Continental rifting and post-breakup evolution of Southwest Iberia: Tectono-stratigraphic record of the first segment of the North Atlantic Ocean

Ricardo Nuno de Sousa Lemos Pereira

Submitted in partial fulfillment of the requirements for the degree of Doctor of Philosophy

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Declaration

I hereby declare that this thesis, submitted in fulfilment of the requirements for the degree of Doctorate of Philosophy, represents my own work. This work has not been previously submitted to this, or any other institution, for any degree, diploma or other qualification.

To my mother and father,

Lizete and Carlos

Author note and status of publications

The chapters comprising the bulk of this thesis were prepared as research papers published in international peer-reviewed journals. Partial results of the research were additionally presented in scientific conferences. Their present status is as follows:

Chapter 4 was published in "Pereira, R. and Alves, T. M. (2011). Margin segmentation prior to continental break-up: a seismic-stratigraphic record of multiphased rifting in the North Atlantic. Tectonophysics, 505, 17-34. DOI: 10.1016/j.tecto.2011.03.011". Preliminary results within this chapter were presented in international peer-reviewed conferences and published in:

- Pereira, R. and Alves, T. M. (2009). Mesozoic rifting of the SW Iberian margin - Implications to the hydrocarbon potential of Alentejo Basin. Society of Petroleum Engineers - 71st European Association of Geoscientists and Engineers Conference and Exhibition, Amsterdam, Netherlands, EAGE, 2983-2987.
- Pereira, R. and Alves, T. M. (2010). Multiphased syn-rift segmentation on the SW Iberian margin. 2nd Central and North Atlantic Conjugate Margins Conference, Lisbon, Portugal, 224-227.
- Pereira, R. and Alves, T. M. (2010). Multiphased rifting and margin segmentation across Southwest Iberia and South Newfoundland conjugate margin. AAPG International Conference and Exhibition, Calgary, Canada, American Association of Petroleum Geologists.

Chapter 5 was published in "Pereira, R., Alves, T. M. and Cartwright, J. (2011). Post-rift compression on the Southwest Iberian margin (Eastern North Atlantic): A case of prolonged inversion in the Ocean-Continent Transition. Journal of the Geological Society 168, 1249-1263. DOI: 10.1144/0016-76492010-151". Partial results in this chapter were presented in a conference and published as "Pereira, R., Alves, T.M., and Cartwright, J., (2010). The continent to ocean transition across the SW Iberian margin: The effect of syn-rift geometry on post-Mesozoic compression, 2nd Central and North Atlantic Conjugate Margins Conference, Lisbon, 228-230."

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Chapter 8 (Discussion), comprises parts of published conference abstracts, as follows:

- Pereira, R. and Alves, T. M. (2012). Is southwest Iberia an upper plate or a lower plate margin? 3rd Central and North Atlantic Conjugate Margins Conference, Dublin, Ireland, PIPCo RSG Ltd., 170-171.
- Pereira, R., Alves, T. M. and Cartwright, J. (2012). Tectono-stratigraphic evolution of the Southwest Iberian margin: a tail of the Central Atlantic. 3rd Central and North Atlantic Conjugate Margins Conference, Dublin, Ireland, PIPCo RSG Ltd., 75-76.
- Pereira, R. and Alves, T. M. (2012). Tectono-stratigraphy of multiphased rifting on the distal margin of Southwest Iberia (North Atlantic). Deep-water continental margins: The final exploration frontier?, London, UK, Geological Society of London, 73-74.

Although the articles are jointly co-authored with the PhD supervisors, the work published is that of the lead author, Ricardo Pereira. Editorial work was provided by the project supervisors in accordance with a normal thesis chapter.

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Alice and Francisco… your smile and unconditional love has always been my anchor... May your dreams come true.

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Abstract

The Southwest Iberia continental margin, located in the south-eastern North Atlantic Ocean and in proximity of an oceanic triple junction separating the westernmost Tethys, the Central and North Atlantic Ocean, is part of a world-class example of a magma-poor hyper-extended rifted margin that records the complete rift-to-drift evolution, mantle exhumation and subsequent tectonic inversion. Nevertheless, the Southwest Iberian margin remains a poorly investigated province and key uncertainties are yet to be addressed. The current work presents an integrated analysis of the tectono-stratigraphic rift-to-drift evolution of the Southwest Iberian margin and discusses its overall geodynamic implications.

The tectono-stratigraphic analysis of the continental margin reveals that three major extensional pulses controlled the architecture of the discrete tectonic sectors prior to continental breakup. Growth strata within each of these sectors denote persistent tectonic subsidence and demonstrate not only the progressive westwards rift locus migration towards the breakup position, but also conclusive evidence of multiphased rifting. In such a context, the current geometry of the margin is interpreted to have resulted mainly from rifting between the conjugate margins of Iberia-Newfoundland, but also from the combined continental extension between Nova Scotia and Morocco and the oblique rifting in the westernmost Tethys. The integrated tectono-stratigraphic analysis carried out herein shows that eight discrete Megasequences can be assigned to major tectonic events and used for modelling burial history of the discrete rift segments, consequently demonstrating that extension was significant not only during the transition to seafloor spreading, but also during the Early to mid-Jurassic. This analysis additionally reveals that similar depositional architectures can be grouped into meaningful Tectonic System Tracts, namely, the Rift Initiation System Tracts (RIST), the Rift Climax System Tracts (RCST), and the Late Rift System Tracts (LRST). The revised framework proposed in this work demonstrates that sequence stratigraphy can be used to describe and predict sedimentary facies distribution in continental rifted margins, as it recognises that multiple tectonic-stratigraphic (rift) cycles can occur on deep-offshore rift basins since the onset of rift-related extension until continental break-up.

The investigation of the tectono-stratigraphic controls and effects of margin inversion reveal that after a period of relative tectonic quiescence, post-rift tectonic reactivation affected the margin almost continuously since the latest Cretaceous to the present day. It is also revealed that the continental crust and their adjacent strata accommodated long-lived crustal shortening, which was neither synchronous nor similar in style. The magnitude and architecture of shortening is shown to be essentially dependent on the inherited syn-rift geometry and rheological behaviour of previously extended continental crust, the existence of detachments rooted at viscous early rifting deposits and the position of the ocean–continent transition zone. Mechanisms controlling the location and magnitude of crustal shortening were mainly dominated by the opening of the Gulf of Biscay during the Late Cretaceous, by continental collision of the Iberia microplate with North Africa during the Eocene-Miocene, and by the recent westward convergence with the oceanic domain.

The role of oblique deformation throughout the SW Iberian margin was assessed and is herein revealed to be more significant than anticipated. Transcurrent deformation, as part of a wider area of strike-slip tectonics, is thus dominantly controlled by first-order transfer zones, namely by the offshore prolongation of the Messejana-Plasencia Fault Zone (MPFZ). Here, growth strata reveal the development of a rift-related dextral releasing bend that accommodated both NW-SE oblique rifting in the westernmost Tethys and E-W rifting of the Iberia-Newfoundland conjugate margins. Post-rift change in kinematics of the MPFZ towards a predominant left-lateral restraining bend, demonstrate that first-order transfer zones play a significant role in segmenting distinct areas of the continental margin and in accommodating noticeable intra-plate deformation. The MPFZ is also revealed both as a major area of sediment bypass since the Late Cretaceous and the locus of early canyon incision since the Palaeogene, as well as an area where potential destructive earthquakes and tsunamis can be generated.

The results presented in this work suggests Southwest Iberia is an upper-plate rifted continental margin, which bears implications for the re-assessment of evolution of the Iberia-Newfoundland conjugate margin as a whole.

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Introduction

'Begin at the beginning,' the King said gravely, 'and go on till you come to the end: then stop'.

Lewis Carrol, Alice's adventures in Wonderland

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1. Introduction

1.1. Rationale

Rifted continental margins are one of the many research subjects intensively addressed by the geoscience community, aiming to contribute to an immense group of essential questions, either purely scientific, or of local to global industry impact. Academia, Industry and governments have been addressing this theme in order to fully understand the processes controlling the evolution and the economic potential of such areas, which constitute significant hydrocarbon bearing provinces. Within this context, the Atlantic continental margins of Portugal and Spain (usually referred to as West Iberia), persists as a preferred region where these themes can be thoroughly investigated, and from which a vast number of questions are still under debate. The West Iberia continental margin remains as one of the least explored provinces in the North Atlantic and where significant resources are still expected to be discovered.

The West Iberian margin has often been a primary research ground to many of the concepts of the geodynamic evolution and architecture of continental rift margins (e.g. Boillot et al., 1979; Le Pichon and Sibuet, 1981; Tankard and Balkwill, 1989; Manatschal and Bernoulli, 1998, 1999; Boillot and Froitzheim, 2001). In great part, these models are the result of significant data acquired from several deep-sea drilling campaigns, namely the Deep Sea Drilling Program (DSDP) Leg 13 and the Ocean Drilling Program (ODP) Legs 103, 149, 173 and 210. Recently, during 2011-2012, a new campaign of the Integrated Ocean Drilling Program (IODP, Leg 339) took place on the Southwest Iberian margin with the purpose of studying deep-water circulation between the Mediterranean and the Atlantic. In parallel, the Estrutura de Missão para a Extensão da Plataforma Continental (EMEPC) has been conducting several geological, geophysical and biological studies. These studies have been accompanied by comprehensive fieldwork focusing not only on the geometry of rotational tilt block, but also on the depositional architecture of growth strata (e.g. Wilson, 1979; Wilson et al., 1989; Ravnås and Steel, 1998; Alves et al., 2003c; Azerêdo et al., 2003; Rey et al., 2006).

The West Iberian margin is therefore a preferred province to clarify some of the most striking controversies and unclear questions on the evolution of continental rifted margins (e.g. Karner et al., 2007), which include among others: 1) the exact age of continental breakup and the formation of normal oceanic crust on rifted margins; 2) the rigorous definition of breakup; 3) the number of rifting events occurring prior to seafloor spreading and their timing; and 4) how igneous underplating affects the rifting process.

The initial driver of the research undertaken during this PhD was the hypothesis that the southwest continental margin of Portugal (commonly referred as the Alentejo Basin) could contain hydrocarbon accumulations of economic importance. This goal was defined prior to the beginning of this PhD project as part of my current position as an exploration geologist at Partex Oil and Gas. The Alentejo Basin was one of the areas of interest for the company, in which several uncertainties regarding its geological evolution hindered a more accurate assessment of exploration risk on the margin. The outcome of this research would also have an impact on the understanding of other prospective areas were Partex Oil and Gas is currently participating, either as an operating company or as a shareholder. Moreover, the geometry, organization and extension of strata that might constitute traps for hydrocarbon accumulation are also one of the issues that need clarification. The latter questions were resolved only partly by this thesis, as there is still limited knowledge on some of the onshore stratigraphic units and more significantly on their prolongation to the offshore and how these could be related to the overall evolution of the North Atlantic. Many of these uncertainties also depended on the insufficient quality of older seismic data imaging the continental margin, which hampered a more insightful understanding of such questions. The acquisition of recent high-quality multichannel seismic data in Southwest Iberia opened the way for new studies, which constitute the basis for the innovative results documented in the present work.

This work aims to construct a meaningful analysis of the evolution of the Southwest Iberian margin, by integrating large scale geodynamic models along with the regional tectono-stratigraphic investigation of a rifted continental margin subsequently affected by inversion.

1.2. Tectono-stratigraphic analysis of continental rifted margins

1.2.1. Geodynamics of continental crust extension

Extension of continental crust and the formation of rift margins are largely controlled by the combined stresses between the lithosphere and asthenosphere, that with time result in the progressive thinning of the lithosphere and eventually, in the complete separation of the continental crust segments with the formation of oceanic crust (e.g. Ziegler and Cloetingh, 2004; Rosenbaum et al., 2008; Merle, 2011).

The dynamic rift processes regulating continental extension are dominantly controlled by asthenospheric convective systems that induce the thinning of the lithosphere and often cause adiabatic decompression with associated melting and magma rise, which are the result of the complex interplay between plate-boundary forces, drag frictional forces acting on the base of the lithosphere and deviatory tensional stresses (e.g. Ziegler and Cloetingh, 2004). Examples of these processes, often associated with significant hydrocarbon provinces can be found throughout the globe, such as in the East African Rift, the Atlantic or the Australian Rift (e.g. Lambiase and Morley, 1999; Ziegler and Cloetingh, 2004).

Margins resulting from lithosphere extension are commonly referred to as a consequence of “active” or “passive” continental rifting (e.g. Turcotte and Emerman, 1983; Merle, 2011 and references therein). The distinction between these two types of rifting models is mainly dependent on the involvement of deep dynamic sub-lithospheric processes and not on the geometry of such extensional systems (e.g. Corti et al., 2003; Rosenbaum et al., 2008; Merle, 2011). Active rifts are dominated by thermal upwelling of the asthenosphere and often develop large igneous provinces, whereas passive rifts are in large extent the result of plate boundary forces, with scarce igneous activity (Fig. 1.1)

(Corti et al., 2003; Ziegler and Cloetingh, 2004; Rosenbaum et al., 2008; Merle, 2011). As such, Merle (2011) proposed a revised classification of rift systems based on four main geodynamic end-members and on the dominant process controlling continental extension (Fig. 1.2): 1) subduction-related rifts, 2) mountain-related rifts, 3) plume-related rifts, or 4) transform-related rifts.

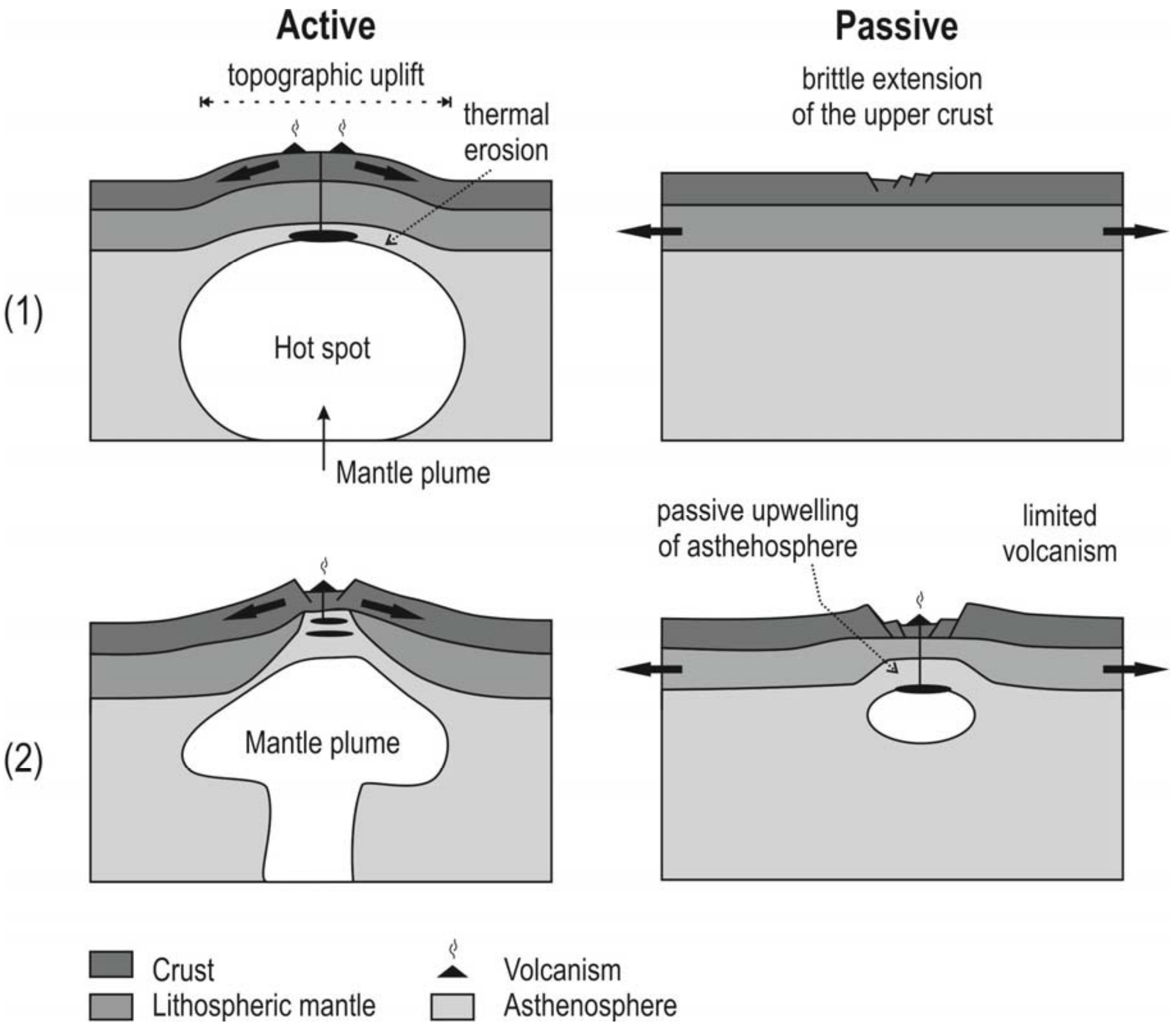

Figure 1.1 - Schematic diagram for the evolution of continental rifting in different stages (1) and (2) for Active rifting and Passive rifting models. Modified from Corti et al. (2003) and Merle (2011).

