstein to Mushchelkalk facies throughout the whole of the CIB.

The westward Tethyan transgression effected the northern margin sediments of the CIB by influencing the environment of deposition. Superimposed high resolution fluctuations in sealevel manifested in the form of Buntsandstein deltaic facies (delta lobes in Chapter 3). These possibly represent the rise and fall of an encroaching Tethyan sea establishing itself on a continent landmass. Such a fluctuating signal is difficult to identify in the southern areas of the CIB or in the Ebro Rift Basin but is likely to have affected sedimentation in the basin in much the same way. Following this flooding of the non-marine environment occurred resulting in a marine environment and depositing the Muschelkalk limestone facies across the whole of the CIB.

7.3 Sequence Stratigraphic Framework

Our ability to understand sequence stratigraphic frameworks for individual non-marine continental successions remains a challenge due to the complex interaction within depositional sequences of allocyclic and autocyclic controls. Sequence stratigraphy was first designed for the classification and interpretation of shallow marine and clastic shoreline deposits (Posamentier & Vail, 1988), but has since been tentatively applied to non-marine strata (e.g. Shanley & McCabe, 1994; Richards, 1996; Turner, 1999). In its original form, sequence stratigraphy relied on the presence of sea-level in manipulating depositional characteristics, however, with the absence of direct eustatic control in non-marine environments the ratio of sediment supply to accommodation space (base level) is considered. From this foray into non-marine classification it has been possible to begin to understand and recognise systems tracts, sequence boundaries (SB) and flooding surfaces (FS), which, in turn, helps to assemble a stratigraphic framework across the CIB region.

For this study the terms Lowstand, Highstand and Transgressive Systems Tracts need to be applied and therefore explained. A Lowstand in the context of this refers to deposition during lows in relative sealevel and in the context of this study refers to the absence of marine conditions in depositing the sediment (and applies to the alluvial fans in particular). The Transgressive Systems Tract (TST) this indicates the gradual influence of marine conditions and rising sealevel on the deposition of sediment. Highstand Systems Tract is the overriding influence of marine conditions on the deposition of sediment in the CIB.

7.3.1 Sequence stratigraphy of the Northern margin of the CIB

Detailed outcrop analysis of the northern margin of the CIB was undertaken in order to interpret the sequence stratigraphy of the basin margin deposits. From the outcrop at Monterde, a total of seventeen palaeosol horizons are identified as important markers within the succession, in addition to at least one major sequence boundary and three flooding surfaces. It is from these indicators that it has been possible to construct a preliminary sequence stratigraphic framework for the northern margin of the CIB.

7.3.1.1 Palaeosol surfaces (PS-1 to PS-17)

Moderately mature palaeosols from alluvial fan facies association 1 (facies 1c: chapter 3) mark extended periods of fan exposure, hiatuses in open fan deposition, and therefore, unconformities between the various stratigraphic units (Fig. 7.10) which can be interpreted as an overall Lowstand Systems Tract (LST). The sediments