In parallel, passive margins can be classified either as “volcanic” or “non-volcanic”, depending on the relative amount of magmatic activity associated with extension process (e.g. Geoffroy, 2005; Reston, 2007). Volcanic passive margins are commonly associated with the intrusion of hot mantle volcanic rocks during continental breakup, with the occurrence of flood-basalts and tuffs, often observed on seismic data, showing strongly reflective Seaward Dipping Reflectors (SDR) sequences (Geoffroy, 2005). In contrast, “magma-poor passive margins” (sensu Manatschal, 2004), although not excluding the occurrence of volcanism usually are characterised by (e.g. Reston, 2007):

- Low-moderate sediment accumulation rates
- Extreme crustal thinning and highly rotated fault blocks
- Detachment faults rooting at deep crustal levels
- The presence of a transitional domain from the continental to the oceanic crust

Although not entirely devoid of magmatism, the West Iberia (and other “magma-poor” rifted margins in the Atlantic) shows episodic magmatic activity during the rifting process and subsequent post-rift evolution. Throughout West Iberia magmatism is described in the Late Triassic-Early Jurassic, the Late Jurassic and the Late Cretaceous (e.g. Pinheiro et al., 1996; Tucholke and Sibuet, 2007; Martins et al., 2008; Miranda et al., 2009; Martins et al., 2010).

In such a setting, the ascent of magma coupled with extension of the lithosphere is the expression of adiabatic decompression, partial melting of the lower lithosphere and upper asthenosphere, which is dependent on the rate and magnitude of stretching and the potential temperature of the asthenosphere (Ziegler and Cloetingh, 2004).

	Tectonic evolution “Active” and “Passive” processes	
Plume-related	ACTIVE (possibly with a passive component at a late stage)	
Mountain-related	PASSIVE (Possibly with an active component at a late stage)	
Subduction-related	Slab retreat	PASSIVE
	Stagnant slab	ACTIVE
	Slab detachment	ACTIVE
Transform-related	PASSIVE	

Figure 1.2 – Simplified classification for rifted continental margins (Merle, 2011).

1.2.1.1. The models of lithospheric extension

Ever since the early establishment of plate tectonics models as a theory to explain the separation of continents, several models have been invoked to explain the processes, geometries or rheological behaviour of the lithosphere during extension (e.g. McKenzie, 1978; Wernicke, 1981; Lister et al., 1986; Buck, 1991; Corti et al., 2003; Karner et al., 2007; Crosby et al., 2008; Rosenbaum et al., 2008; Merle, 2011).

The interplay of the processes controlling extension of the lithosphere result in the formation of typical architectures that have been grouped in principal end-member models explaining the geometry of rifted margins, usually based on the main kinematic controls of extension, the symmetry of the conjugate margins and the existence of deep crustal detachments (Corti et al., 2003; Rosenbaum et al., 2008). These models depend mainly on the variation of distinct components such as thermal structure, strength, rheology heterogeneities, strain rates, thickness and the nature and composition of the lithosphere (Corti et al., 2003; Rosenbaum et al., 2008).

Acknowledging the distinct architectures of passive rifted margins, three main types of geometries and modes of extension are considered namely, the Narrow Rift mode, the Wide Rift mode and the Core Complex mode (Fig. 1.3) (Buck, 1991; Rosenbaum et al., 2008). Both narrow and wide rifts are interpreted to result from the extension and thinning of the lithosphere dominantly controlled by thermal uplift of the convective asthenosphere (and therefore dominated by active rifting), from which the latter result from slow strain of divergent margins and gravity collapse of the upper continental crust (Buck, 1991; Brun, 1999).

Narrow rifts have an approximate order of width of a few hundreds of kilometres where intense normal faulting generates a horst-graben geometry, with type-examples being the Rhine Graben, the Gulf of Suez, the East African Rift or the Sergipe-Alagoas Basin (Brazil) (Buck, 1991; Davison, 1997). Conversely, wide rifts, such as the North American Basin and Range, or the São Paulo Plateau on the South-eastern Brazilian margin, show typical extension of normal faulting along a 600-800 km ribbon along the continent (Buck, 1991; Davison, 1997).

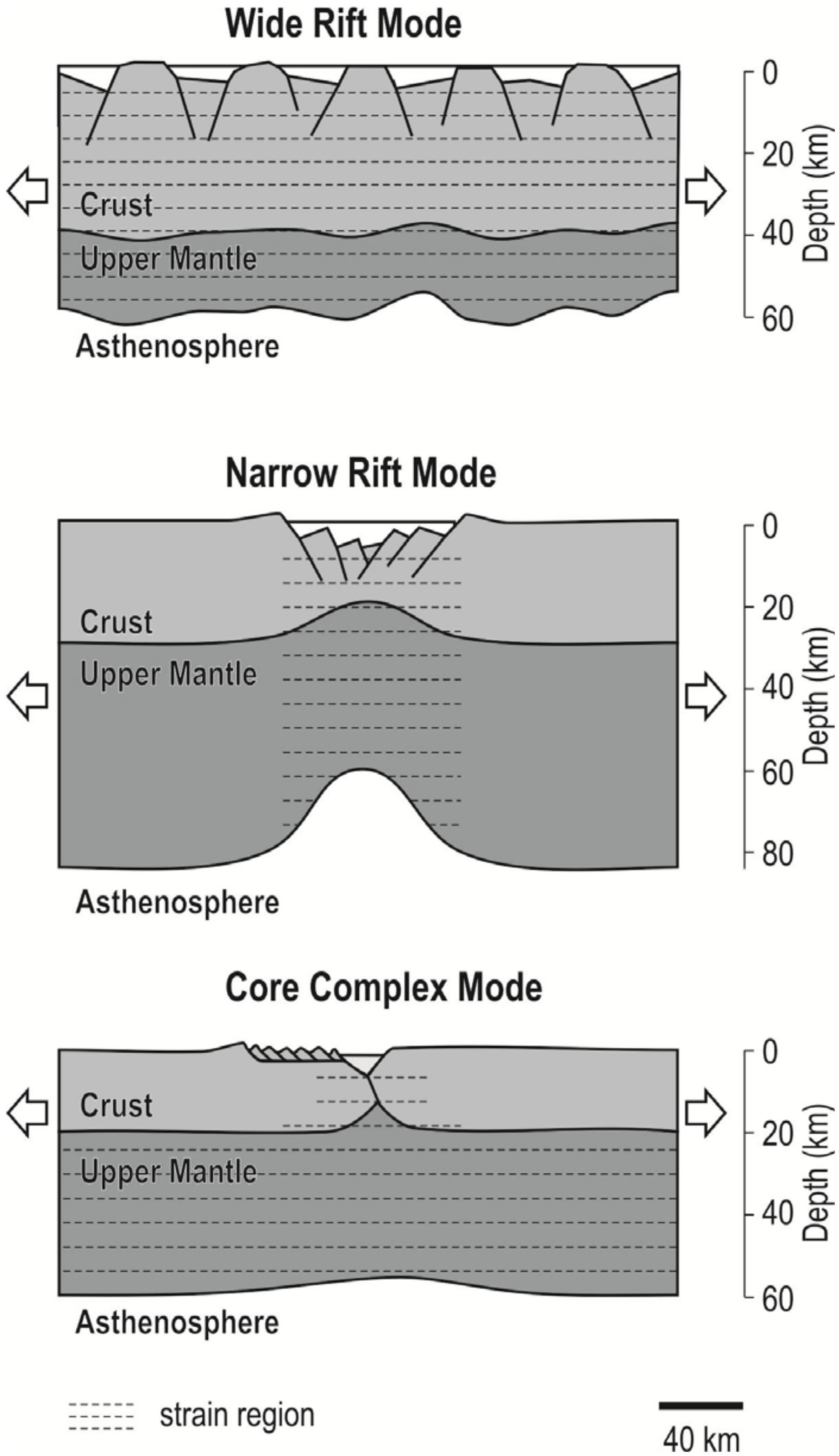

Figure 1.3 – Schematic architecture of modes of lithospheric extension. Modified from Buck (1991) and Rosenbaum et al. (2008).

These two types also differ on the extension rate, where wide rifts are associated with larger extensional values, whereas narrow rifts are characterised by lower rates (e.g. Davison, 1997).

The Core Complex model invokes the existence of areas with high-grade metamorphic rocks and the occurrence of a lower crust low-angle detachment (Wernicke, 1981; Bosworth, 1985; Wernicke, 1985), which can be considered a variation of a wide rift model (Merle, 2011). However for some authors the terms “narrow” and “wide” rift are purely descriptive and have no mechanical, kinematic or major geodynamic significance (e.g. Davison, 1997). The formation and evolution of core complex models of lithospheric extension was summarised by Lister et al. (1986, 1991) anticipating depth-dependent controls of differential extension between the brittle and ductile layers across the lithosphere, invoking the occurrence of a deep crustal detachment to explain the symmetry or asymmetry of passive rifted margins. The different explanations are traditionally referred as the “simple shear”, the “pure-shear” and the “delamination” models (Fig. 1.4).

The “pure-shear” model defined by McKenzie (1978) was postulated for the Basin and Range province (continental United States of America) and is often used to predict crustal thickness, subsidence history and gravity profiles of other symmetric passive margins, and assumes homogeneous thinning of the lithosphere. However, in the case of asymmetric rifted margins it does not fully explain the variations in the architecture of continental crust (Lister et al., 1986), such as the case of the Iberia-Newfoundland (Manatschal and Bernoulli, 1998, 1999).

Subsequently, Wernicke (1981) an later Coward (1986), postulated the existence of a deep lower crust detachment that aimed to account for the variations in crustal thinning, the geometry of rift-related normal faults, the existence of marginal highs, ribbons and plateaus, where often multiple detachments control the evolution of the rifted margins (Lister et al., 1986). The “delamination model” of the lithosphere is presented as an alternative explanation for thinned continental margins that show steepening lower crust detachments (Lister et al., 1986).

The postulate that rifted margins can be asymmetric and that extension is largely controlled by deep detachment faults formed under simple-shear led Lister et al. (1986) to suggest the existence of an “upper-plate” and a “lower-plate” geometry for passive continental margins, both showing distinct subsidence/uplift signatures and unique distribution of the Ocean-Continent Boundary along the margin (Fig. 1.5).

The latter authors consider that the upper-plate is characterised by:

- A basal low-angle normal-slip detachment fault of large areal extent, on which substantial relative displacement has occurred;
- Significant extension of about 100-400%, resulting from listric and/or domino-like block rotation bounded by high-angle normal faults;
- Continued rift-related sedimentation over tilt blocks;
- A master lower crust detachment dipping towards the continent;
- Relatively simple geometry of the segmented upper crust, from which normal faulting shows limited rotational component;
- The existence of underplated magma at Moho levels, below the upper plate margin.

Equally, these authors consider that the lower-plate is broadly characterised by:

- Deep crystalline rocks overlain by highly faulted remnants of the upper plate;
- Highly structured basement with rotational normal faults, tilt blocks and half-grabens typical of so-called rift phase margin development;
- Distinct signature of rift-stage structure and their uplift/subsidence characteristics, commonly with rapid uplift of the proximal margin;
- Rift-shoulder uplift during extension as the load of the upper plate is removed and a broad arch or culmination is developed.

The model also predicts the lateral change of geometric setting from upper- to lower-plate, associated with the occurrence of orthogonal transfer zones acting as preferred domains for stress accommodation, which subdivide the margin into distinct tectonic segments (Lister et al., 1986; Etheridge et al., 1989).

Taking into account the implications of the model proposed by Lister et al. (1986), recent advances in the study rifted passive margins consider that finite stretching models of the upper crust differ from those estimated for the lithosphere, which is referred as the “upper-plate paradox” (Rosenbaum et al., 2008). Consequently, simple shear models explaining the geometry of the Iberia-Newfoundland conjugate margins can have distinct solutions regarding the polarity of the deep crustal detachment (e.g. Rosenbaum et al., 2008). Nonetheless, the northwest Iberian margin has been interpreted as a lower plate margin (Wilson et al., 1989; Reston et al., 1995; Manatschal and Bernoulli, 1998, 1999; Alves et al., 2009).

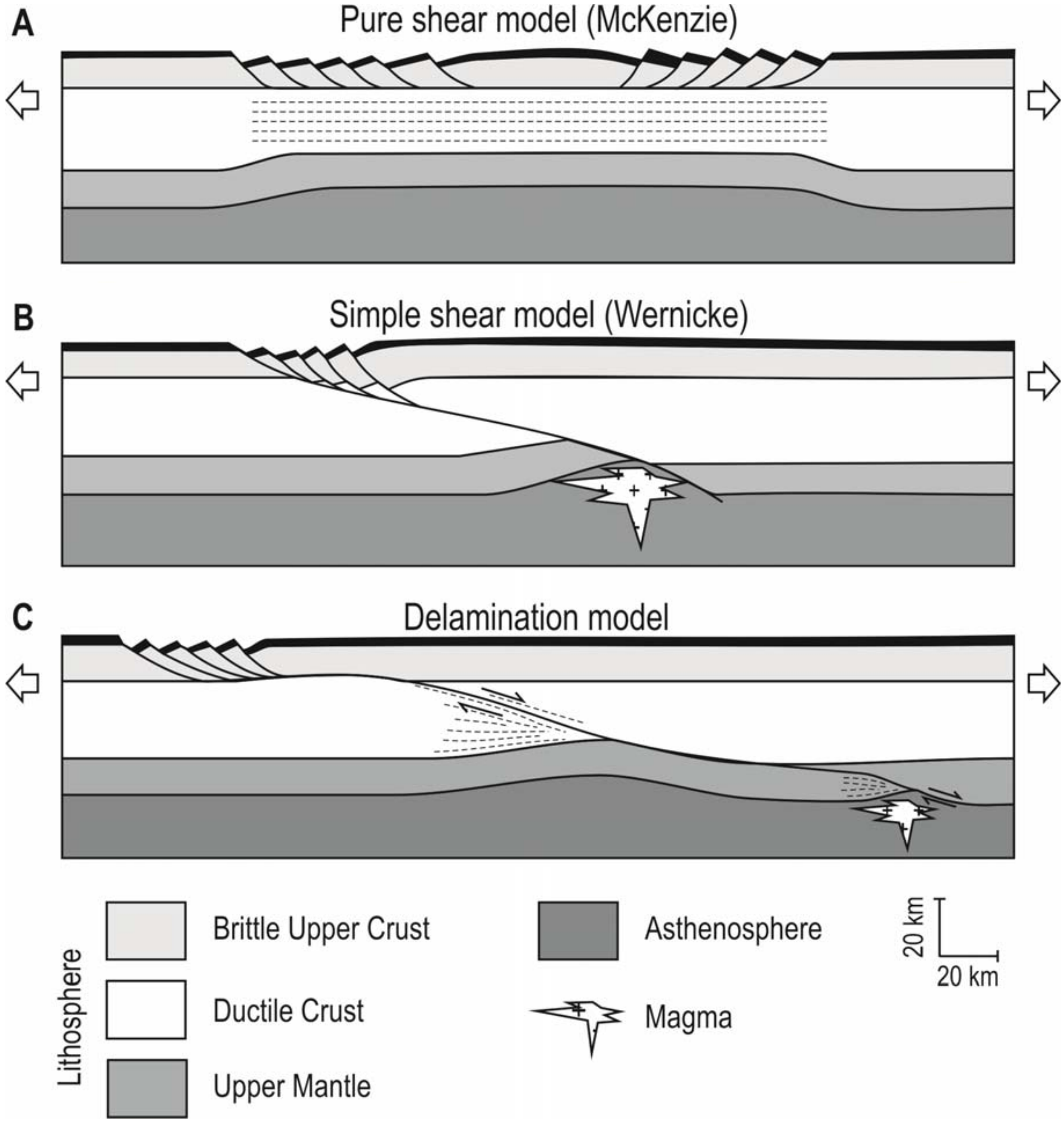

Figure 1.4 – Schematic model of continental lithosphere extension. Modified from Lister et al. (1986).

Although the models presented above are commonly accepted to explain the geometry and evolution of rifted continental margins, increasing evidence of alternative explanations point to distinct processes and architectures for such geodynamic setting. Nagel and Buck (2004) suggest a symmetric upper crust collapse over a mid-crustal detachment in the rift centre presents on both sides of rifted margins of Iberia-Newfoundland.

Experimental models based on the Labrador-Greenland conjugate margins, point to asymmetric Moho geometries, which are interpreted to have generated asymmetric rifting (Corti and Manetti, 2006).

Apart from the conceptual models, rift margins have been modelled through geophysical and geological methods, showing that during the initial stages the relative predominance of shear zones reveals two distinct modes of deformation where simple shear dominates during the early stages of continental rifting, whereas during transition to seafloor spreading, pure shear prevails (Michon and Merle, 2003).

The discovery of hyper-extended segments of the rifted continental crust associated with mantle exhumation, mainly based on evidence from magma-poor margins of Iberia-Newfoundland and the Alps induced a number of recent questions, namely (e.g. Unternehr et al., 2010; Bronner et al., 2011; Sutra and Manatschal, 2012): 1) how does the crust thin to such highly extended domains; 2) what mechanisms control extreme crustal thinning and mantle exhumation; 3) what is the relative timing of exhumation and the rupture of the lithosphere; and 4) how can these hyper-extended models be applied to other rifted margins. Hyper-extended rifted margins are therefore characterised by mantle exhumation in response to depth-dependent extreme thinning of the continental crust and polyphased faulting that bounds highly rotated crustal blocks (often rooting at the Moho) (Boillot and Froitzheim, 2001; Whitmarsh and Wallace, 2001; Manatschal, 2004; Unternehr et al., 2010).

1.2.1.2. The ocean-continent transition

In the last two decades, advances in knowledge of the processes and geometry of extension of continental crust during rifting, revealed the importance of depthdependant extension and mantle exhumation on non-volcanic passive margins, such as the case of the Iberia-Newfoundland margins, Papua New Guinea or the Great Australian Bight sector (e.g. Boillot and Froitzheim, 2001; Manatschal, 2004; Sibuet et al., 2007b; Rosenbaum et al., 2008). In the case of the Iberia-Newfoundland, geophysical data (e.g. Pinheiro et al., 1992; Pinheiro et al., 1996; Sibuet et al., 2007b; Tucholke et al., 2007; Afilhado et al., 2008), deep-offshore drilling campaigns (Wilson et al., 2001; Tucholke and Sibuet, 2007) and outcrop analogues (Manatschal and Bernoulli, 1999; Manatschal, 2004), have addressed the complexity of the formation of the Ocean-Continent Transition (OCT) zone.

The OCT consists of the region between the seaward edge of fault blocks of thinned continental crust and the landward edge of the oceanic crust and is composed mainly of serpentinised peridotites and gabbroic units of apparent continental mantle affinity that were exhumed by extreme thinning of the continental crust often preceding the creation of oceanic crust during rifting (Whitmarsh and Wallace, 2001; Tucholke et al., 2007; Rosenbaum et al., 2008; Sutra and Manatschal, 2012). Alternatively, it is proposed that the OCT can be formed as the result of ultra-slow sea-floor spreading (Srivastava et al., 2000). Nonetheless, the OCT is revealed as a wide region (150-180 km) that shows the absence of the lower crust on both margins and is associated with the presence of a series of highly rotated tilt-blocks forming distinct sub-basins separated by basement highs, some with continental affinity (e.g. Wilson et al., 2001; Manatschal, 2004; Tucholke et al., 2007; Rosenbaum et al., 2008). Consequently, throughout the West Iberian margin several authors have estimated the position of the OCT, although this transition zone is far more constrained on the Galicia segment than that on the Southwest Iberian margin (e.g. Pinheiro et al., 1992; Sibuet et al., 2007b; Afilhado et al., 2008).

The understanding of the mechanisms associated with the formation of the OCT and the complexities inherent to the study of such exhumed mantle has profound implications on the estimation of the timing of continental breakup (e.g. Tucholke et al., 2007; Bronner et al., 2011). Sibuet et al. (2007b) summarise the main aspects concerning this problem, which account for the existence of significant magnetic anomalies that have been traditionally interpreted as the “real” onset of seafloor spreading.

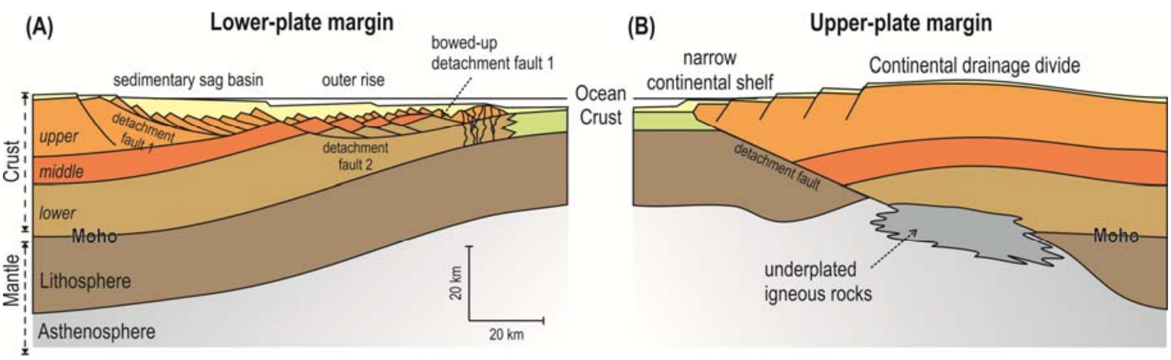

Figure 1.5 – Schematic model of detachment-fault for passive continental margins, showing the upper plate and lower plate geometry. Modified from Lister et al. (1986).

These authors also suggest that magnetization of altered serpentinites may produce similar magnetic anomalies and therefore, mask the age of the formation of oceanic crust on more proximal areas of the OCT.

As such, based on the results from deep-sea drilling off the Galicia margin, two periods of mantle exhumation were identified, revealing the multiphased nature of extension during the transition to seafloor spreading (Sibuet et al., 2007b). Although similar processes are described on the Southwest Iberian margin (Mauffret et al., 1989a; Pinheiro et al., 1992; Srivastava et al., 2000; Tucholke et al., 2007), limited information exists regarding the exact nature, age of the formation of oceanic crust and the extension of the OCT in this region.

1.2.1.3. Zonation of magma-poor rifted margins

In order to explain the exhumation of lithospheric mantle during the late stages of continental rifting, the overall geometry and evolution of continental margins during extension, the simple shear Wernicke's model has evolved and accounted for evidence from Jurassic outcrops on the Briançonnais-Adriatic margins in the Alps and from the geophysical and borehole data from the Galicia margin (Froitzheim and Manatschal, 1996; Manatschal and Bernoulli, 1998, 1999; Manatschal, 2004; Péron-Pinvidic and Manatschal, 2009).

It is observed that rifted margins, during their evolution develop distinct geometries as a result of the tensile forces exerted in the lithosphere. A transect across the margins of the Alps and Northwest Iberia, reveals two distinct crustal architectures, which include the proximal and distal margin, both revealing two main phases of rifting with associated westwards migration of the rifting site (Manatschal and Bernoulli, 1998, 1999; Manatschal, 2004) (Fig. 1.6).

The proximal margin extends seawards of the mainland and terminates by the Slope Fault System (sensu Alves et al., 2006) and is characterised by normal faults dipping towards the basin centre, forming an assembly of rotated fault blocks with nearly symmetric geometry segmenting the upper continental crust with thicknesses usually in excess of 20-30 km (Manatschal and Bernoulli, 1998, 1999; Manatschal, 2004). This sector broadly coincides with the Thinned Domain and Continental Domain suggested by Afilhado et al. (2008). Fault systems in this sector are dominantly formed during the early phase of rift extension probably inherited from a previous pre-rift fabric and are also dependent on the rheology of the upper continental crust (Manatschal, 2004).

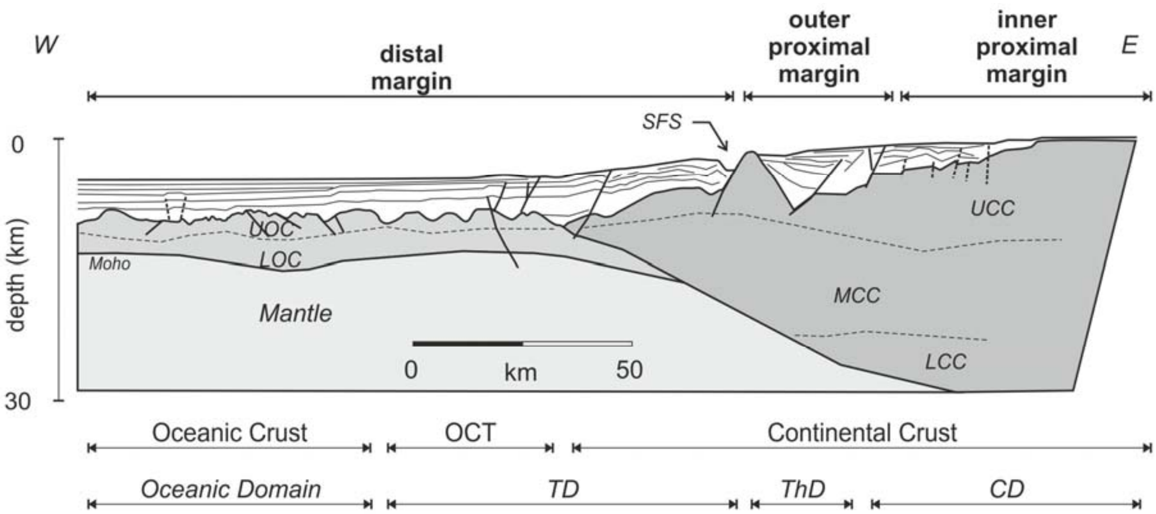

Figure 1.6 – Schematic geometry of non-volcanic passive margins showing the different sectors of the thinned continental crust in relation with the zonation proposed by several authors. Adapted from Afilhado et al. (2008). CD – continental domain, LCC – lower continental crust, LOC – lower oceanic crust, MCC – middle continental crust, OCT – ocean-continent transition, OD – oceanic domain, TD – transitional domain, ThD – Thinned domain, UCC – upper continental crust, UOC – upper oceanic crust, SFS – Slope Fault System.

The distal margin extends seawards of the Slope Fault System (Fig. 1.6) and is characterised by highly rotated upper crust tilt-blocks (with high β values) over a deep crustal detachment surface dipping landwards, interpreted as representing the root of simple shear detachment (e.g., the S reflector in the case of the Galicia margin) (Boillot et al., 1979; Manatschal and Bernoulli, 1999). The hyper-extended domain of the continental crust thins rapidly from about 30 km to less than 5 km within a distance of only 75 km (Manatschal and Bernoulli, 1998, 1999; Manatschal, 2004). The final architecture of this sector of the margin is shaped during the Advanced Rifting Stage with previous early rift faults being reworked as listric faults deeply rooted on the ductile Moho transition (Froitzheim and Manatschal, 1996; Manatschal, 2004). Additional fault geometry is induced during the polyphase brittle extension (Reston, 2007). In this sector, the magmatic weakening of the lithosphere coupled with rising asthenosphere induces significant rheological modifications, which increases significantly the potential to continuously thin the unroofed mantle and extremely thinned continental crust and subsequently generate new oceanic crust (e.g. Reston, 2009).

Differences within both sectors of the continental margin can also be found on the geometry of sediments overlying the tilt-blocks (Manatschal and Bernoulli, 1999; Wilson et al., 2001; Manatschal, 2004). As such, on the proximal margin accommodation space is created dominantly by vertical displacement and limited block rotation inducing the deposition of typical syn-rift growth strata derived from the hinterland, whereas on the distal margin, syn-rift deposition tends to be characterised by sub-parallel accumulation of deep pelagic sediments, some sourced from the footwall of the high-β drifting crustal blocks (Wilson et al., 2001; Manatschal, 2004). A detailed overview on the controls and expression of marine and non-marine deposition on rift systems is presented in the next section (Ch. 1.2.2).

Although simplistic, this zonation allows a quick understanding of the architecture of passive margins, with similar examples of geometries evidencing the changing location of rifting main tensile efforts found offshore Morocco (e.g. Le Roy and Piqué, 2001), the North Sea (Nøttvedt et al., 1995) and the East Brazil rift system (e.g. Chang et al., 1992; Contreras et al., 2010).

1.2.2. Tectono-sedimentary controls on extensional basins

Extension of the continental lithosphere during rifting is a complex interplay of distinct geodynamic processes that lead to thinning and fragmentation of its uppermost brittle layers, resulting in the simultaneous creation of basins and their associated uplifted areas. As such, during the formation of rifts, tensile forces, mantle upwelling along with the rheology of the lithosphere take primordial control on the generation of new domains of subsidence. Several mechanisms and models have been developed to explain the processes that ultimately may lead to complete oceanization (Ziegler and Cloetingh, 2004). Within such geodynamic settings, distinct types of sediments may be accumulated in either non-marine or marine environments, each possible of bearing significant hydrocarbon accumulations (e.g. Lambiase and Morley, 1999; Doust and Sumner, 2007).

Apart from these controls, a group of other processes play a major role in deposition in extensional basins, such as climate, variations of sea level, drainage or sediment supply (Leeder and Gawthorpe, 1987; Frostick and Steel, 1993; Ravnås and Steel, 1998).

The following sections present a brief summary of the main tectono-stratigraphic concepts regarding the geometric features and controls of tectonics on rift basins, the depositional and environmental aspects of basin infill and the main tools that allow describing such depositional settings.

1.2.2.1. Basin development and geometry

Deposition within rift basins is largely controlled by the geometry of the segmented upper crust, commonly organised into tilt-blocks and half-grabens bounded by major normal faults that result in the formation of more or less pronounced asymmetric basins, as a result of dominant normal to oblique extension (Ingersoll and Busby, 1995 and references therein). Examples of such type of geometries have been extensively described from both from ancient (e.g. the North Sea, the Aegean) and recent rifts (e.g. the East African Rift), either based on outcrops, boreholes, geophysical data or analogue models (e.g. Leeder and Gawthorpe, 1987; Frostick and Steel, 1993; Lambiase and Bosworth, 1995; Ravnås and Steel, 1998; McClay et al., 2001).

Since the onset of extension, fractures and faults (often changing polarity along rift axis) tend to form in response to tensile failure of the brittle crust, Faults may be created in large number revealing limited displacement and somewhat scattered orientation and density (Gawthorpe and Leeder, 2000; McClay et al., 2001) (Fig. 1.7). With time, continued extension tends to favour the interaction and linkage into dominant segments, which in a more advanced stage results in the formation of main faults controlling the overall geometry of a basin, along which, displacement of faults and subsidence on tilt-blocks progressively increases (Fig. 1.7) (Gawthorpe et al., 1994; Gupta et al., 1998).

Subsidence pattern during a rift phase is characterised by an initial period of limited fault displacement and consequent minor subsidence, followed by a period of maximum displacement along which, accommodation space is increased significantly and ultimately, a final period of diminished subsidence that occurs during the latest stages of a rift (Gupta et al., 1998). Accordingly, the period of maximum subsidence and fault displacement coincides with the climax of a rift phase. However, in several rift basins, more than one phase of rifting can be described in what can be broadly referred as multiphased rifting (e.g. Chang et al., 1992; Nøttvedt et al., 1995; Ravnås et al., 2000; Alves et al., 2006).

The tilted geometry of rotational blocks is diverse and within each case the overall topography of the newly formed sub-basin must be addressed individually, although bearing in mind the regional evolution of the rift margin as a whole. Either bounded by listric or planar faults (forming a single or a series of half-grabens), rift sub-basins share a common architecture that include (Leeder and Gawthorpe, 1987; Lambiase and Bosworth, 1995; Ravnås and Steel, 1998):

- an uplifted footwall and an associated subsiding steep slope hangingwall, above which sedimentary deposits tend to accumulate;
- basin-bounding master faults with lengths of 10-35 km, although some can extend in excess of 50 km;
- polarity reversal of individual faults bounding each sub-basin;
- the presence of relay ramps that accommodate tensor change during extension and fault linkage;
- transfer faults, often segmenting the margin into discrete sub-basins;
- a zero rotational component of each block, in relation to an inertia point, usually referred as “fulcrum”.

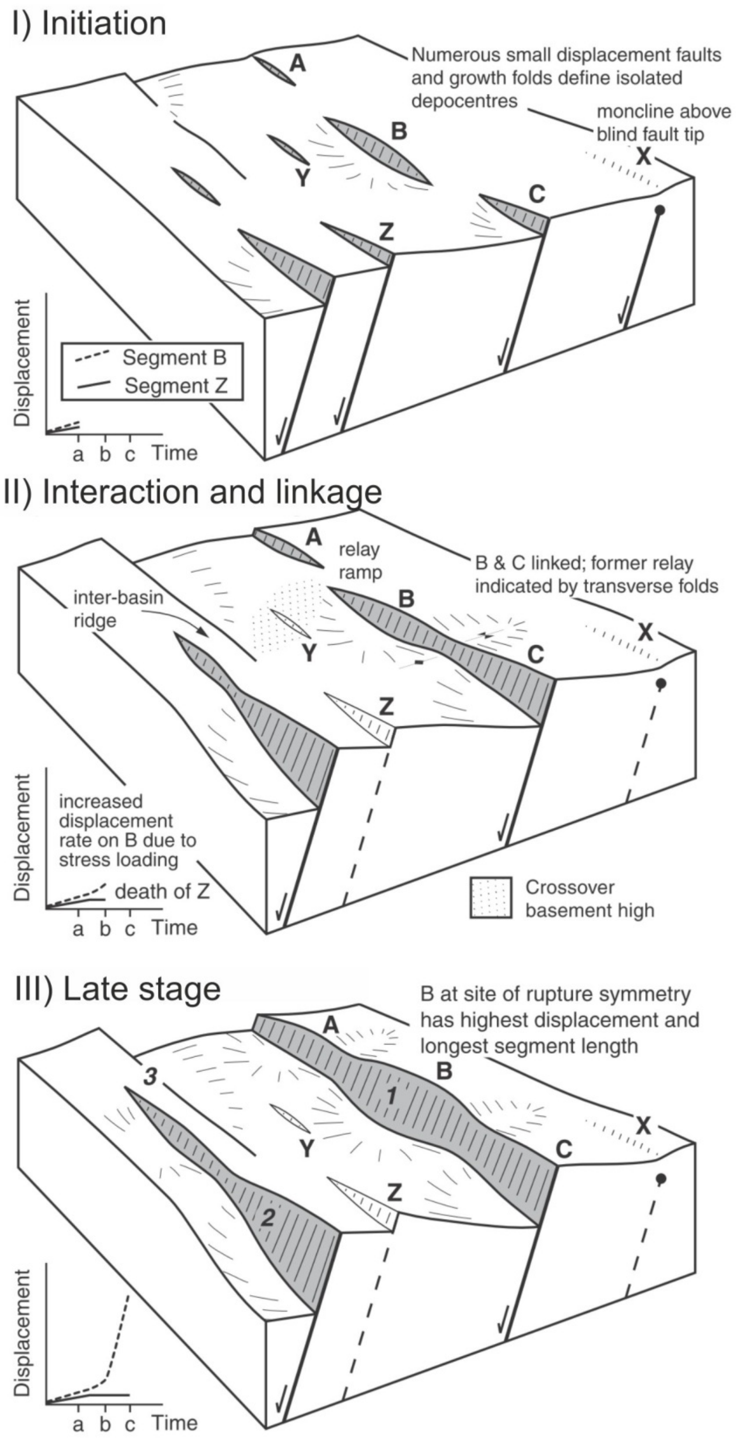

Figure 1.7 – Schematic block-diagram depicting the evolution of normal fault arrays, illustrating the displacement history and fault coalescence since the onset of extension (I), the coalescence stage (II) until an advanced stage (III) of organisation of master faults bounding the main sub-basins (modified from Gawthorpe and Leeder, 2000). During stage II, faults X, Y and Z cease to accommodate extension and subsidence is focused in segments A, B and C that progressively tend to link as master faults in stage III, which control the main depocenters and drainage.