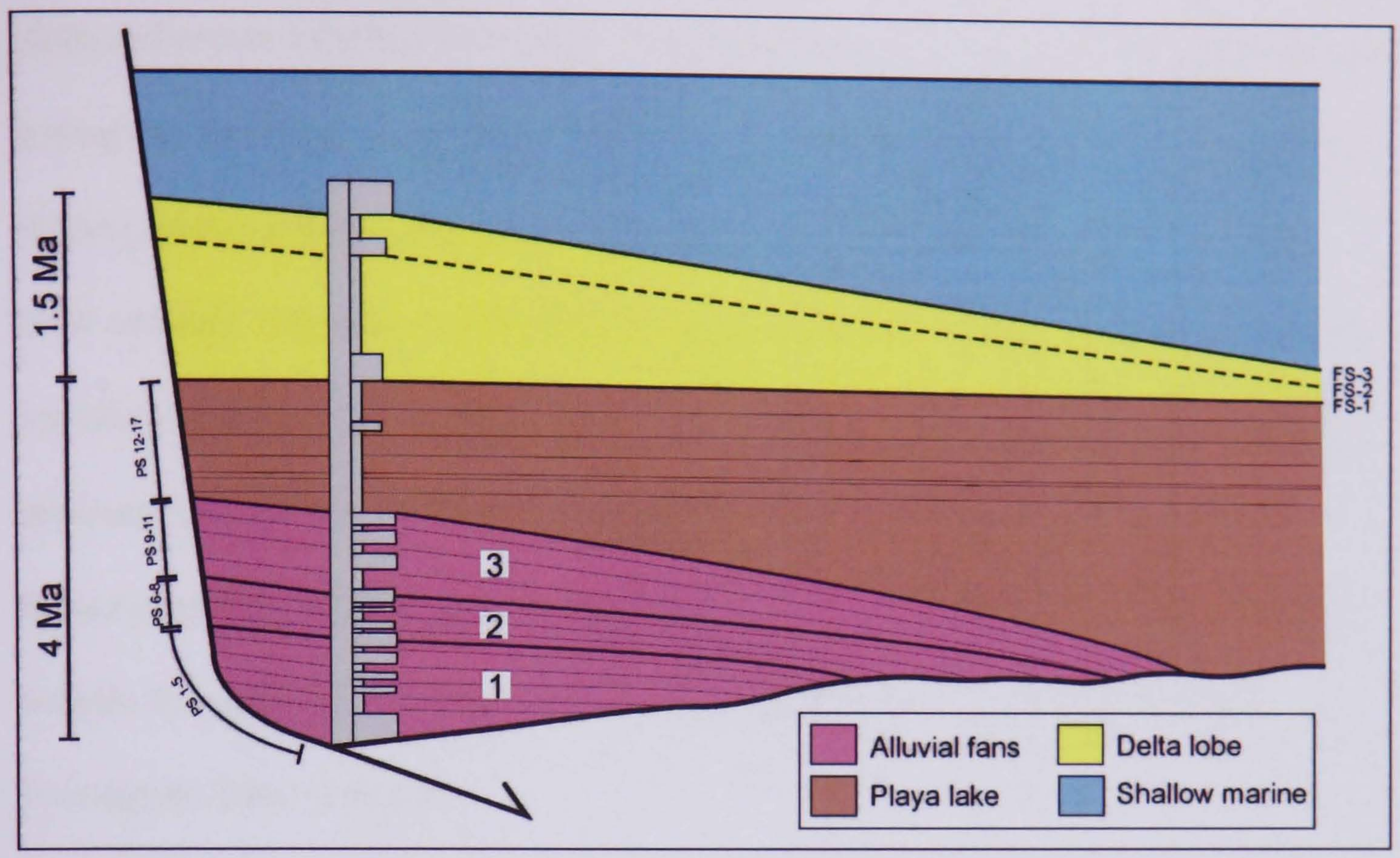


Fig. 7.10: Schematic diagram showing palaeosol development across depositional systems at the northern margin of the CIB.

that lie between these unconformities represent open-fan deposition (Facies 1a and 1b: Chapter 3). These stratigraphic units are laterally extensive and extend across most of the alluvial fan surfaces. The thickness and coarse composition of the units indicates a continued, flashy sediment supply and basinward base level lowering in order to accommodate a three stage development of the fan deposits, playa lake existence and subsequent delta lobe deposition.

Palaeosol Surface (PS) 1 to 5 represents the main pedogenic hiatuses of the first fan phase occurring along the margin. Alluvial fans formed as a result of low frequency, high magnitude flood events, with exposed surfaces of each coarse clastic influx providing the substrate for poorly-drained palaeosol horizons. The development of PS-6 to -8 represents a similar sequence of alluvial fan palaeosol facies interaction and relates to the second fan stage. PS-9 to -11 are related to the third alluvial fan stage which is followed by playa lake domination of the low-lying basin margin areas coexisting with some minor alluvial fan interplay. Here in the playa sediments a further five palaeosols (PS-12 to -17) are found indicating periodic drying and lowering of the lake level, plus intermittent increases salinity noted from Halite pseudomorphs, associated with climatic hydrological throughput and base-level controls. This playa succession is finally topped off with a definitive sequence boundary and flooding surface (FS-1). From high resolution sequence stratigraphy application to the fan sediments it is possible that further sequence boundary or flooding surface fluctuations can be identified in the overall LST, however this lies outside the scope of this study and would provide an interesting hypothesis to investigate in more detail.

Finally, completing the analysis of soil horizon development across the northern margin, three minor palaeosols are noted within the delta lobe deposits. This series of delta lobes are considered TST deposits triggered by the westward advance of the Tethys Sea and allowing only limited soil formation. Could it be that poorly formed palaeosols developing prior to a transgressive marine incursion, occurred during regressive periods or are they symptomatic of reduced sediment supply prior to renewed flooding?

7.3.1.2 Flooding surface 1 (FS-1)

This flooding surface is regionally extensive and can be traced across the entire study area (Fig. 7.10). It marks the base of the delta lobe sandstone succession of the Alhama formation. Across much of the study area, FS-1 is marked with a sharp facies transition from playa lake sediments to the deltaic sandstones, which, as it is an abrupt change in facies type, can be classified as a sequence boundary (SB) in accordance with Richards (1996). The flooding surface is marked by the occurrence of poorly sorted sandstones, which are usually carbonate cemented and an abundance of broken shelly debris. The surface is always moderately bioturbated with *Palaeophycos, Thalassinoides* and *Planolites.*

The flooding surface of this initial transgressive event (TST) represents an important event marked by the deposition of the first marine sediments of the Buntsandstein facies in the CIB and renewed sediment supply to the basin margin. The presence of FS-1 is interpreted to be related to a tectonically controlled sea-level rise and renewed Ateca High fault activity. This marks the time of deepening of the CIB along its north eastern margin probably due to increased subsidence rates as coupling of smaller faults becomes localised with more significant impact on sedimentation.

7.3.1.3 Flooding Surface 2 (FS-2)

Flooding surface 2 is a marine flooding surface marked by the facies transition from delta lobe and associated deposits of the majority of the Buntsandstein (Facies 3a and 3b) to the laminated algal sediments of the upper Buntsandstein facies (Facies 3c). During a basin-wide marine transgression (TST), sea-level increased and flooded areas bordering the previously-formed fan lobes regressed creating a shallow marine environment in which algal growth thrived (Muñoz et al., 1992). This led to the development of flat-laminated algal mats, and even poorly formed stromatolite domes. The absence of sediment flux to the basin at this time allowed a sustained period of continued algal mat development helped by relative tectonic-quiescence along the basin margin.

FS-2, in comparison to FS-1, represents the continued Tethys realm and is interpreted as a gradual eustatic sea level rise.

7.3.1.4 Flooding Surface 3 (FS-3)

The third marine flooding surface (FS-3) is marked by the facies transition from the upper sections of the Buntsandstein facies to that of shallow marine Muschelkalk facies. Advanced stages of Tethys transgression meant that many land surfaces had now been flooded and marine conditions dominated the whole of the CIB. Basin subsidence is greatly reduced, or of little influence, and whilst the basin boundary faults are still tectonically-active, they have a lesser influence on rift basin sedimentation. In a sequence stratigraphic context, this flooding surface marks the evolution from a Transgressive Systems Tract to that of Highstand Systems Tract (HST) conditions.

7.3.2 Basin-scale sequence stratigraphy

Across the whole of the CIB, a preliminary sequence stratigraphic framework can be constructed and compared to similar rift basins of the Iberian Basin to the south-east and the Permo-Triassic Ebro Basin to the north (Figs. 7.11 a-e). Within the CIB it has been noted that there are kilometric scale thickness of Buntsandstein continental red beds in certain locations (e.g. Riba de Santiuste and Rueda de la Sierra) followed by deposits that show indications of a marine influence, and finally capped off by marine Muschelkalk limestone. Limitations to the availability of outcrops, especially in the central areas of the basin, reduce any sequence stratigraphic framework applied to the facies as qualitative, however it provides the basis for further investigation beyond these new interpretations.

Buntsandstein deposits in the CIB are composed of mainly fluvial and alluvial facies controlled by interplay of climate and tectonics. Climate appears to dictate the sediment supply and internal drainage characteristics, whereas tectonism influences base-level, drainage routing, geometry of the rift basin and basin slope. It is the latter factor of slope gradient that has a marked affect on the style of fluvial deposition in the intrabasinal and southern areas of the CIB on account of the abrupt shift in fluvial regime from meandering to braided. This transition from meandering to braided channel pattern, as previously addressed in Chapter 4, transpired as a result of changes in the basin gradient from NW to SE, a scenario supported by Ouchi (1985). These changes in base level may contribute to a high resolution (4th or 5th order) sequence stratigraphic framework for the Buntsandstein of the CIB, though this is difficult to substantiate because the scales over which fluvial and alluvial systems react to environmental and climatic changes are equal to or smaller than this. However, marine incursions and associated flooding surfaces can be identified and used to form a general first- to second-order (Emery, 1996; Shanley & McCabe, 1994) sequence stratigraphy for the basin over several million years.

From the nature of the Buntsandstein fluvial and alluvial deposits, during the Early Triassic, a prolonged lowstand (LST) period was experienced across much of the basin. Within this succession there are periods when palaeosols developed though instead of this being related to a shift in the systems tract of the basin, it is likely to have occurred as a result of climatic fluctuations reducing the sediment supply or avulsion of the channel to another area.

It is these deposits of the Montesoro Beds, Hoz de Gallo Fm and Rillo Gallo Sandstones Fm (Sopeña & Sánchez-Moya, 1997) and the Riba de Santiuste Conglomerates Fm and the Riba de Santiuste Sandstones Fm (Ramos et al. 1986; Sánchez-Moya et al. 1996) that are chronostratigraphically linked to the Iberian Basin Buntsandstein deposits which contain a succession of alluvial fan conglomerates (Boniches Fm) leading into lacustrine muds and floodplain fines (Alcotas Fm) and followed by fluvial sandstones (Cañizar Fm) (López-Gómez & Arche, 1993). For a fluvial system to be contemporaneous with a lacustrine system implies SE drainage from the CIB dried up, was directed into the Iberian Basin but separated from the lake system, or evolved to carry a finer sediment load and ultimately drained into the lake system. Permo-Triassic lacustrine delta deposits in

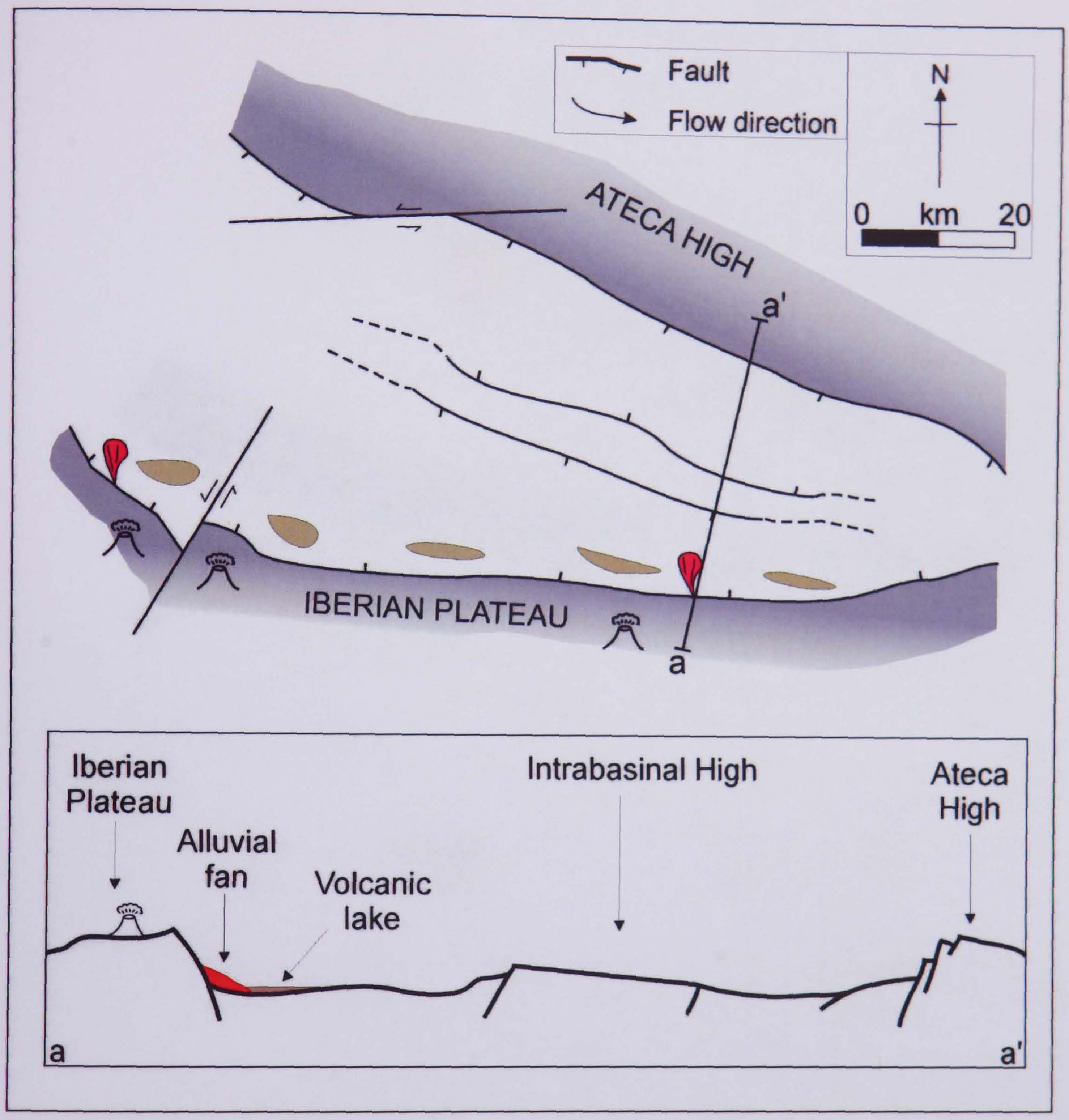


Fig. 7.11a: Evolution of depositional systems and volcanism in the CIB in both plan view and cross section (Mid-UpperPermian).