Studies based on outcrops reveal a correlation between the displacement of the master fault and its approximate length, such as $D=cL^n$, where D is the maximum displacement, L refers to the trace length of the main fault bounding a sub-basin, c is a rheological constant and n is the exponent, ranging between 1 and 2 (Gawthorpe and Leeder, 2000 and references therein). Such relation allows not only the estimation of the displacement of a fault, its length, but also allows to understand the linkage and evolution of individual faults throughout a rifted area (Gawthorpe and Leeder, 2000).

The intricate combination of such variables during the evolution of rift basins typically produces a wedge-shape geometry of the infilling deposits when observed in dip section and an overall elongated half-ellipse in map view (e.g. Leeder and Gawthorpe, 1987).

1.2.2.2. Controls on infill architecture

As mentioned above, a number of distinct tectonic parameters exert their influence on the creation of new basins and the generation of new accommodation space. As such, primary external factors influence the infill pattern within a sub-basin, which include the global variations of the sea-level (eustasy), the constantly changing sediment supply and the modifications on the drainage pattern (e.g. Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000).

Relative base-level variation and eustasy

One of the primary aspects controlling sedimentation on rift basins is the recurrent global variation of the sea-level, commonly referred to as eustasy. As such, the concept of base-level is of fundamental importance, as it bears major significance both on marine and on continental depositional settings.

Accordingly, it is herein considered that the base-level refers to “the global reference surface to which long-term continental denudation and marine aggradation tend to proceed” (Catuneanu, 2006). As a simplification, this author also points out that this conceptual surface reflects the sea-level during a certain period, but also has applications to equilibrium profiles on fluvial systems and continental rift basins that are not directly connected to the sea.

Although often debated in literature whether if it is eustasy or tectonics controlling deposition in many rift basins, it is dominantly accepted that during extension of the continental crust, tectonic subsidence is the main driver for the creation of new accommodation space.

Eustatic variations occur during longer periods, whereas tectonic induced modifications of the base-level are typically focused during short periods of increased deepening of the basin substratum (Ravnås and Steel, 1998 and references therein). Nonetheless, eustatic variation are often recorded in rift basins, especially during periods of diminished tectonics subsidence and are mainly recorded on the shallower areas of the hangingwall, which are wider or narrower depending on the steepness of the tilt-blocks (Ravnås and Steel, 1998).

In marine rift basins (as opposed to non-marine basins), global eustasy and local sea-level variations show distinct effects depending on the position of the individual sub-basins in relation with proximal or distal domains of an extensional margin and are accordingly referred as slightly, partly or fully submerged sub-basins (Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000). Within this setting, sub-basins can vary from non-marine dominated on the proximal margin to fully submerged on the distal margin.

Sediment supply, drainage and climate

In rift basins sediment accumulation on depocentres is largely controlled by a group of independent parameters that influence the distinct types of deposits trapped or formed on such areas, such as climate, the distance to the hinterland, the evolving drainage network and the nature of the inherited pre-rift substrate (Ravnås and Steel, 1998).

Climatic factors, such as water and surface temperature, wind force and its dominant directions, season variations and rainfall are known to exert a noteworthy influence not only on the nature of sediments formed, transported and accumulated within a basin, but also on vegetation and associated fauna, on weathering processes and profiles (Ravnås and Steel, 1998; Allen and Allen, 2005 and references therein). Moreover, as pointed by these authors, rift basins which are often elongated and extend through a vast area, commonly show significant geomorphological and climatic variations.

Another aspect that plays a significant role in deposition in rift basins is the relative position of each sub-basin across the extending area of the rift, as sediment transport is restricted to underwater current flows (either continental or marine) or wind dispersal. The distance to the hinterland dominates most of the volume of sediment sourced from uplifted continental areas, as well as its nature and depositional type (Leeder and Gawthorpe, 1987; Ravnås and Steel, 1998; Allen and Allen, 2005). Additionally, intra-basinal erosion can contribute to the bulk of sediments accumulated (Ravnås and Steel, 1998). As a result of sediment input and the volume of the catchment area, sub-basins can be referred as starved (with less sediment than the volume available), balanced (when sediment supply meets the volume of the sub-basin) or overfilled (if the volume of sediment available is larger than the accommodation space) (Prosser, 1993; Ravnås and Steel, 1998).

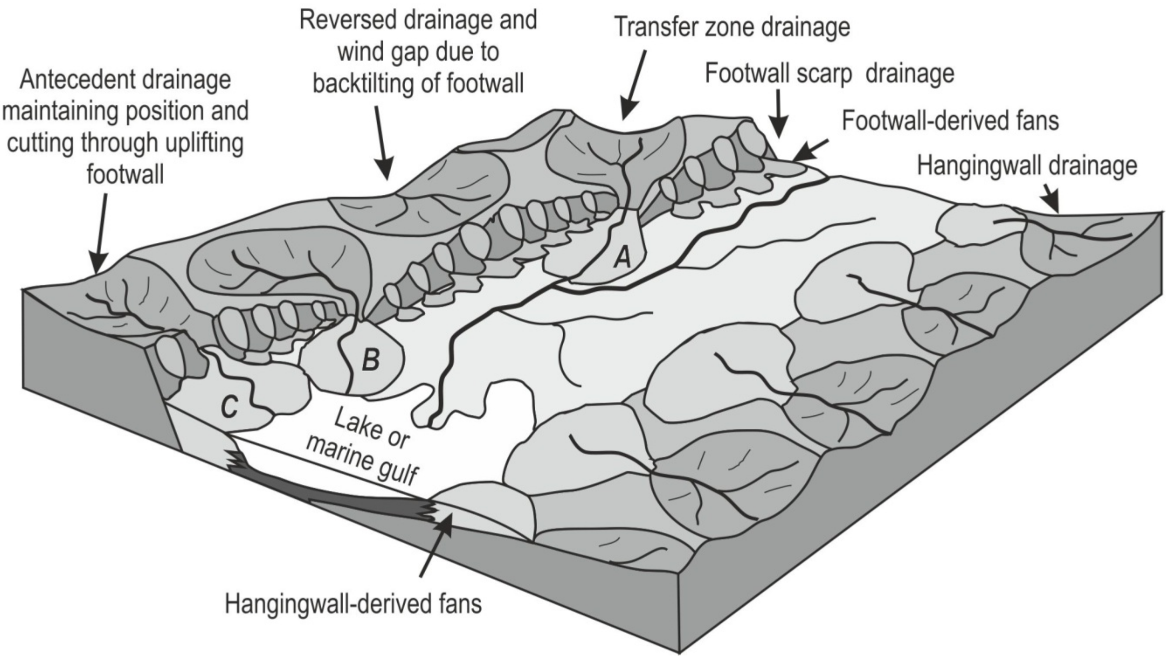

Figure 1.8 – Schematic diagram illustrating the main drainage network and depositional systems developed during rifting throughout a sub-basin (modified from Gawthorpe et al., 1994). A and B depict alluvial fans sourced from relay ramps; C is a fan delta sourced from a previous drainage basin.

During the evolution of rift basins, in result of the constant re-organization of the morphology of tilt-blocks, drainage networks on the different areas of the sub-basin are consequently modified in function of the new base level (Frostick and Steel, 1993;

Prosser, 1993; Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000). Drainage patterns within a sub-basin tend to develop both as transverse systems in dependence of the available fault network, or axially mainly along the elongated depocentres of the sub-basin, but are also shaped by the formation of relay ramps and transfer faults (Leeder and Gawthorpe, 1987; Ravnås and Steel, 1998). In summary, the main influxes of sediment on non-marine rifts can be sourced from (Gawthorpe et al., 1994) (Fig. 1.8): 1) the uplifted footwall, with transverse erosion across master faults; 2) the tilted hangingwall; 3) axial drainage systems; 4) transfer zones and relay ramps; 5) pre-existing drainage systems; and 6) reverse drainage networks due to back-tilting of footwall. Conversely, on marine rift settings, sediment transportation largely depends on surface and deep oceanic flows that are progressively established during continental extension.

In addition to the former aspects that control the deposition on rift basins, the inherited nature of pre-rift crustal blocks plays a major role in the type of materials available during erosion and weathering, as original rocks (igneous, metamorphic or sedimentary) are degraded and along the transportation process, continuously modified through particle fragmentation, dissolution and formation of new mineral assemblages (e.g. Frostick and Steel, 1993).

1.2.2.3. Tectono-sedimentary models

As a result of continental extension and the establishment of rift basins, new depositional environments are subsequently created and are largely dependent on the external controls referred above. Consequently, distinct depositional facies can be recognised, from which extensive comprehensive reviews on sedimentary environments were presented, either for marine (e.g. Leeder and Gawthorpe, 1987; Prosser, 1993; Gawthorpe et al., 1994; Ravnås and Steel, 1998) and non-marine rift basins (Crossley, 1984; Leeder and Gawthorpe, 1987; Frostick and Steel, 1993; Lambiase and Bosworth, 1995 and references therein). Such facies (or depositional tracts) show coeval affinities and can be often assigned to a specific depositional environment or position within a sub-basin (Leeder and Gawthorpe, 1987; Ravnås and Steel, 1998).

The combination of the former controls and the continued infill of the basin results in the formation an overall wedge shape geometry of the syn-rift strata that can be observed on seismic data and on outcrops, often showing a typical depositional architecture (e.g. Bally, 1987; Prosser, 1993; Ravnås et al., 1997) (Fig. 1.9).

The alternate distribution of these distinct facies occurs both in time and throughout a basin. Examples of progressive transition from typical continental deposition since the onset of continental rifting towards a marine deposition is well exposed on outcrops from West Portugal (e.g. Wilson et al., 1989; Azerêdo et al., 2003) (Fig. 1.9) or observed in geophysical and geological data from the North Sea (Frostick and Steel, 1993).

The following section briefly describes the main depositional facies that are commonly found on non-marine and marine settings.

Non-marine

Deposition on continental (non-marine) settings is dominantly characterised by a drainage system isolated (or showing limited connectivity) from the sea and therefore, sea-level variations exert limited control on the variation of base level. However, tectonic subsidence and intra-continental base-level variations can be similar to those observed on marine settings (Gawthorpe and Leeder, 2000).

Deposition under non-marine conditions is often associated with the early stages of evolution of a rift, but also on the evolution of proximal areas of the rifted area.

During extension of continental rifts, the embryonic fault network tend to progressively coalesce towards a mature architecture of fault-bounded basins and subsequently, the reorganization of the drainage along tectonic slopes, mainly through the formation of rivers and lakes in the vicinity of master faults and scarps. Details on deposition in these environments have been addressed extensively (e.g. Nichols, 2009), and therefore are not included in this summary. Examples of deposition on recent continental rifts can be found in East Africa (e.g. the East African Rift System, the Rio Grande Rift, the Baikal Rift System) (e.g. Gawthorpe and Leeder, 2000), whereas for ancient rifts examples can be found on the North Sea, the Iberian margin, North Africa or the Brazilian margin (e.g. Chang et al., 1992; Leeder, 1993; Ravnås and Steel, 1998; Le Roy and Piqué, 2001).

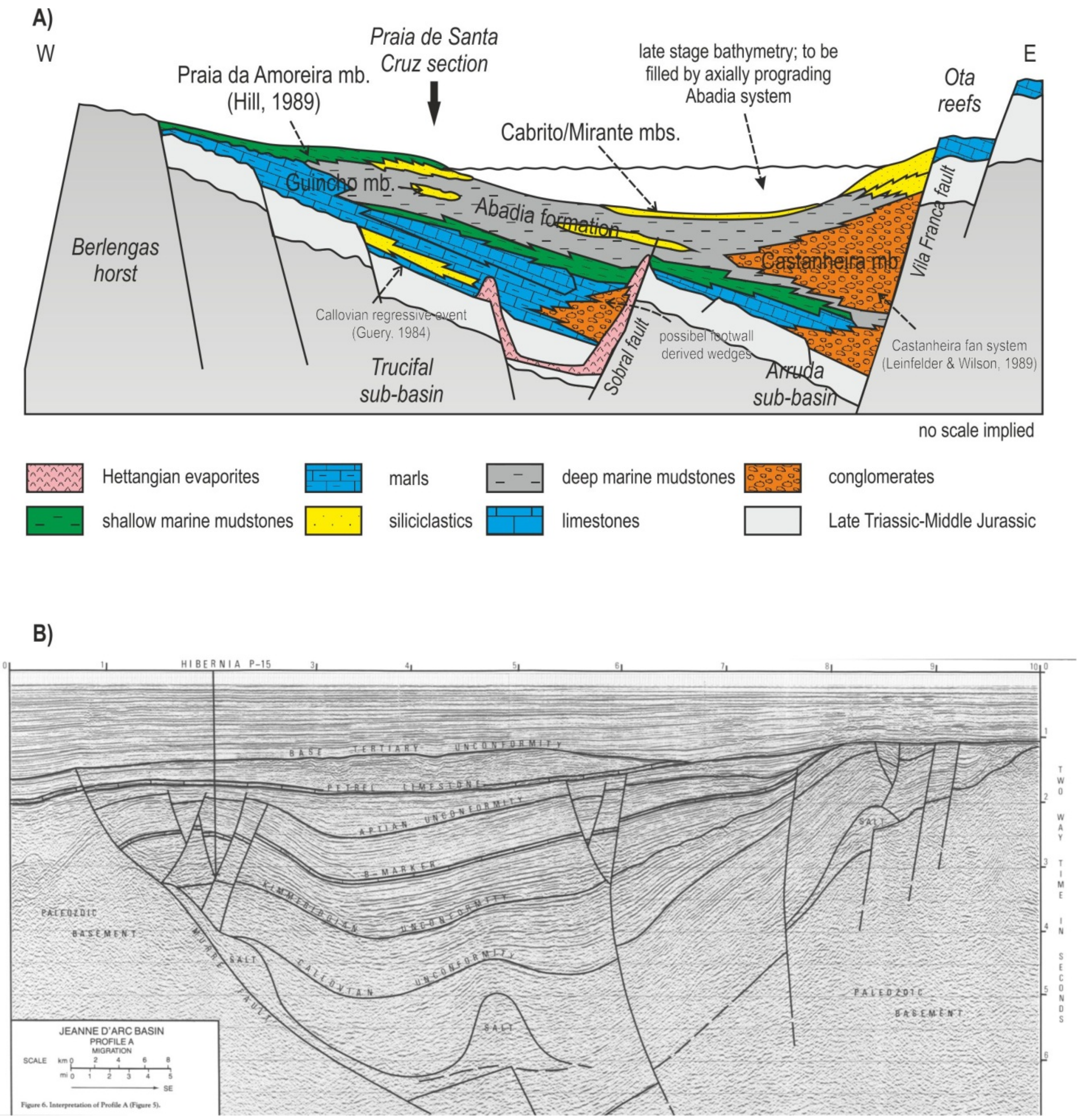

Figure 1.9 –Wedge geometry of syn-rift strata. A - Schematic basin transverse infill pattern of the Oxfordian-Kimmeridgian syn-rift of the Lusitanian Basin (modified from Ravnås and Steel, 1998); Note the overall wedge shape of growth strata and the vertical stacking of progressively marine dominated successions co-existing with continental derived alluvial fans (Castanheira mb.) controlled by master fault; B - Interpreted seismic section in the Jeanne d'Arc Basin, Newfoundland showing the Jurassic to Early Cretaceous growth strata (Bally, 1987).

In such setting, representative depositional architectures can be present, which include aeolian deposits, fluvial channels, fluvial plains, playas, alluvial fan and deltas, or lakes (Leeder and Gawthorpe, 1987; Lambiase and Morley, 1999; Gawthorpe and Leeder, 2000) (Fig. 1.10). Deposition in close connection with fault scarps, commonly include the occurrence transverse driven deposits, such as alluvial fans and alluvial deltas, often associated with lakes (Leeder and Gawthorpe, 1987; Gawthorpe and Leeder, 2000).

Away from master faults, fluvial plains and rivers show axial orientation and progressively divert forming abandoned meander belts and oxbows, whereas hangingwall alluvial cones are commonly formed on uplifted areas of the footwall (Leeder and Gawthorpe, 1987; Gawthorpe and Leeder, 2000) (Fig. 1.10).

Examples of fluvio-deltaic deposits can be found from the Triassic of the North Sea, Iberia, Newfoundland and Morocco, where distinct depositional patterns can be assigned either to active extension or thermal subsidence (e.g. Laville and Petit, 1984; Hiscott et al., 1990; Frostick and Steel, 1993; Azerêdo et al., 2003).

Marine

Deposition in marine settings comprises those environments that reveal the influence of temporary incursions of the sea or the permanent installation of marine conditions on the successions accumulated throughout the sub-basins during continental extension. Accordingly, these include depositional environments as diverse as restricted and open lagoon systems, shorelines, continental platforms and slopes, or the deeper marine pelagic domains (Fig. 1.11).

Sediments deposited in these settings are, not only highly variable in nature and volume throughout the rifted area, but also reveal the significant impact of major eustatic variations during periods of relative tectonic quiescence (Ravnås and Steel, 1998).

Under shallow-marine conditions, continued tidal influence, sporadic climatic events (e.g. storms) lead to the accumulation along hangingwall dip-slopes of shoreline and coastal deposits, deltas and fan deltas (Leeder and Gawthorpe, 1987; Ravnås and Steel, 1998) (Fig. 1.11A). In dependence of master faults and footwall derived scarp facies, deposition derived from the uplifted footwall is mainly controlled by transverse feeder systems commonly resulting in the accumulation of terminal alluvial fans often associated with the installation of canyons, as in the case of the Castanheira member in the Arruda sub-basin (the Lusitanian Basin, Portugal) (Ravnås and Steel, 1998) (Figs. 1.9 and 1.11B).