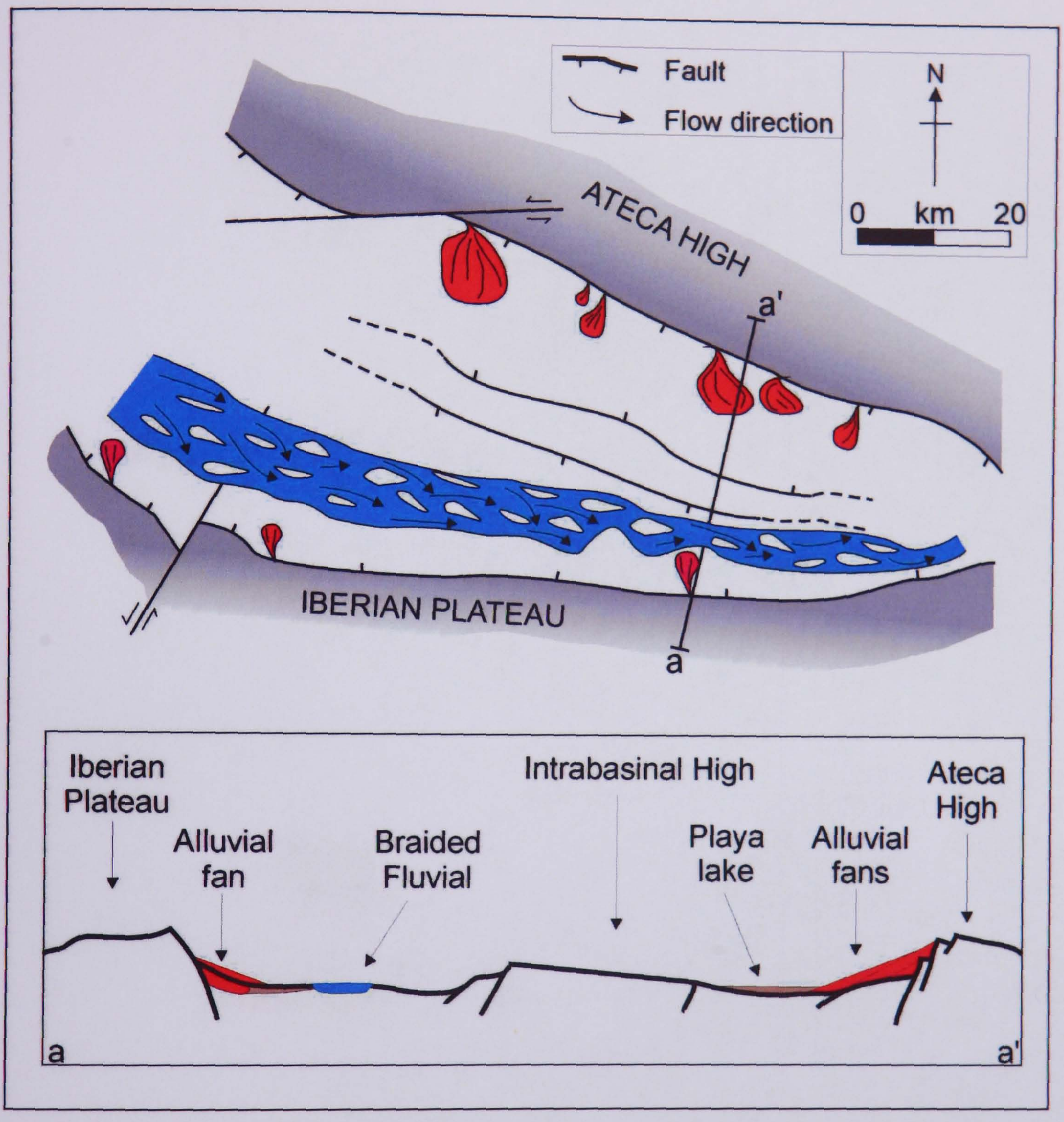


Fig. 7.11b: Evolution of the Buntsandstein depositional systems continues but volcaniclastics are now absent at the southern margin (Upper Permian).