On the hangingwall tilted section axial deposits commonly include fluvio-deltaic and shoreline systems that markedly contrast with those from deep marine settings (Ravnås and Steel, 1998). The Late Oxfordian of the Cabaços fm. in the Lusitanian Basin reveals transitional lagoon deposits associated with the rejuvenated subsidence of the margin, progressively influenced by marine conditions (Azerêdo et al., 2002a)(Fig. 1.9A).

Another type of depositional facies tracts that often accumulate on shallow marine rifted basins leads to the deposition of carbonate successions on costal to shelfal conditions, mainly on the uplifted tilted ramps of sub-basins. In such setting, carbonate reefs and build-ups are commonly established, as in the case of the Ota member of the Montejunto Formation (Lusitanian Basin, Portugal) (Ellis et al., 1990) (Fig. 1.9A).

On the distal areas of rift basins, under deep marine conditions, turbidites, mass-transport deposits, canyon-toe sediments or contourites may accumulate a mixture of coarser and finer sediments that are deposited either axially or transversely to rift orientation (Leeder and Gawthorpe, 1987; Ravnås and Steel, 1998; Faugères et al., 1999) (Fig. 1.11B). Recent examples from Central Greece show coastal-marine axial drainage systems from which, transverse fans and cones were deposited (Leeder and Gawthorpe, 1987). The Kimmeridgian outcrops of the Abadia Fm. in the Lusitanian Basin, reveal an extensive succession of deep-marine mixture of basinal, slope and hangingwall ramp, submarine channel and fan-deltaic sediments (Ravnås et al., 1997) (Fig. 1.9A).

Accordingly, the diversity of the above mentioned depositional tracts and their relative association to the shallow or deep-water settings allows the use of such features as a predictive tool for hydrocarbon exploration (Frostick and Steel, 1993; Lambiase and Morley, 1999).

1.2.2.4. Depositional architecture of syn-rift sequences

Deposition on continental rifted margins, from inception of extension to seafloor spreading, follows a complex interplay of tectonic, eustatic and sedimentary processes, briefly summarised above.

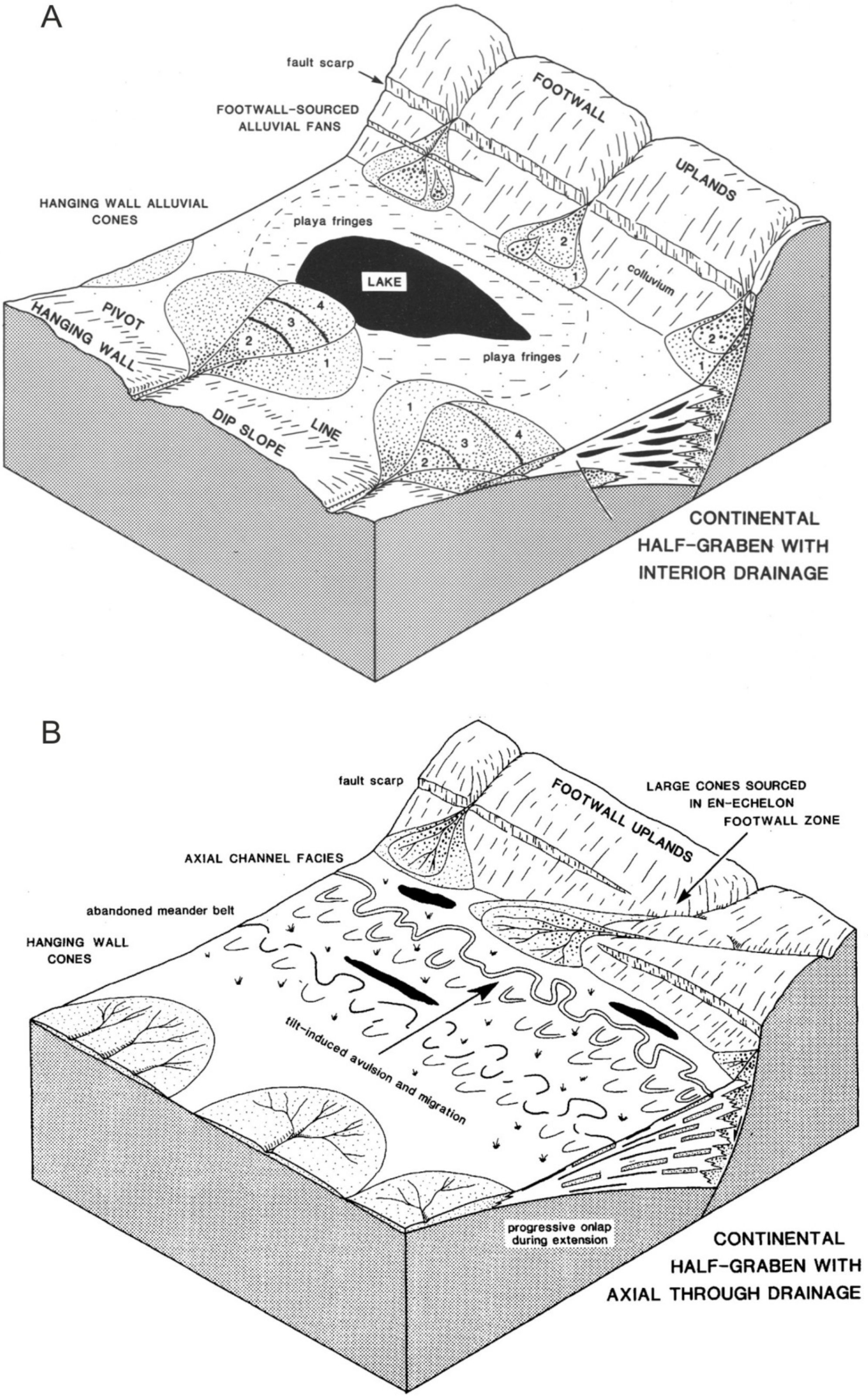

Figure 1.10 – Non-marine depositional features in relation with their position on the tilt-block of a rift sub-basin and with the dominant type of drainage pattern. A - interior drainage and B - axial drainage (Leeder and Gawthorpe, 1987).

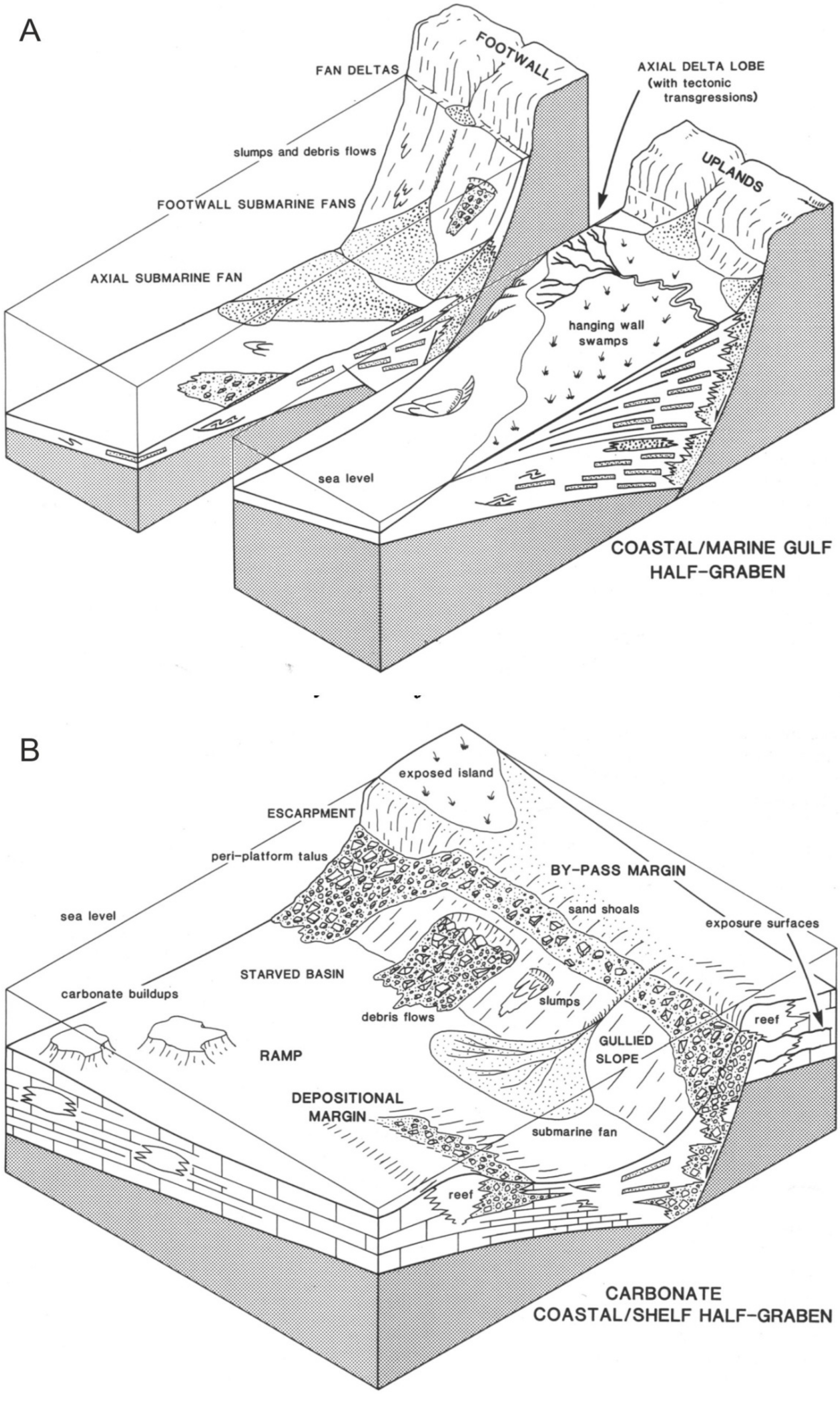

Figure 1.11 – Schematic marine depositional features in relation with their position on the tilt-block of a rift sub-basin (Leeder and Gawthorpe, 1987). A – Costal/marine basin; B – Coastal/shelf basin with carbonate facies in association with tilt-block position.

The analysis of the internal architecture of the multiple depositional tracts (despite the variability found on both marine and non-marine settings), reveals similar accumulation patterns that have been addressed in detail in literature with reference to various regions of the world and from distinct geological ages where similar processes occurred (Leeder and Gawthorpe, 1987; Frostick and Steel, 1993; Ravnås and Steel, 1998; Lambiase and Morley, 1999; Gawthorpe and Leeder, 2000).

Acknowledging that continental extension is one of the principal processes controlling the creation of new accumulation space, it has been documented that tectonic subsidence of continental crust (and their related fault bounded overlying strata) can include distinct pulses of subsidence and that fault linkage plays a significant role in explaining the resulting stratigraphic patterns (e.g. Gupta et al., 1998). The change from slow to rapid subsidence has been associated with the transition from the first pulses of rifting to a paroxysmal phase of subsidence and extension, and ultimately to a diminished rate of tectonic subsidence during a later rift phase, with subsequent transition to post-rift, which is dominated by thermal subsidence (Prosser, 1993; Lambiase and Bosworth, 1995; Gupta et al., 1998). Moreover, evidence that subsidence in rift basins often outpaces sediment accumulation and that in such conditions eustatic variations have minor control in the modifications of the base level, resulted in the limited application of sequence stratigraphy analysis applied to extensional settings.

Prosser (1993) using seismic stratigraphic tools tied to well information from several areas in the North Atlantic established the foundations for the analysis of marine rift basins through the application of the concept of "tectonic systems tracts". Prosser's work describes the discrete tectono-stratigraphic units revealing the linked depositional systems that can be identified on most extensional basins, namely: 1) the Rift Initiation; 2) the Rift Climax; 3) the Immediate Post-Rift; and 4) the Late Post-Rift.

Lambiase and Bosworth (1995) on the other hand identified four distinct structural stages each with individual tectono-sedimentary responses, which include: 1) initial faulting; 2) development of half-graben morphology; 3) filling of half-graben; and 4) regional subsidence. Other approaches applied similar and simplified nomenclatures to individualise similar tectono-stratigraphic units observed either on seismic, wells and boreholes, such as Rift Initiation Phase, a Rift Climax Phase and Late Rift Phase (Nøttvedt et al., 1995), whereas others considered an Early Stage, a Climax Stage and a Late Stage (Ravnås and Steel, 1998). Ravnås et al. (2000) analysing the multiple rift phases recorded in the North Sea, suggest the use of three phases of subsidence with the formation of a proto-rift phase, a syn-rift phase and an inter-rift stage (for incomplete rifting) or post-rift phase, from which an hierarchical approach could be applied.

In the present work, aiming to obtain a compromise between the different terminologies, the terms Rift Initiation, Rift Climax and Late Rift are used to integrate the distinct pulses of subsidence within a rift phase and their correlative depositional and tectonic systems tracts. Consequently, the hierarchy of continental extension events presented in this work considers that a rift episode (ultimately resulting in the creation of oceanic crust) can be subdivided into discrete phases, each typically comprising the above mentioned tectonic pulses (Fig. 1.12). Accordingly, an indicative ranking of sequences would include a first order cycle spanning the entire rift process (commonly of over 10's of M.y. of duration) that could group intermediate phases of second order and within these, subsequent shorter third order cycles (Ravnås et al., 2000). The ranking of such rifting events is broadly coeval with the stratigraphic cycles proposed by Catuneanu (2006), for sequence stratigraphy description of continental margins dominantly controlled by eustasy (Fig. 1.12).

Rift Initiation

Onset of continental extension is accompanied by the creation of a dense network of faults along which sub-basins start to form (Gupta et al., 1998). Successions within this systems tract are often deposited above a pre-rift unconformity (that commonly includes a metamorphic or igneous basement or deformed sedimentary terrains), with its first deposits associated to subaerial fluvial systems. In cases of a renewed rift phase, basal strata overlay an older inter-rift or late rift pulse (Fig. 1.13).

The Rift Initiation systems tract is characterised by an overall thin wedge with internal reflectors usually hummocky and discontinuous, showing that sedimentation kept pace with limited tectonic subsidence (Prosser, 1993). Such type of reflectors suggest the deposition of fluvial successions, although other non-marine depositional tracts can be identified, such as aeolian deposits or alluvial fans (Gawthorpe and Leeder, 2000). On outcrops and boreholes the rift initiation systems tract is characterised by the deposition of coarse sediments resulting from the immediate ablation and subsequent weathering, erosion of uplifted areas and the re-organization of the drainage system (Leeder and Gawthorpe, 1987; Ravnås and Steel, 1998; Young et al., 2003). During this period the increasing accommodation space reveals its impact on the development of new drainage systems, which along with the uplift of footwall areas can induce forced regression on areas above the fulcrum of the tilt-block (Ravnås and Steel, 1998; Young et al., 2003).

	Episode	**Phase**	**Pulse**	**Distinctive features**
Order	1st order	2nd order	3rd order	
Duration	>10's My	3-20 My	0,5-5 My	
Tectonic event	Continental Rifting	Rift Phase 2	Late Rift	If continental extension ceases and oceanic crust is created the uppermost boundary is marked by a “breakup unconformity”
			Rift Climax	Formation of a MFS
			Rift Initiation	Regional unconformity overlying a previous extensional phase
		Rift Phase 1	Late Rift	Reduced tectonic subsidence
			Rift Climax	Formation of a MFS
			Rift Initiation	Regional unconformity overlaying a pre-rift terrane

Figure 1.12 - Hierarchy of events during multiphased rifting (showing two rift phases) in relation with the duration of each pulse (adapted from Prosser, 1993; Nøttvedt et al., 1995; Ravnås et al., 2000; Catuneanu, 2006).

On continental arid climates, such deposits often include alluvial fans with retrograding conglomerates and coarse sandstones, dominantly aligned along incipient faults, whereas away from normal fault zones siliciclastics and marls may accumulate on fluvial, shoreface and foreshore environments (Leeder and Gawthorpe, 1987) (Fig. 1.10). This is the case of the delta-derived Pleistocene deposits from the Gulf of Corinth in Greece (Leeder and Gawthorpe, 1987) or the Permo-Triassic rift units from the North Sea

(Ravnås et al., 2000). In more humid to highly pluvious climates lakes can be formed, in association with more persistent fluvial systems (Gawthorpe and Leeder, 2000).

In shallow marine settings, onset of deposition in response to tectonic subsidence is characterised by the accumulation of retrograding fluvial-coastal plain sediments, alluvial and deltas fans, which show large dependence of sediment supply to fill the new accommodation space (Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000) (Fig. 1.11A). In the Lusitanian Basin (West Portugal), the Oxfordian of the Cabaços formation, reveals lacustrine to shallow marine limestone deposits often associated with source rock potential, onlapping a regional unconformity (Ravnås and Steel, 1998; Azerêdo et al., 2002a) (Fig. 1.9A).

Rift Climax

The period marked by the maxima of tectonic subsidence within a rift phase is termed the rift climax and often coincides with the time when fault linkage is established to its final architecture (Prosser, 1993; Gupta et al., 1998). During this pulse, tectonic subsidence often outpaces the volume of sediments accumulated in sub-basins, commonly resulting in the formation of starved basins (Ravnås and Steel, 1998).

Internal architecture of rift climax deposits is characterised on seismic data by divergent downlapping reflectors revealing the progressive tilting of the hangingwall that are often poorly defined closer to fault scarps (Fig. 1.13). In cases where seismic resolution allows resolving the internal architecture, an Early rift climax, Mid-rift climax and Late rift climax minor systems tracts can be identified (Prosser, 1993). As such, Prosser's work reveals that the Early rift climax include the formation of downlaps overlying the previous sequence, associated with aggrading lozenge-shaped reflectors close to the footwall and prograding offlaps on the hangingwall. The mid-rift climax is characterised by retrogradational reflectors on the hangingwall dip-slope, whereas the late rift climax sequence is characterised by sub-parallel and continuous reflectors commonly draping previous units.

As a result of the re-organization of the tilt-blocks, new uplifted areas along footwalls are subsequently degraded and eroded providing significant amount of sediment that is driven into depocentres of sub-basins (Ravnås and Steel, 1998). Sediments accumulated during this pulse are characterised by finer material at the base, consequently overlain by coarser deposits towards the top, defining overall retrograding to aggrading sequences (Gawthorpe et al., 1994; Ravnås and Steel, 1998; Ravnås et al., 2000)(Fig. 1.13).

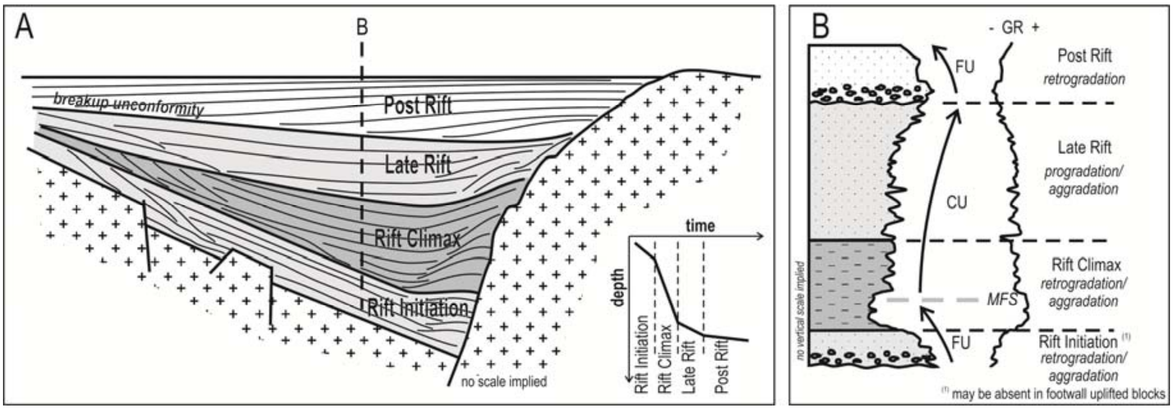

Figure 1.13 – Schematic architecture and depositional sequences of tectonic systems tracts on a single-phase rift event. A – Idealised seismic section across a sub-basin. B - In outcrop, borehole and wireline data. Based on Prosser (1993), Gawthorpe et al. (1994) and Ravnås and Steel (1998). Simplified rift subsidence curve adapted from Gupta et al. (1998).

During this period, drainage systems throughout the rifted margin reveal significant rearrangement, which on non-marine settings include the transverse deposition of alluvial fans resulting from the erosion of exposed areas and the renewed axial influx of fluvial siliciclastics and deepening of lake systems on the tilted hangingwall (Gawthorpe et al., 1994; Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000). On shallow marine and deep marine areas of the sub-basins, tectonic-induced base level rise allow the creation of increasingly deeper marine deposits that include turbidites on more proximal areas of the sub-basins and the accumulation of clays and fine sediments on the hangingwall dip-slope, which are often associated with the increased potential to form good quality source rocks (Watson et al., 1987; Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000). A key example of productive source rocks associated with rift climax systems tracts can be found from the North Atlantic, in the Late Jurassic deep marine sequences of the Kimmeridge Clay and Draupne Formations (e.g. Ravnås et al., 2000; Kubala et al., 2003) and from similar geodynamic settings around the world (Katz, 1995). The formation of such deep water facies marks the period within the rift phase where the highest base level is attained and therefore, the formation of a Maximum Flooding

Surface (MFS), which can commonly be traced throughout a sub-basin and is broadly coeval on a margin scale (Fig. 1.13B).

Deposits within this systems tract are characterised by retrogradation to aggradation and subsequent progradation, that include not only clays (either on deep marine or lacustrine settings) but also variable volumes of interbedded coarser siliciclastics driven from axial and transverse transport across and along master faults and relay ramps (Prosser, 1993; Ravnås and Steel, 1998; Lambiase and Morley, 1999; Gawthorpe and Leeder, 2000).

Late Rift

The final events of rifting are characterised by a progressive decrease of tectonic subsidence rates and are commonly associated with sedimentary infill of the accommodation space (e.g. Gawthorpe et al., 1994; Gupta et al., 1998; Ravnås and Steel, 1998).

On seismic data, the Late Rift pulse includes gently diverging to sub-parallel reflectors that at its the base, showing downlaps at the centre of sub-basins, stronger onlaps close to fault scarps and updip reflection terminations on the hangingwall (Prosser, 1993) (Fig. 1.13). The upper part of the Late Rift systems tract is characterised by parallel and continuous reflectors blanketing the distinct sectors of the rifted margin, evidencing the cessation of tectonic subsidence (Prosser, 1993) (Fig. 1.13).

Deposits associated with this linked deposition system are characterised by progradational and/or aggradational sequences formed in response to the ultimate re-organization of the drainage system and if sediment supply is significant, the progressive infill of accommodation space, whereas if the system is sediment deprived then, the whole or parts of a basin will be revealed as starved (Ravnås and Steel, 1998). These include the installation of prograding fluvio-deltaic and lacustrine systems on non-marine settings, whereas that on marine environments shoreline to deep marine deposits, respectively allow the accumulation of carbonate to distal siliciclastic prograding deposits (Ravnås and Steel, 1998). Additionally, the increasing decline of the tectonic influence on the depositional controls allow that progressively, eustatic derived processes can be recorded and become increasingly more important in sedimentation during the infill of the existing accommodation space.

In summary, deposition in rift basins is controlled by distinct factors that are captured on the sedimentary record throughout the rifted margin. As such, across the margin, typical syn-rift successions reveal the association of three-fold, two-fold or one-fold patterns of sediment stacking generally characterised by retrogradation-to-progradation with a maximum of flooding occurring during the rift climax (Ravnås and Steel, 1998 and references therein).

Syn-rift unconformities and the breakup unconformity

Since the onset of continental segmentation, the evolution of rift basins is controlled by noticeable and distinct events of extension of the continental crust that are accompanied by periods of tectonic subsidence. In the cases were the rifting process is completed, extension of the continental crust ultimately leads to the formation of oceanic crust, thus comprising a full rift cycle among extensional conjugate margins. Within the rifting process one or more phases of extension may therefore be present and consequently, the distinct pulses of subsidence are marked throughout the rifting margins by widespread and varied unconformities bounding each of the main events (e.g. Hubbard, 1988; Hiscott et al., 1990; Prosser, 1993; Nøttvedt et al., 1995) (Fig. 1.12).

Nøttvedt et al. (1995) pointed that the onset of rifting is marked by a ”proto-rift unconformity” that is characterised by an angular unconformity bounding the pre-rift substratum from the overlying syn-rift growth strata. Additionally, these authors demonstrate that the lithostratigraphic hiatus representing such unconformity is largely variable, which depend on the magnitude, areal extent and nature of the basal substratum. In the Alentejo Basin (Southwest Portugal), such contact is marked by a spectacular angular unconformity that reveals the Late Triassic red beds directly overlying the tightly folded deep marine Carboniferous deposits (Oliveira, 1984).

Conversely, the unconformity bounding the uppermost limit of the rift related growth strata is referred as the “syn-rift unconformity” and separates the underlying wedge-shaped deposits from the post-rift depositional units above, that are characterised by widespread sub-parallel seismic reflectors blanketing the margin (Prosser, 1993; Nøttvedt et al., 1995). This unconformity, which marks the end of tectonic subsidence is often discontinuous and its significance and magnitude may vary throughout the margin. It can be best observed on rift shoulders and crests of tilt-blocks, where it is represented by a single surface, whereas on subsiding areas of the hangingwall, multiple unconformities may form or ultimately be marked by continuous deposition (Nøttvedt et al., 1995; Ravnås and Steel, 1998). The syn-rift unconformity is not a regional boundary and its significance may change, coinciding or not with the "breakup unconformity".

The notion of "breakup unconformity" applied in this work refers to the unconformity formed approximately by the same time of the onset of seafloor spreading (e.g. Driscoll et al., 1995). However, its significance is yet to be fully clarified, notwithstanding the advances resulting from data obtained from geophysical methods, magnetic anomalies, deep-sea drilling campaigns and outcrop analogues (Srivastava et al., 2000; Karner et al., 2007; Tucholke et al., 2007 and references therein). As pointed by Tucholke et al. (2007) the breakup unconformity can be misinterpreted because the cessation of extension may not generate a consistent marker or it may represent an event other than the final fragmentation of the continental crust. This paradox is most prominent in non-volcanic passive margins such as the Iberia-Newfoundland conjugates, where the exhumation of the mantle, the formation of oceanic crust and the formation of magnetic anomalies can be diachronic and consequently form distinct unconformities (e.g. Tucholke et al., 2007; Bronner et al., 2011). Moreover, in cases where rift locus migration occurs across the proximal to the distal margin, the last recorded period of rift subsidence can be diachronous throughout the different sub-basins, as observed in Northwest Iberia between the Lusitanian and the Peniche Basins (Alves et al., 2009).

The complexities of identifying a "true" breakup unconformity were summarised by Soares et al. (2012), which proposes the use of Breakup Sequence to include the strata deposited during a period of subsidence cessation and lithosphere rupture.

Nonetheless, in the absence of accurate geophysical and geological data allowing to pinpoint an exact age for continental breakup and its correlative unconformity (as in the case of the Southwest Iberian margin) the criteria of Driscoll et al. (1995) are used as proxies for the identification of the breakup unconformity, which include: 1) bedding of syn-rift strata beneath the unconformity are divergent towards the depocentre; 2) growth faults associated with rifting occur beneath the unconformity; 3) faulting and offset should diminish significantly across the breakup unconformity; 4) subsidence rates decreases across the unconformity; and 5) igneous activity preferably occurs prior to the unconformity.

Notwithstanding the regional significance of these rift bounding unconformities, other important depositional boundaries are recorded along the evolution of a rifted margin and within their correlative basins and sub-basins, which can be used as proxies for lithostratigraphic framework.

1.2.2.5. Syn-rift sequence stratigraphy

Concepts of sequence stratigraphy have been extensively applied to explain the cyclic patterns of deposition, the analysis of correlative surfaces and stratigraphic successions throughout passive continental margins where eustasy dominantly controls the infill of accommodation space (e.g. Emery and Myers, 1996; Catuneanu, 2006; Catuneanu et al., 2009). However, on geological settings where tectonic subsidence plays a major role in the creation of new accommodation space and variations of the base level, the applicability of the sequential stratigraphic tools has been widely discussed and despite the foundation works allowing the insightful analysis of successions (e.g. Prosser, 1993; Gawthorpe et al., 1994; Howell and Flint, 1996), a complete understanding of the organization through time and space of rift-related depositional systems tracts is still far from concluded (Martins-Neto and Catuneanu, 2010).

The analysis and the application of sequence stratigraphic models to rift basins must then consider the tectono-eustatic interplay and account for the depositional variations along the dip and strike orientation of the sub-basins, i.e. in response to the constantly changing physiography of the tilt blocks during rifting (Frostick and Steel, 1993; Howell and Flint, 1996). Moreover, the kinematics and the rotation of the tilt blocks throughout a basin in relation with the fulcrum results in the simultaneous subsidence and uplift of the opposed areas of the dipping hangingwall and consequently, the respective sediment accumulation on the depocentre and erosion of the footwall (Ravnås and Steel, 1998).

Notwithstanding the differences of rift basins and divergent passive margins the traditional approaches in the identification of depositional systems tracts, namely the Lowstand Systems Tract, the Transgressive Systems Tract and the Highstand Systems Tract (sensu Emery and Myers, 1996 and references therein) can be identified along the successions controlled by tectonic subsidence.

The Lowstand Systems Tract (LST) is the first tract of a sequence that can be assigned to the rift initiation, as a result of the onset of tectonic subsidence and the re-organization of the drainage network in relation to newly uplifted and drowned areas, which include generalised regressive depositional sequences, defining an overall retrograding to aggrading trend (Howell and Flint, 1996). The LST is marked at the base by a basal regional unconformity marking the inception of a rift pulse, commonly associated with downlapping reflectors on seismic and the accumulation of coarse sediments progressively overlain by finer successions (Ravnås and Steel, 1998). Such deposits include forced regressive successions that on non-marine setting show alluvial fans transversely deposited across master faults and in shallow to deep marine conditions the accumulation of submarine fans resulting from the degradation of uplifted sections of the tilt block (Howell and Flint, 1996). Onset of rift subsidence in the Suez Rift shows conglomerate to mudstone facies from fluvial deposits immediately above the pre-rift Eocene limestones (Young et al., 2003), and on the Lusitanian Basin, a regional angular unconformity spanning from the mid to Late Callovian to the early Oxfordian above which continental to restricted marine limestones reveal progressive marine influence towards the Kimmeridgian (Wilson et al., 1989; Azerêdo et al., 2002a). However, due to the late depositional response to subsidence or depending on the position on seaward areas, the LST may not be identified on rift successions (Gawthorpe et al., 1994; Howell and Flint, 1996; Ravnås et al., 1997; Martins-Neto and Catuneanu, 2010).

The Transgressive Systems Tract (TST) is the intermediate tract within a sequence and is deposited during a relative base level rise accompanied by the increase in the available accommodation space (Emery and Myers, 1996). It can be broadly correlated with the rift climax, which is marked by the paroxysmal subsidence of rifting and the period when sub-basins attain a maximum drowning (Gawthorpe et al., 1994). During this phase, the TST is characterised by progressive deepening of the basin and consequently, a Maximum Flooding Surface can be identified (Emery and Myers, 1996). Deposits within this unit are dominantly retrogradational to aggradational, with dominant mudstone deposition but often showing the influx of coarser sediments yield by weathering from exposed areas or from submerged segments above the fulcrum (Prosser, 1993; Ravnås and Steel, 1998). As a result of the maximum subsidence associated with this rift pulse in a sub-basin, deposits within this systems tract often show source rock potential, as in the case of the Brenha formation of the Early Jurassic of the Lusitanian Basin (Azerêdo et al., 2003) or the North Sea (Ravnås and Steel, 1997).

The Highstand Systems Tract (HST) represents the final portion of a sequence that is characterised by overall progradation and aggradation of the margin during the Late Rift pulse (Prosser, 1993; Emery and Myers, 1996; Ravnås and Steel, 1997). Subsequently to the maximum drowning of the basin, tectonic subsidence is reduced and during this period, eustasy is often expressed throughout the rifting margin mainly on updip areas of the hangingwall (Ravnås and Steel, 1998). Deposits within this depositional systems tract are dominantly characterised by progradation and aggradation that in the case of balanced to overfilled sub-basins gradually lead to the complete infill of the accommodation space (Ravnås and Steel, 1998). Examples of cyclic deposition during this phase can be found among other areas from the Late Jurassic of the North Sea (Ravnås and Steel, 1997).

1.3. Aims and objectives

The present work aims to expand the knowledge on the tectono-stratigraphic processes and signatures that control and characterise the evolution of extensional continental margins, by presenting a comprehensive analysis of the Southwest Iberian margin in the context of the West Tethys and the Central-North Atlantic.

The study area, being one of the least studied provinces of the North Atlantic is identified as a key domain to explain several unclear aspects (see section 1.2), not only regarding the local evolution south-western domain of the Iberian plate, the Iberia-Newfoundland conjugate margins, but more significantly to elucidate on more broaden questions of other magma-poor rifted continental margins.

Additionally, this work investigates the architecture of rifted margins and how their structural segmentation can control deposition on deep-water continental margins. More specifically, the role of strike-slip zones on margin segmentation, the distinct patterns of subsidence throughout the margins and the effects of convergence on the thinned continental crust. These are revealed as key topics that aim explaining the tectono-stratigraphic complexities of this southernmost domain of the eastern North Atlantic, known to have formed adjacent to a triple-junction between the African, Eurasia and American tectonic plates.

In view of that, the specific aims of this research are as follows:

1) to integrate and revise distinct datasets in order to construct a meaningful compilation of the major lithostratigraphic units and their approximate ages;
2) To identify the main events and processes controlling the formation of regional and local unconformities;
3) To identify the main seismic-stratigraphic units and correlate them with outcrops, borehole and dredge data;
4) To generate subsidence models that explain the timing and location of crustal thinning
5) To elaborate an integrated and comprehensive correlation of the regional seismic-stratigraphic and lithostratigraphic units in the context of the Central and North Atlantic evolution;
6) To characterise the structural architecture and processes during the extensional evolution of the continental margin;
7) To characterise the structural architecture of post-rift strata and explain the controls of shortening and tectonic inversion throughout the thinned continental crust;

8) To construct a seismo-stratigraphic framework that can explain the distribution, geometry and significance of correlative growth strata;
9) Investigate the implications of regional transfer zones on the segmentation of the margin;
10) Improve the constraint of the age of continental breakup on the Southwest Iberian margin;
11) Provide an integrated view of the evolution of the Southwest Iberia in the context of passive continental margins;
12) Discuss the implications for future hydrocarbon prospectivity throughout the Southwest Iberian margin.

1.4. Thesis layout

The work developed during the research, which addresses the questions stated above, is the result of an integrated approach covering distinct themes that contribute to the comprehensive understanding of the evolution of the southwest Iberian margin in the context of the evolution of the Central and North Atlantic Ocean. As such, the main chapters of the thesis were organised based on the chronology of the work developed during the research period and subdivided into discrete main geological themes progressively inter-connected around the main subjects. Consequently, the main research results were published in both peer-reviewed journals and presented in conferences, and consist in the principal organization of this thesis into 9 novel and meaningful chapters. Chapters 4 to 7 include the original abridged abstract, geological setting, methods, dedicated discussion and partial conclusions that guide the reader through the results of each research theme. References to other sections of the thesis are indicated when necessary.

Chapter 1, in which this section is included, consists on the presentation of the main concepts used in the analysis of rifted continental margins, both by addressing its broader geodynamic context, and by summarizing its internal architecture and depositional controls. This chapter also highlights the principal questions still in debate and introduces the reader to the main themes developed in this work.