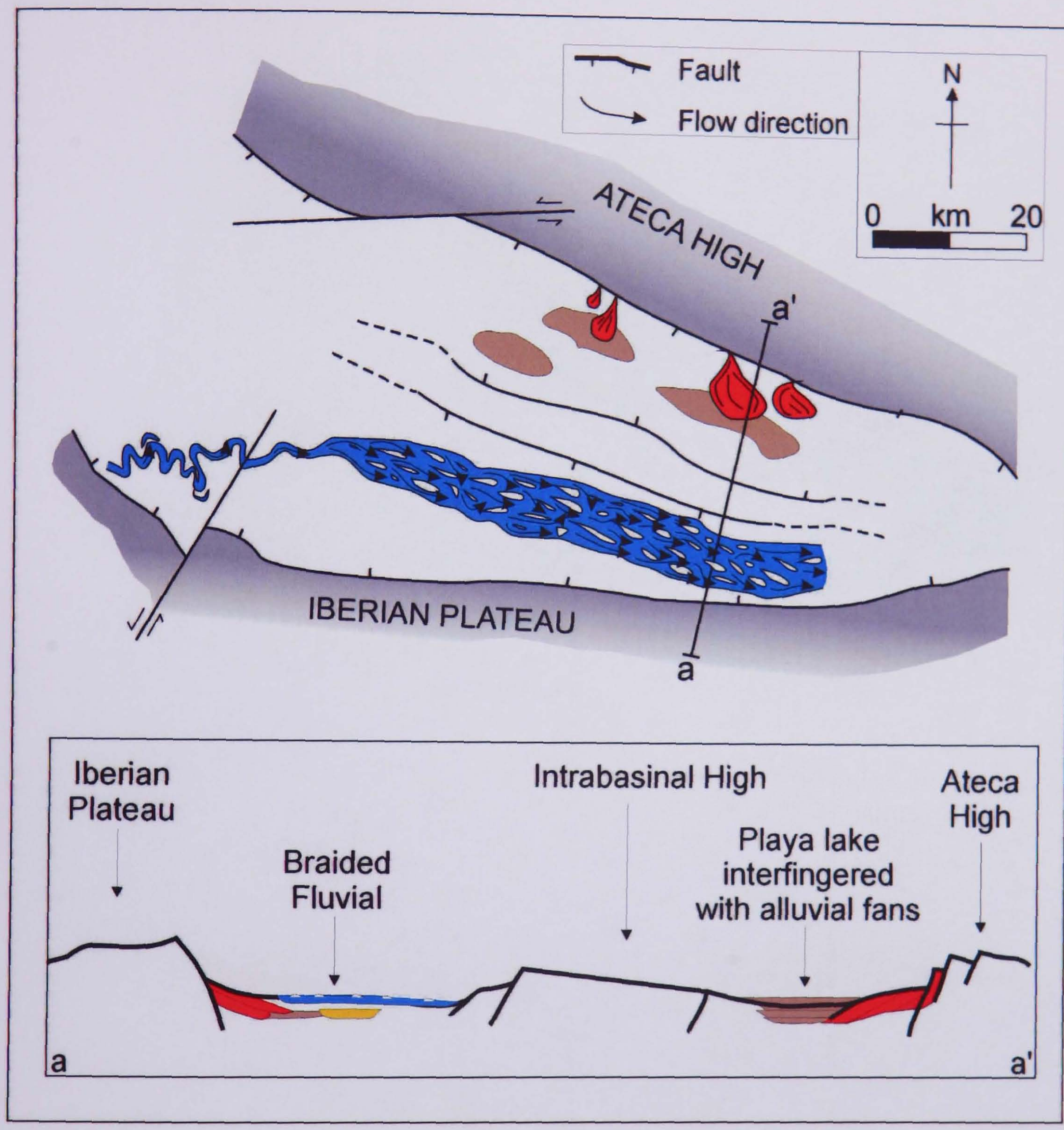


Fig. 7.11c: Buntsandstein fluvial systems dominate the southern margin whilst separated from the northern margin where alluvial fans and playa lakes exist (Early Triassic).