Chapter 2 summarises the relevant information regarding the geological setting of the Southwest Iberian margin in the context of the Central and North Atlantic, by describing the principal lithostratigraphic units, geodynamics and the tectonic evolution of the West Iberian margin.

Chapter 3 presents the distinct methods used in the research, which are applied in the analysis of the multichannel seismic data, well data and outcrops and constitute the basis of the present work.

Chapter 4 presents the outcome of the investigation of the tectono-stratigraphic evolution of the Southwest Iberian margin and the segmentation resulting from multiphased continental extension in the context of the Tethys and the Central and North Atlantic. This chapter discusses the distinct architecture and timing of rifting throughout the margin and its implications for the evolution of the Iberia-Newfoundland conjugate margins by demonstrating un-anticipated noteworthy multiphased subsidence during continental rifting.

Chapter 5 focuses on the relation of the rift architecture throughout the margin with the subsequent tectonic inversion and discusses the implications for the understanding of deep-water continental margins and the location of the Ocean-Continent Transition zone.

Chapter 6 presents a comprehensive tectono-stratigraphic analysis of the main depositional sequences throughout the margin and analyses novel burial history models that explain the subsidence patterns of multiphased rifting throughout the margin. Additionally, this chapter discusses the impact of the use of sequence stratigraphy tools to predict facies on non-marine to marine rift basins on the distal margin.

Chapter 7 addresses the role of regional strike-slip zones during continental rifting and post-rift inversion, their impact in the segmentation of the margin and controlling canyon incision. This chapter elaborates on the repercussions of first-order transfer zones in the evolution of Iberia and its impact on future palaeogeographic reconstructions of the Central and southern North Atlantic.

Chapter 8 presents an integrated discussion of the main results deriving from core research themes revealed in the thesis and consequently debates its implications to the understanding of the rift-to-drift evolution of the Southwest Iberian margin and the North Atlantic.

In Chapter 9, the final conclusions of the thesis are presented.

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Chapter 2

Geological Setting

"It was about this time that vast numbers of geologists from all over the world began to appear on the scene (…) But now all the wise men of this and other lands began to arrive in force, the inspectors of landslides and natural disasters, erratic strata and blocks, each carrying a tiny hammer in one hand, tapping on everything that so much as looked like stone."

The Stone Raft, José Saramago

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2. Geological Setting

2.1. Location and physiography of the Southwest Iberian margin

The studied area, commonly referred as the Alentejo Basin is located in the south-western part the continental margin of Portugal and covers approximately 300 km^2 on the onshore and 19.000 km^2 on its offshore area (Fig. 2.1). It is bounded to the South by the Sagres Plateau and the Messejana-Plasencia Fault Zone (MPFZ), to the West by the Tagus Abyssal Plain (TAP) and in the North by the Setúbal Canyon, whereas its eastern boundary is represented by the outcropping Palaeozoic terranes (Mougenot et al., 1979; Mougenot, 1988; Alves et al., 2009) (Fig. 2.1). The Alentejo Basin is one of a group of Mesozoic rift basins, together with the Algarve Basin to the East and the Lusitanian, Peniche, Porto and Galicia Basins to the North that share a common rift-to-drift evolution in the context of the Mediterranean and the Atlantic (e.g. Alves et al., 2009).

The physiography of the Alentejo Basin and the Southwest Iberian margin is characterised by a shallow continental slope (< 1000 m deep) gently dipping to the West, crosscut in the South by the São Vicente Canyon (SVC) that sources the Horseshoe Abyssal Plain and to the North by the Setúbal Canyon that reaches the Tagus Abyssal Plain (Mougenot et al., 1979; Alves et al., 2003a; Terrinha et al., 2009) (Fig. 2.1). The continental margin ultimately deeps West of the Pereira de Sousa Fault scarp (PSF), to over 5000 m, towards the Tagus Abyssal Plain. The Gorringe Bank, comprises a significant structural high subdividing the latter from the Horseshoe Abyssal Plain to the South (Mougenot et al., 1979). Other prominent features observed on the deep offshore domain of include the Príncipes de Avis Seamounts, the Descobridores Seamounts and the Marquês de Pombal High (MPH) (e.g. Mougenot et al., 1979; Terrinha et al., 2009).

Within such setting, the Alentejo Basin is located in the vicinities of a major tectonic plate boundary, between the triple-junction of the Azores-Gibraltar Fault Zone to the South and Madeira-Tore Rise to the North (Pinheiro et al., 1996).

2.2. Geodynamic evolution of Southwest Iberian margin in the context of the West Tethys and the Central to North Atlantic

2.2.1. Continental rifting and margin segmentation

The Alentejo Basin as part of the West Iberian margin (along with the Lusitanian, Peniche, Porto and Galicia Basins) is included in an extensive province that records the evolution of the West Tethys (present day Mediterranean) and the northern Central Atlantic and the southern part of the North Atlantic Ocean (e.g. Mougenot et al., 1979; Mauffret et al., 1989b; Tucholke et al., 2007; Alves et al., 2009) (Fig. 2.1).

West Iberia and Newfoundland (Canada) are considered type-examples of conjugate magma-poor asymmetric rift margins that record the distinct periods of continental extension (e.g. Pinheiro et al., 1996; Tucholke et al., 2007). However, the vast literature addressing this problem has not reached a consensus regarding the number and magnitude of rifting events, their exact age and more often their regional implications (Pinheiro et al., 1996; Tucholke and Sibuet, 2007; Alves et al., 2009). Part of these uncertainties regard the scarce information available away from the areas investigated by the deep-sea drilling programs and models derived from onshore geology, but more significantly as a result of limited available data on the Southwest Iberian margin and its relation with neighbouring Atlantic provinces, as presented in Chapter 1.

Palaeogeographic models and reconstructions of the West Tethys and the Central-North Atlantic often do not show the Alentejo Basin or underestimate the continuous Mesozoic record (e.g. Masson and Miles, 1986; Hiscott et al., 1990; Schettino and Turco, 2009). Works that depict this province (e.g. Malod and Mauffret, 1990; Srivastava and Verhoeff, 1992; Osete et al., 2011), reveal the crucial significance of this segment of the Atlantic and its implications for the clarification of rifting on the southern Iberia-Newfoundland margins.

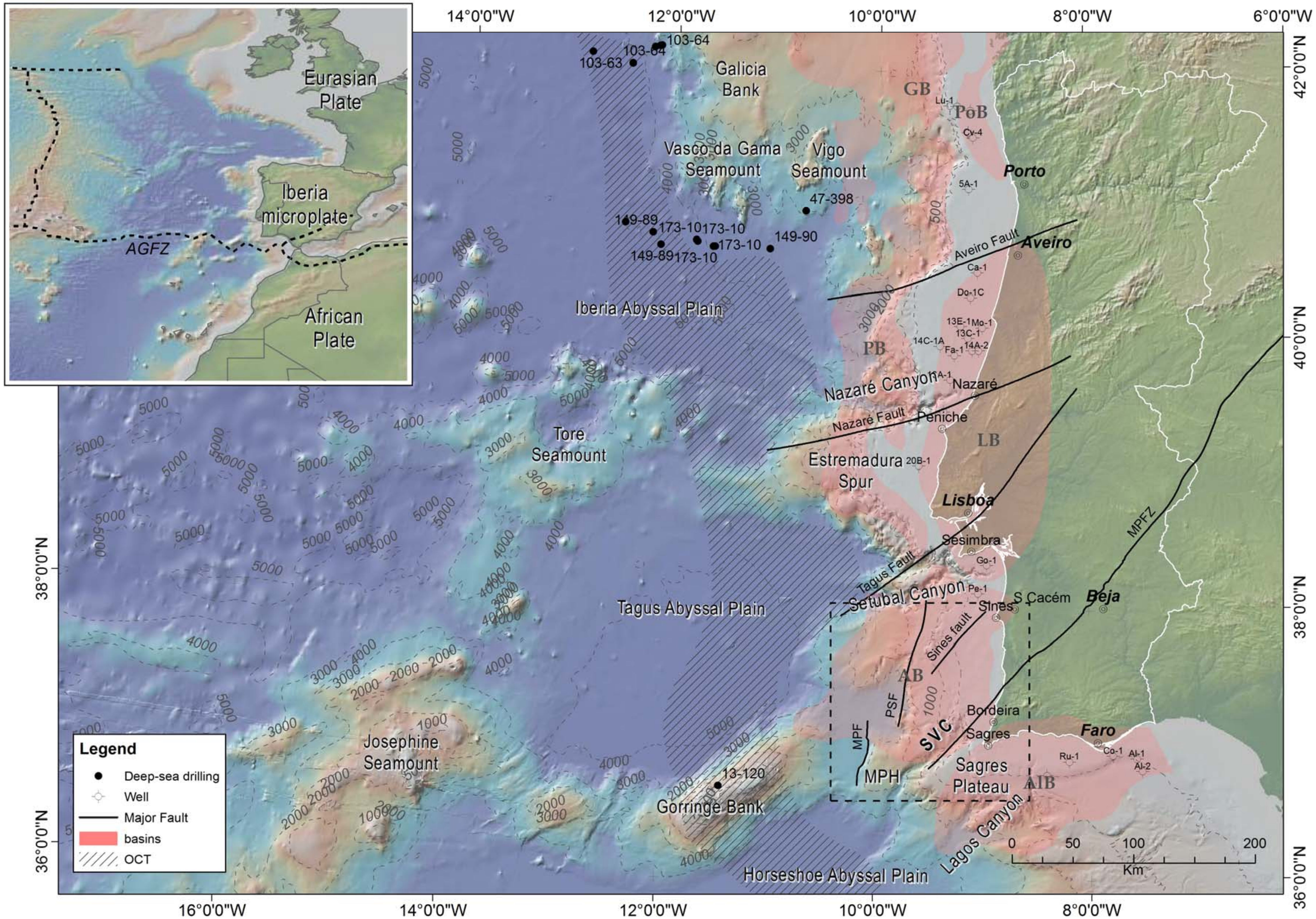

Figure 2.1 – Location of the study area in relation with the main Mesozoic Basins (AB – Alentejo Basin, AlB – Algarve Basin, LB – Lusitanian Basin, PB – Peniche Basin, PoB – Porto Basin, BG – Galicia Basin) and the prominent physiographic features (SVC – São Vicente Canyon, MPH – Marquês de Pombal High, MPF – Marquês de Pombal Fault, PSF – Pereira de Sousa Fault, AGFZ – Azores-Gibraltar Fault Zone). Ocean-Continent Transition zone from Rovere et al. (2004). Background bathymetry from GeoMapApp.

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Tucholke and Sibuet (2007) considered two main phases of rifting between Iberia and Newfoundland (Late Triassic-Early Jurassic and Middle Jurassic-Early Cretaceous), whereas Pinheiro et al. (1996) suggested that the West Iberian margin was affected by three rift episodes (Late Triassic-Early Jurassic, late Oxfordian-early Kimmeridgian and Valanginian/Hauterivian-Aptian). Alternatively it has been considered that continental extension of the West Iberian margin reveals the existence of four rifting events, namely in the Late Triassic, during the early to middle Jurassic, the Late Jurassic and the Early Cretaceous (Stapel et al., 1996; Rasmussen et al., 1998; Alves et al., 2002; Alves et al., 2006; Alves et al., 2009). In this section the approach of the latter authors is summarised, acknowledging that notwithstanding the validity of the former authors (or others), it represents a more insightful review of the processes and events describing the multiphased evolution of the Iberia-Newfoundland rift.

Figure 2.2 shows the position of the Alentejo Basin in the Southwest Iberian margin in relation with other basins in the Central and North Atlantic (approximately during Late Triassic to Early Jurassic) and simultaneously presents a schematic view of the interpreted age of seafloor spreading in its distinct major transfer-zone bounded tectonic segments, revealing not only the multiphased northwards migration of the locus and timing of onset of oceanic crust, but also the possible affinities of neighbouring basins that allow explaining the evolution of the study area (Mauffret et al., 1989b; Tankard and Balkwill, 1989; Welsink et al., 1989; Pinheiro et al., 1996; Tucholke et al., 2007; Tucholke and Sibuet, 2007; Alves et al., 2009).

As a result of Atlantic extension the architecture of the Southwest Iberian margin reveals distinct structural domains that include: 1) the proximal and distal margin (Manatschal and Bernoulli, 1998, 1999; Alves et al., 2009); or 2) the Continental Domain (with thickness of the continental crust exceeding 25 km), the Thinned Domain (with thickness approaching 15-25 km), the Transitional Domain (with approximately 5 to 15 km) and the Oceanic Domain (less than 5 km thick) (Afilhado et al., 2008) (Fig. 1.6).

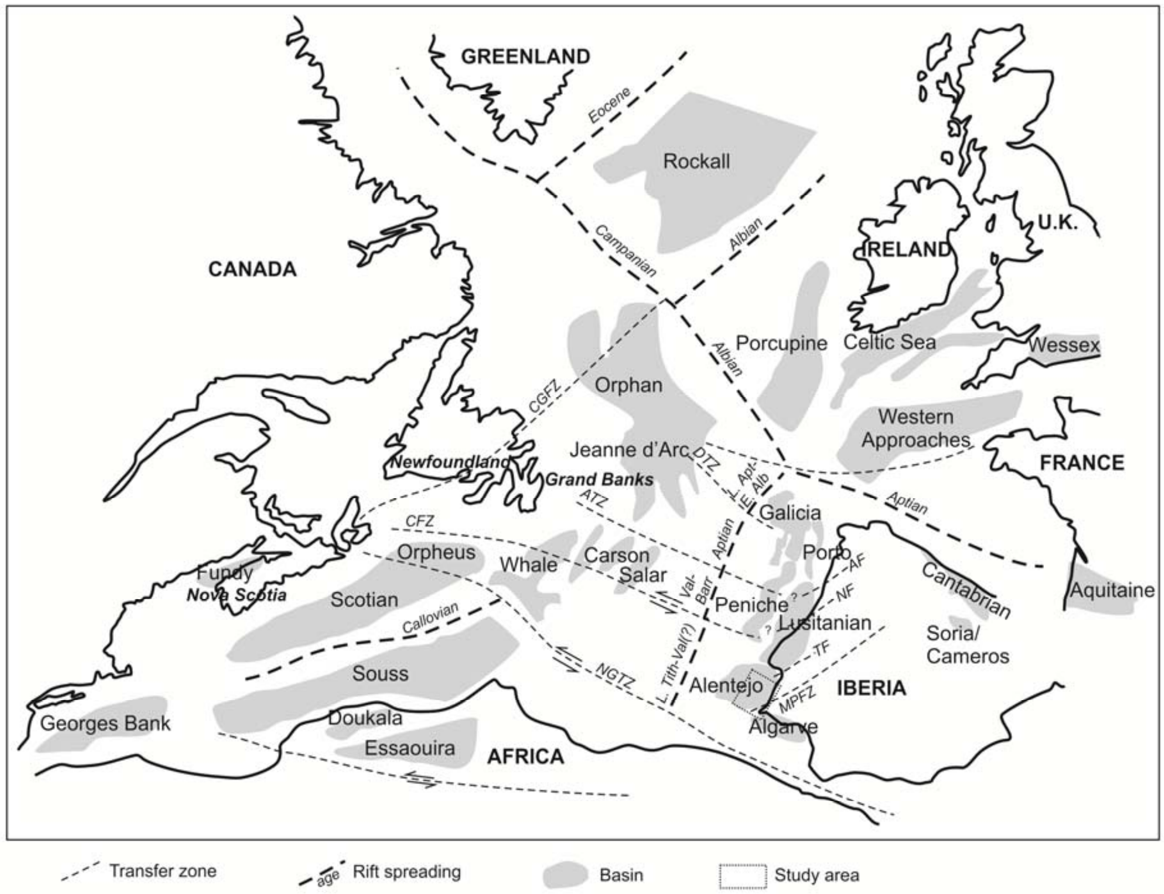


Figure 2.2 – Palaeogeographic reconstruction of the North Atlantic during the initial rifting stages (Late Triassic to Early Jurassic), revealing the main Mesozoic rift basins (modified from Tankard and Balkwill, 1989; Hiscott et al., 1990). Age of seafloor spreading from Hiscott et al. (1990). NGTZ – Newfoundland-Gibraltar Transfer Zone, MPFZ – Messejana-Plasencia Fault Zone, NF – Nazaré Fault, TF – Tagus Fault, AF – Aveiro Fault, CFZ – Collector Fault Zone, ATZ – Avalon Transfer Zone, DTZ – Dominion Transfer Zone, CGFZ – Charlie Gibbs Fracture Zone.

2.2.1.1. Rift Phase I – Late Triassic to earliest Jurassic

The first extensional phase developed on a pre-existing continental crust consisting of accreted Palaeozoic terranes that resulted from the closure of the Iapetus and Rheic oceans (Ribeiro et al., 1979; Tucholke and Sibuet, 2007). In the Portuguese territory, the pre-Mesozoic terranes include the Central Iberian Zone (COZ), the Ossa-Morena Zone, the South Portuguese Zone (SPZ) and the Pulo do Lobo Ophiolite unit (e.g. Ribeiro et al., 1979). Altogether these domains are the primary sources of sediment of the newly formed basins and their structural tectonic fabric is often reworked during continental extension (Ribeiro et al., 1990).

In the Late Triassic (Carnian, but possibly earlier) continental extension initiated on a Wide Rift Mode in a widespread rift basin that extended over 800 km between the present Canadian Labrador and Nova Scotia margin, and from the Galicia to the Alentejo margin (Pinheiro et al., 1996; Tucholke and Sibuet, 2007). Subsidence along grabens and half-grabens during this period is limited (Stapel et al., 1996) and originated the early rift architecture dominated by the deposition of continental red beds overlain by shaly to evaporitic Hettangian successions (Tankard and Balkwill, 1989; Welsink et al., 1989; Azerêdo et al., 2003 and references therein) (see section 2.3, for detailed lithostratigraphic description of Portuguese units).