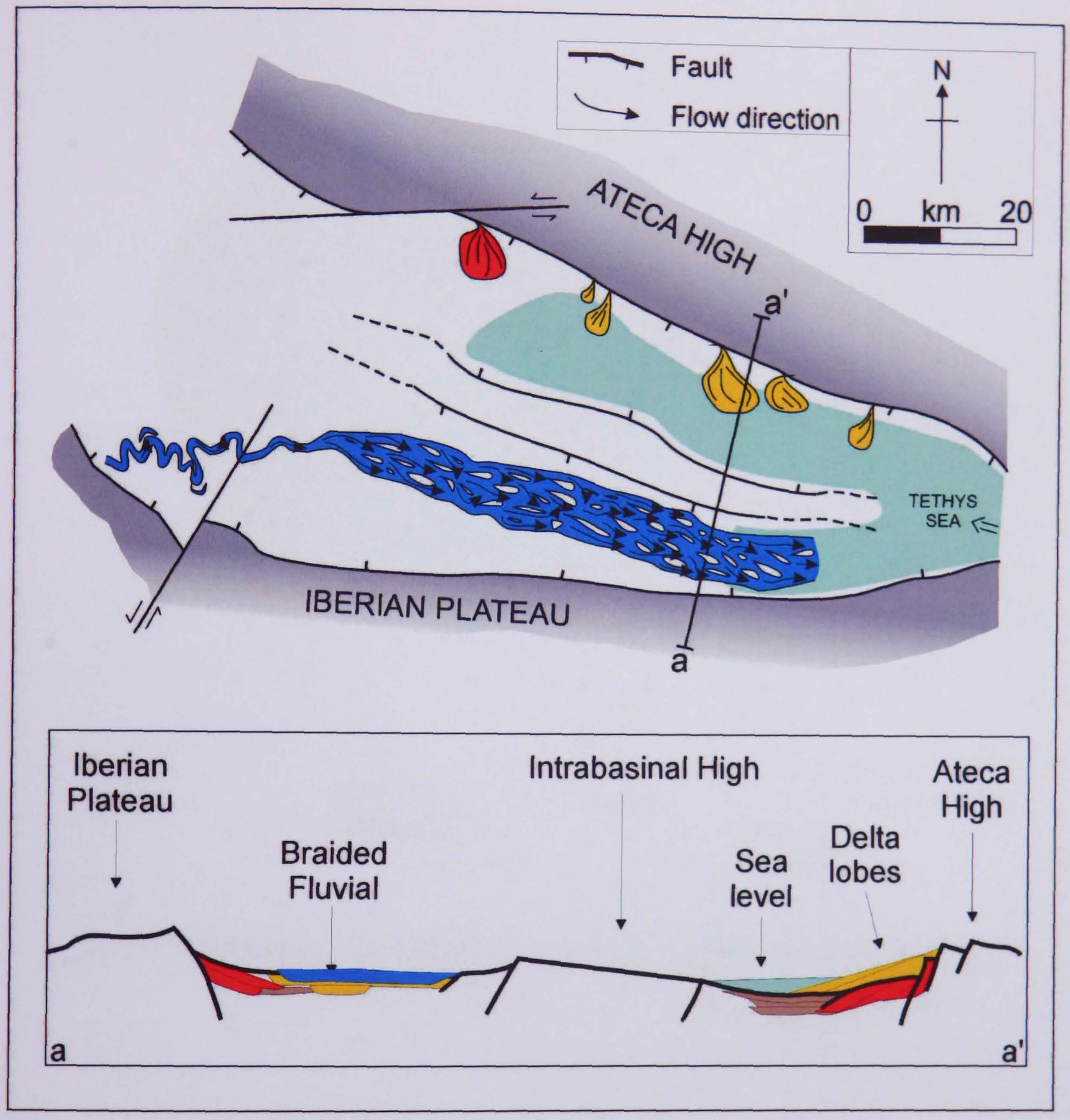


Fig. 7.11d: The Tethyan transgression reaches the easterly and central areas of the basin flooding land surfaces and interacting with the continental systems (Early-Mid Triassic).

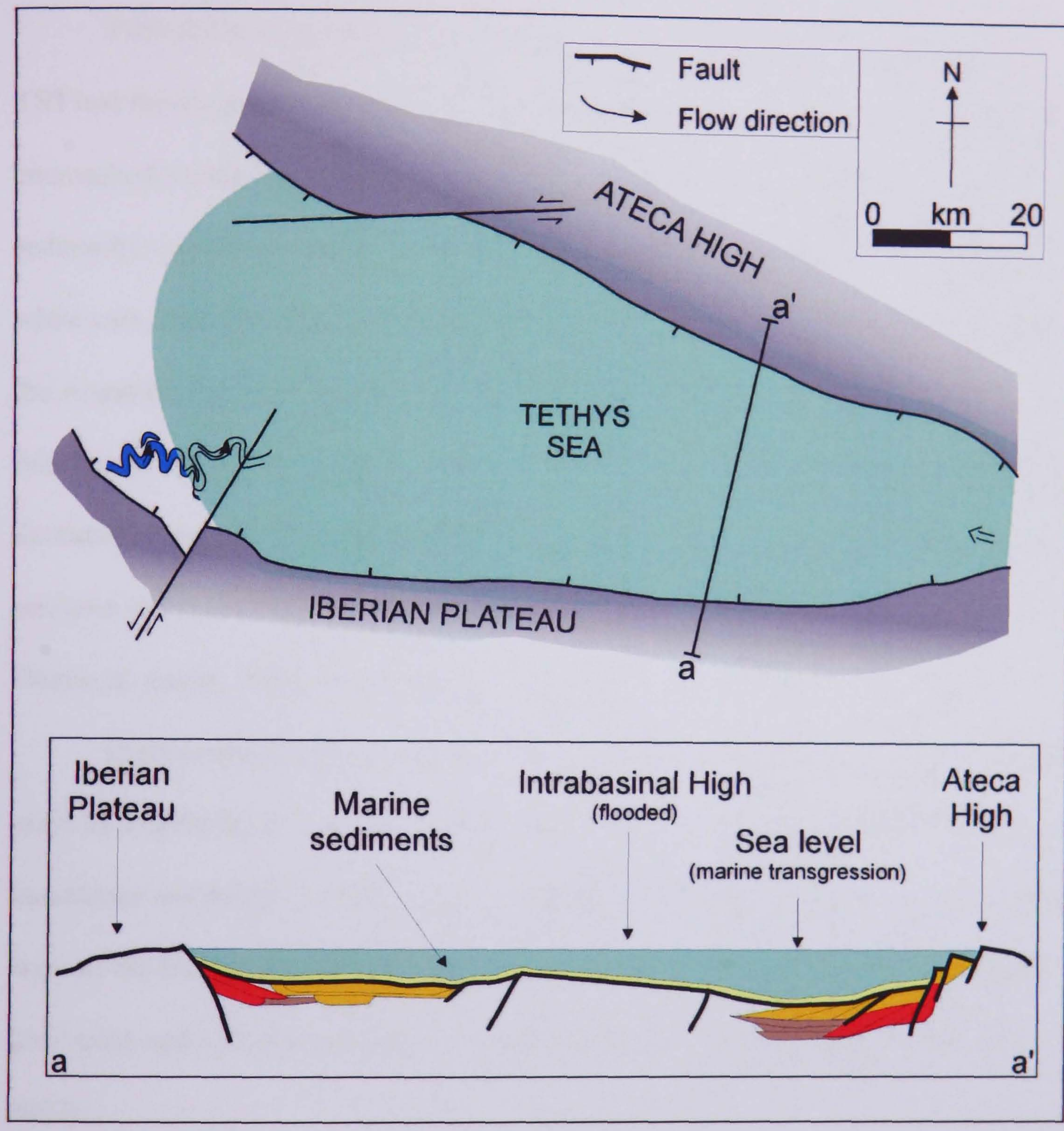


Fig. 7.11e: Complete flooding by the Tethys Sea results in marine conditions across the whole of the CIB (Middle Triassic).

the Iberian Basin are absent from facies descriptions in the literature suggesting the latter explanation is not correct.

Further Buntsandstein sedimentation in the CIB led to deposition under a TST and the occurrence of Flooding Surfaces from sea-level rises. As the Tethys Sea encroached westwards over the Iberian Ranges, the influence of marine waters and sediment increased on the established continental systems. Pale pink arkoses and white carbonate sandstone units are representative of this transgression and occur in the Arandilla Fm, Rill de Gallo Fm, and Torete Fm at Rueda de la Sierra (Sopeña & Sánchez-Moya, 1997) and in the Cercadillo Sandstones and Mudstone Fm at Riba de Santiuste (Ramos et al. 1986; Sánchez-Moya et al. 1996). These are coeval with the sea-level influenced Cañizar and Eslida Formations from the Iberian Basin (López-Gómez & Arche, 1993) (Fig. 7.6).

Highstand system tract (HST) deposition occurred across both basins with the onset of Muschelkalk facies deposition, during the late-Anisian (Middle Triassic), of limestones and marls of shallow marine settings, which rose to flood even the highest areas of the Iberian Ranges (and forming a prominent Flooding Surface) before sea-level once again dropped, resulting Keuper evaporate deposits (López-Gómez et al. 2002).

With regards to the isolated Ebro Basin during the Permo-Triassic, a similar pattern of sequence stratigraphic history is observed from the information collected from the outcrops. During the Thüringian-Scythian, Buntsandstein alluvial and fluvial sandstones deposited under a LST, developing and prograding eastwards during the Tethyan transgression (TST) and finally becoming flooded during the Muschelkalk marine incursion (HST).

7.4 Summary

This chapter has drawn together all strands of research throughout the study and offered a comprehensive interpretation of the evolutionary stages of the CIB during the Permo-Triassic. In particular, the nature of Buntsandstein facies, Muschelkalk facies and the transitory beds in-between are discussed and applied to a chronostratigraphic framework. Sequence stratigraphic concepts and a fresh use for the Fischer plot technique in the field of non-marine sedimentation are applied to the Buntsandstein sediments of the northern rift basin margin with some interesting results. From these Fischer plots it is possible to determine the rate of accommodation space creation versus cyclical sedimentation thicknesses - data which is plotted in diagrammatic form. It is also clearly seen from detailed sedimentological analysis that climate and tectonics play a major role in the control of not only basin margin sedimentation, but also intrabasinal depositional systems (Fig. 7.3). This influence can be compared to adjacent rift basins of the Permo-Triassic Ebro Basin and the Iberian Basin, as well as rift basins worldwide. It is hoped our understanding of the evolution of a rift basin, preserved from the ancient, and the controls on the sediment infill into that basin will benefit from this thesis study and that future work will use these advances as a platform for further research.

Chapter 8

Conclusions

8.1 Discussion and Implications

Deposits of the CIB provide an excellent example of ancient, synrift sedimentation within a tectonically active rift basin during the Permo-Triassic. The excellent preservation and ease of access has allowed the structural geometry of the basin and the syntectonic rocks to be documented, especially for the northern and southern margins (Chapters 3 and 4) and in the adjoining Permo-Triassic Ebro Basin. Understanding the structural evolution of the Iberian Rift basins, in particular the CIB allowed the detailed analysis of its interrelationship with the development of transverse and axial drainage systems.

8.1.1 Synrift transverse drainage systems

Compartmentalisation by intrabasinal faulting affected the drainage pattern over the whole of the CIB and separated northern margin and southern margin depositional systems. Drainage adopted two dominant directions: transverse and axial drainage. The former occurred in its most influential form at the northern margin of the CIB (see Chapter 3), along which climate and active tectonics played a key role in controlling the sedimentation. These allocyclic controls not only dictated the appearance of flux to the basin, but also the positioning and timing of the depositional events.

Alluvial fans juxtaposed along the northern margin of the CIB formed as the result of periodic, southerly-directed sediment flux from uplifted catchment areas to the north. The climatically-forced low frequency, high magnitude events occupied accommodation space created by fault activity and associated basin floor subsidence. Palaeosol horizons across the whole fan surfaces enable divisions and a preliminary timeframe to be constructed for alluvial fan deposition prior to interfingering with playa lake facies further out into the basin.

Routing for the sediment flux was controlled entirely by sediment conduits formed as the result of relay ramps, transfer zones and breaching of the normal-faulted basin margin. A lack of evidence suggesting downcutting or terracing took place means the probability of incision and stability of the conduits is unlikely. Importantly, the active, fault-controlled structural conduits remained fixed for a period of c. 7 Ma, playing a major role in the continued delivery of sediment to the basin, encouraging delta lobes to supersede alluvial fans during Middle Triassic transgressions of the Tethys Sea. The longevity of the structural corridors permitting bypass of sediment from source to sink and their irregularly-spacing contrasts with models suggested in the literature (e.g. Talling et al., 1997; Gawthorpe & Leeder, 2000).

However, transverse drainage was not restricted to the northern margin of the CIB. Minor alluvial fans and pockets of other transversely-directed flux were observed in sediments at the southern margin of the CIB (Chapter 4) and along the western margin of the Permo-Triassic Ebro Basin (Chapter 5). Though these transverse alluvial fan systems were limited to only an initial role in the synrift infill of the CIB, they are nevertheless important in determining the depositional history of Buntsandstein facies sediments during the Permo-Triassic. The significance of along-strike transverse drainage variations in the CIB is an aspect of ancient rift basins rarely represented in the literature.

8.1.2 Synrift axial drainage systems

Axial drainage systems in the CIB occupied the southern areas of the basin having been diverted and restricted from the northern marginal areas of the rift basin by the fault-controlled intrabasinal high. It was this drainage to the southern areas that originated in the NW of the basin and intermittently switched between the Permo-Triassic Ebro and the CIB.

Outcrops locations studied along-strike of the southern margin of the CIB reveal thick accumulations of Buntsandstein facies sediments identified as perennial axial fluvial deposits. Fluvial deposition along the southern margin was controlled by a combination of climate and tectonics (Chapter 4). Transfer zones (Sigüenza and Teruel faults, Chapter 4; Deza fault, Chapter 5) orientated perpendicular to the basin margin faults had a marked affect on the gradient of the basin floor altering basin physiography and altering fluvial style. A change from meandering to braided fluvial system occurred up succession at Riba de Santiuste (Chapter 4) under the influence of gradient changes, however initiated fault block rotation along the transfer fault helped maintain axial river profile along the CIB in spite of this. The result was a transition from meandering to braided fluvial system axially along the southern margin of the CIB during the Permo-Triassic.

Axial fluvial systems in the Permo-Triassic Ebro rift basin acted similarly to depositional systems in the southern areas of the CIB. However, due to reactivation of fault-controlled structures in the present day geology there are difficulties in interpreting Permo-Triassic basinal structures and the affect they had on sedimentation. The Deza transfer fault situated in the NW of the CIB and running transversely through to the Ebro basin may have dictated the drainage between the two basins and altered the basin floor gradient producing a change in fluvial facies (Chapter 5).

In terms of lateral extent transversely across the CIB fluvial systems in the southern areas were prevented from interacting with northern margin systems by an inferred subtle intrabasinal high formed as a result of structural evolution of antithetic and synthetic faulting within the CIB. Intrabasinal highs are rarely documented in rift basin models in the literature and little is known about their affect on internal drainage within an ancient rift basin. It is hoped this study will address this shortfall and encourage discussion on the internal complexities of ancient rift basins.

8.2 Conclusions

1) The CIB is an ancient half-graben rift basin located in central Spain that provides an excellent record of synrift Buntsandstein facies sedimentation throughout the Permo-Triassic. Compartmentalisation of the rift basin by a central axial, fault-controlled topographic barrier created two main areas that existed during the Permo-Triassic, a northern and southern area, which existed contemporaneously with the juxtaposed Ebro Rift Basin to the north and the Iberian Basin to the South East.

2) Synrift sedimentation in the CIB is typified by time equivalent alluvial fan conglomerates, playa lake sediments and deltaic deposits at the northern margin and red bed meandering and braided fluvial systems at the southern margin, in addition to fluvial and alluvial depositional systems in the Ebro Rift Basin. A chronostratigraphic timeframe created from previously known age dates and regional

stratigraphic correlations aid comparison between formations across the entire rift basins of the Iberian Ranges.

3) Sedimentation at the margins of the CIB occurred as climatically-controlled transverse flux events interrupted by periods of non-deposition encouraging pedogenesis. Sediment flux to the basin exploited structurally-controlled conduits spaced irregularly along the faulted basin boundary. These conduits survived throughout the evolution of the CIB and promoted longevity of depositional systems at the margin.

4) Drainage in the south of the CIB demonstrated the importance of tectonism on controlling basin floor gradient and the consequence fault block rotation has on fluvial profile along axis of the basin. Cross-cutting transfer faults and intrabasinal highs divided the basin, dictated linkage of two major depocentres at each end of the basin and influenced sedimentation pattern in the CIB, compartmentalising the CIB in the process.

5) Comparison between the CIB and rift basins worldwide (e.g. the East African Rift, Rio Grande Rift and the Gulf of Suez/Red Sea Rift) reveals that many geometric, tectonic and sedimentological features are shared between the basins. This highlights the importance of modern analogue basins in furthering our understanding of ancient rift basins in the subsurface.

6) Differentiating between the effects of climate and tectonics in the CIB, and in ancient rift basins as a whole, is not easy especially on short timescale changes.

However, it is clear from this study that the distinction between climate and tectonic controls can be made from lithofacies and structural investigations. The two allocyclic controls compliment each other working coevally to influence sedimentation across the whole of the CIB.

- Climate exerts a strong control on the character of the sediments and may operate on Milankovitch timescales at the northern margin of the CIB. Hinterland drainage enters the basin both axially and transversely, in which climate plays a complex and direct role over much shorter time scales than tectonism.

- Tectonics influences the shape and topography of the basin, the compartmentalisation, the basin floor gradient, the longevity of routing systems and the structure of the margins (including the development of relay ramps).

8.3 Suggestions for future work

A number of gaps in our knowledge of rift basin sedimentation arise from this study either as a result of problems or limitations of this research, or as a result of natural extensions of ideas presented herein.

1) This study on the CIB, and close comparisons within modern day rift basin settings in the East African Rift, Rio Grande Rift and the Gulf of Suez Rift, identifies that the overall ancient rift concepts presented in the literature are correct, but the details are wrong. The CIB provides an excellent opportunity to study an ancient rift

basin in detail, including the influence of allocyclic and autocyclic controls on sedimentation. Given the influence of tectonics on controlling the drainage patterns in the CIB, it would be useful to apply these findings to other ancient rift settings worldwide to build up a greater awareness of process acting in the past. How do juxtaposed drainage systems interact when controlled by punctuated and localised fault block rotation? How do intrabasinal highs impose on depositional systems? Suggested methods could include computer modelling of ancient rift outcrops and examination and comparison of subsurface rift sediments in the North Sea, for example.

2) Given the 'personality' of this individual rift basin and the way in which many of the ideas discussed (Chapter 7) contrast with established rift models, it is suggested that more work needs to be done to highlight the individuality of all rift settings, rather than having a scenario where one model fits all. This could be done in a number of ways from examining the role of transverse flux into a basin and the climatic and tectonic timescales that operates on, to compartmentalisation in buried rift examples and the role tectonism played in influencing drainage pattern.

3) Only tentative sequence stratigraphic frameworks exist for non-marine, continental rift systems and it seems obvious that there is scope for this idea to be developed further in much the same way marine depositional systems can now be classified. Work by Shanley & McCabe (1993) and Turner (1999) and the ideas presented in this study provide a platform of which this new venture can founded. To help with this, fresh new methods such as Fischer Plots and orbital forcing timescales can be applied to ancient and modern rift sediments to investigate this theory further.

A challenge facing research on ancient rift basins in the next decade will involve finding more surface outcrops and interpreting the sediments in order to adapt current models of ancient rift basin sedimentation.

It is my hope that the work presented here has contributed towards a better understanding of an ancient rift basin, synrift sedimentation and the controls upon their development, and will assist future research efforts.

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