This first phase of extension is synchronous not only with continental rifting between North Africa and North America (e.g. Welsink et al., 1989) but also between the Canadian Labrador margin and Irish Celtic Sea or the North Sea (e.g. Steel, 1993; Sinclair, 1995).

2.2.1.2. Rift Phase II – Early to Middle Jurassic

The initiation of rift phase 2 is characterised by significant magmatic activity during the Rhaetian-Hettangian, which is dispersed throughout the south-western part of Iberia (in the Sesimbra region, in Santiago do Cacém and the Algarve Basin) and from the South Portuguese Zone to the Central Iberian Zone, along the MPFZ (Schermerhorn et al., 1978; Ribeiro et al., 1979; Azerêdo et al., 2003; Martins et al., 2008) (Fig. 2.1). Martins et al. (2008), analysing the volcano-sedimentary successions of the Algarve and western Alentejo (in Santiago do Cacém) along with the evidence from the MPFZ (e.g. Cebriá et al., 2003) revealed the age and geochemical affinities with the Central Atlantic Magmatic Province (CAMP) (Fig. 2.3). In contrast in Newfoundland, magmatism is nearly absent with the only occurrences being reported from the Nova Scotia margin (Cirilli et al., 2009). This second phase marks the transition from a wide rift mode type of continental extension to a focused extension mode (Tucholke and Sibuet, 2007). The processes controlling this change in the mode of extension has been thoroughly described for the Galicia and Adriatic margin, showing evidence of seaward migration of the rift locus, ultimately leading to continental breakup (Manatschal and Bernoulli, 1999; Alves et al., 2009).

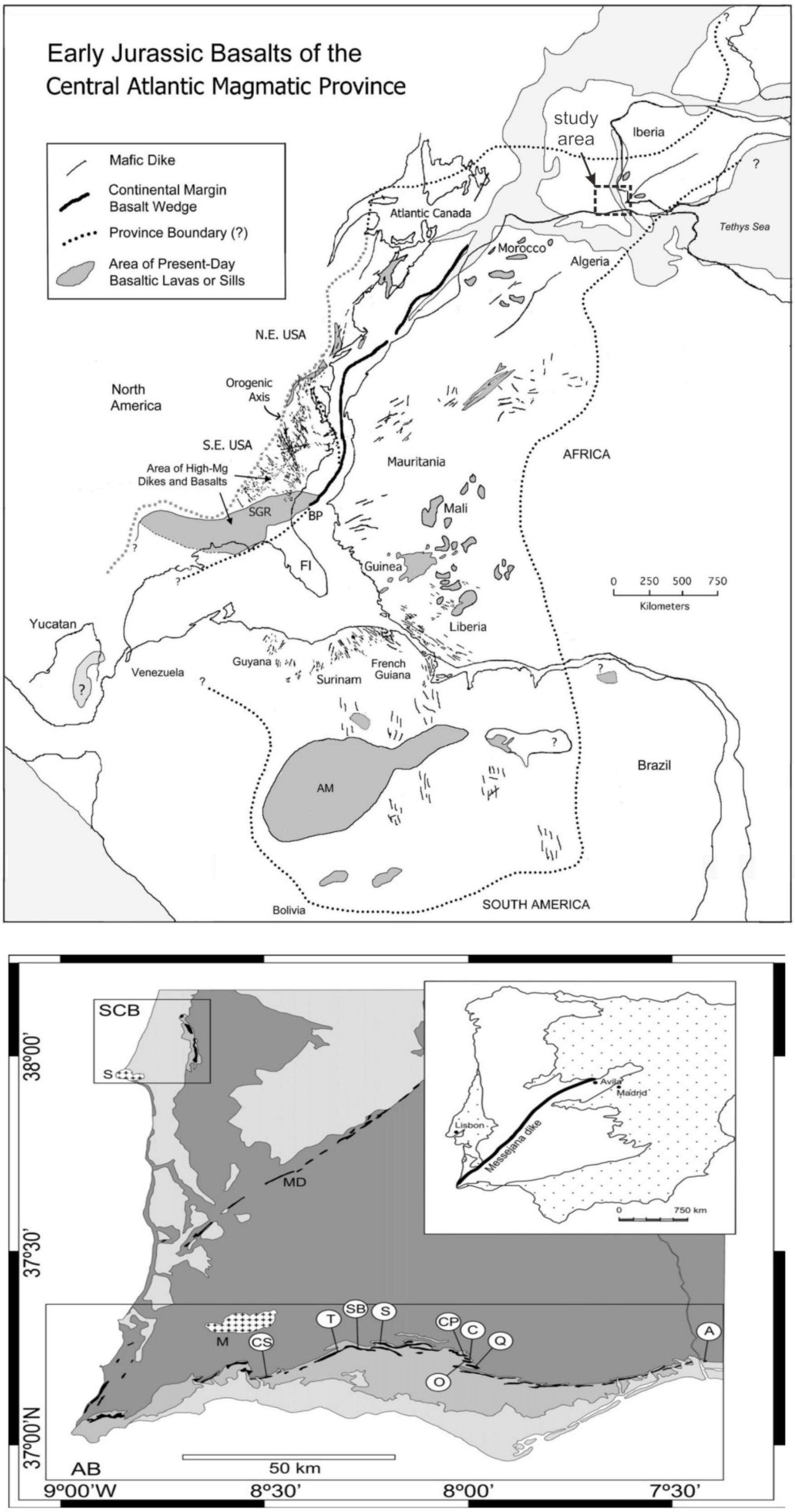


Figure 2.3 – Distribution of magmatism in the Central Atlantic Magmatic Province (CAMP), A) throughout America, Africa and south-western Europe (McHone, 2002) and, B) in southwest Iberia, showing the volcanics of the Algarve and Santiago do Cacém, and dykes along the Messejana-Plasencia Fault Zone (Martins et al., 2008).

The Early to Middle Jurassic is traditionally described as a period when both the Newfoundland and West Iberia underwent limited epeirogenic subsidence associated with minor continental extension (Tucholke and Sibuet, 2007 and references therein).

However, in the Lusitanian Basin subsidence analyses revealed a period of considerable crustal extension (β values of 1,03 to 1,22) and renewed creation of accommodation space from the latest Triassic (Rhaetian) to the Early Jurassic (Plienspachian-Toarcian?) (Wilson et al., 1989; Hiscott et al., 1990; Stapel et al., 1996; Cunha et al., 2009), leading to the widespread and thick formation of a carbonate ramp during the Early to Middle Jurassic (Azerêdo, 1998; Azerêdo et al., 2003). During this phase the margin records the progressive influence of marine dominance with irregular periods of basin inversion, mainly expressed on the Toarcian-Aalenian of the Alentejo and Algarve Basins (Terrinha et al., 2002; Azerêdo et al., 2003).

On the conjugate margins of Morocco-Nova Scotia the Early to Middle Jurassic interval marks the evolution and transition to seafloor spreading that occurred by the early to late Toarcian (Welsink et al., 1989; Laville et al., 2004). In southern Newfoundland, the Early to Middle Jurassic of the Whale Basin reveals weakly rotational strata, followed by increased subsidence in the Bajocian to early Bathonian, that persists until the Late Jurassic (Balkwill and Legall, 1989).

Together with the offshore Moroccan and Nova Scotia rifted margins the southern North Atlantic was segmented during continental extension and subsequent seafloor spreading, bounded by first-order transfer faults that formed correlative geodynamic provinces (Tankard and Balkwill, 1989) (Fig. 2.2). Such transfer zones, which include the Newfoundland-Gibraltar Transform Zone (NGTZ), the Collector Fault Zone (CFZ), the Avalon Transfer Zone (ATZ) or the Dominion Transfer Zone (DTZ) and the Messejana-Plasencia Fault Zone (MPFZ) are major corridors of strike-slip deformation along which, the rift-to-drift re-organization of both oceanic and continental domains have occurred (Schermerhorn et al., 1978; Tankard and Balkwill, 1989; Srivastava et al., 1990b; Tucholke and Sibuet, 2007) (Fig. 2.2).

2.2.1.3. Rift Phase III – Late Jurassic to earliest Cretaceous

Overlaying a regional angular unconformity that extends from the Callovian to the mid Oxfordian (Azerêdo et al., 1998; Azerêdo et al., 2002b), the Late Jurassic of West Iberia marks a new period of intense tectonic subsidence and creation of new accommodation space (Wilson, 1988; Hiscott et al., 1990; Stapel et al., 1996; Cunha et al., 2009). As a result of the continued extension throughout the margin, West Iberia developed two major N-S to NE-SW rift axes cross-cut by first order transfer zones, namely the Aveiro Fault, the Nazaré Fault, the Tagus Fault and the Messejana-Plasencia Fault Zone, that broadly define four distinct structural segments (Alves et al., 2009).

The Late Jurassic marks the transition towards seafloor spreading with the increased seaward thinning of the continental crust with a major axes of subsidence in the proximal margins of the southern Lusitanian and the Alentejo Basins (Alves et al., 2009), which is coeval with the period of extension occurring in the south Newfoundland basins of Whale and Salar-Bonnition (Balkwill and Legall, 1989; Tucholke and Sibuet, 2007). In the Lusitanian Basin stretching estimates for this interval show values of 1,02 to 1,27, thus evidencing a nearly homogeneous extensional rates for the inner proximal margin (Stapel et al., 1996).

In the Tagus Abyssal Plain, magnetic anomalies M20-M17 are interpreted to represent the creation of new oceanic crust (Srivastava et al., 2000) and the cessation of rifting in Southwest Iberia (Mauffret et al., 1989b, a). However, the M-anomalies in this region appear to be located over the interpreted exhumed mantle hindering a conclusive estimation of the age of onset of seafloor spreading in Southwest Iberia (Tucholke et al., 2007; Tucholke and Sibuet, 2007). Pinheiro et al. (1992), conclude that seafloor spreading in the TAP occurred by 133 My ago, during the Hauterivian. Conversely, the discovery of Late Jurassic shallow marine fossils in the Gorringe Bank seems to support the first hypothesis (Conti et al., 2004). Nonetheless, a relatively prolonged phase of extension persisted from the Tithonian to the Berriasian-Hauterivian as documented on the northwest Iberian margin (e.g. Tucholke et al., 2007; Bronner et al., 2011).

The Late Jurassic rifting is associated with the onset of halokinesis of Triassic-Hettangian evaporites that from this period onwards reveal significant importance in controlling the architecture of sub-basins where salt shows sufficient thickness to control deposition (e.g. Alves et al., 2003c).

2.2.1.4. Rift Phase IV – Early Cretaceous

The final phase of continental extension between West Iberia and Newfoundland (Berriasian to Aptian-Albian) is mainly observed on the distal areas of the northwest Iberian margin, evidencing a period of significant tectonic subsidence preceding the creation of oceanic crust (Tucholke et al., 2007). Extension of the continental crust is maximum for the distal margin, with the formation of allochthonous rift blocks overlying a deep crustal detachment (e.g. Manatschal and Bernoulli, 1998, 1999).

During this phase the Lusitanian and Alentejo Basins reveal limited (to absent) tectonic subsidence (Stapel et al., 1996; Cunha et al., 2009), with depositional sequences revealing sub-parallel reflectors on seismic data and outcrops denoting the influence of fluvio-deltaic retrograding successions blanketing the proximal margin during the Early Cretaceous (Rasmussen et al., 1998; Rey et al., 2006; Alves et al., 2009). This indicates that the main locus of rifting migrated westwards in its later stage, also coinciding with a period of intense mantle exhumation west of the Galicia margin (Manatschal and Bernoulli, 1998, 1999; Tucholke and Sibuet, 2007). Separation of the continental crust between the Galicia Bank and the Flemish Cap (North Newfoundland), although completed by the Barremian persisted until the Aptian-Albian boundary with the exhumation of mantle, when, oceanic crust was ultimately created (Tucholke et al., 2007).

2.2.2. The Messejana-Plasencia Fault Zone

The modern Messejana-Plasencia Fault Zone is the onshore expression of a NE-SW left-lateral strike-slip extending over 500 km onshore, along Portugal and Spain (Arthaud and Matte, 1975; Schermerhorn et al., 1978; Ribeiro et al., 1990). The MPFZ is inherited from the Variscan orogeny that was subsequently re-activated during the Late Triassic to the Early Jurassic and along which, magmatic activity is recorded (Arthaud and Matte, 1975; Schermerhorn et al., 1978; Cebriá et al., 2003; Ortas et al., 2006; Silva et al., 2008). Along the MPFZ the intrusion of doleritic dykes of the Central Atlantic Magmatic Province

(CAMP) are revealed to bear importance to palaeogeographic reconstructions in the North Atlantic (Schott et al., 1981; Palencia-Ortas et al., 2006).

The offshore prolongation of the MPFZ is revealed as a NE striking reverse fault dipping to the SE that exerts significant control in the incision of the São Vicente Canyon and on sediment transfer towards the Horseshoe Abyssal Plain (Mauffret et al., 1989b; Terrinha et al., 2009). Moreover, this prominent strike-slip zone marks the northern boundary of the Sagres Plateau and divides the Alentejo Basin from the Algarve Basin to the East.

The MPFZ is also associated with noteworthy seismic activity that reveal a dominant transpressive behaviour (Gràcia et al., 2003b; Geissler et al., 2010). Together with the Marquês de Pombal High and the thrusting units of the Gulf of Cadiz, the MPFZ is recognised as a possible source area for destructive earthquakes (Zitellini et al., 2001; Terrinha et al., 2003; Zitellini et al., 2009).

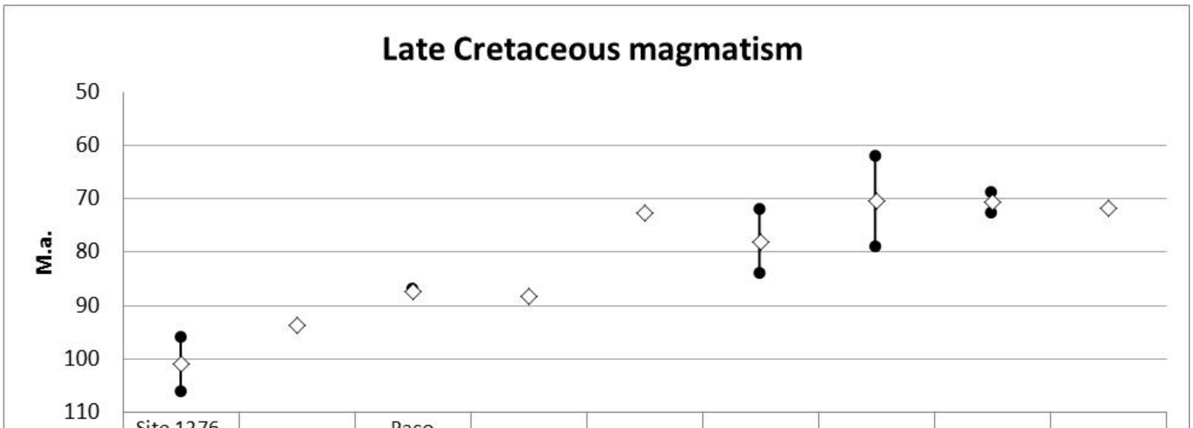
2.2.3. Mesozoic magmatism

The West Iberian margin has been traditionally referred as a non-volcanic (or magma-poor) rifted margin (e.g. Manatschal, 2004; Tucholke et al., 2007). However, distinct and widespread cycles of magmatic activity are recorded throughout the Mesozoic of the Portuguese continental margin, which include:

- Tholeiitic cycle (203-198 My) – Represented in western Iberia by extrusive lava flows in Algarve, Bordeira, Santiago do Cacém and Sesimbra (Verati et al., 2007; Martins et al., 2008) and the Messejana-Plasencia doleritic dike system (Dunn et al., 1998; Cebriá et al., 2003; Rapaille et al., 2003; Silva et al., 2008) (Fig. 2.3). This data reveal the affinity with the Central Atlantic Magmatic Province (CAMP) (Verati et al., 2007) and that the driving force of the early Mesozoic rifting was of the passive type (Martins et al., 2008).
- Early alkaline cycle (146-142 My) – this episode marks the first occurrences of alkaline magmatism in the central Lusitanian Basin, coeval with the period of maximum lithospheric thinning (Grange et al., 2008). In the Gorringe Bank,

the first gabbroic and peridotite occurrences are dated from this period (Féraud et al., 1986; Conti et al., 2004).

- Transitional cycle (135-130 My) – occurs mainly in the Lusitanian basin (but also in the Algarve) as dykes of dolerites, gabbros and diorites and also minor hypovolcanics in Nazaré and Montejunto (Miranda et al., 2009). The analysis of the unroofed sub-continental gabbros and meta-gabbros of the Gorringe and Galicia respectively yielded 138 and 121 My ages (Schärer et al., 2000).
- Alkaline cycle (100-71 My) (Fig. 2.4.) – Main occurrences are recorded from two pulses, which include: 1) the Foz da Fonte, Paço d'Ilhas and Ribamar as part of the the sill and dyke complex of Mafra (*ca.* 100 My) (Miranda et al., 2009) and the magmatism on the distal margin of Galicia (site 1276, ODP Leg 210) that revealed two diabase sills of Albian to Cenomanian age (Tucholke and Sibuet, 2007); and 2) the Lisbon Basaltic Complex (*ca.* 73 Ma) and the intrusive Sines, Sintra and Monchique massifs (84 to 71 My) (Miranda et al., 2009; Grange et al., 2010). Also from the Serra d'Aire, Montejunto evidence of this cycle are present, as well from the western Algarve (Miranda et al., 2009). In the Estremadura Spur, offshore West of Lisbon, a volcanic feature (the Fontanelas Seamount), was identified and correlated with the Late Cretaceous magmatism (Miranda et al., 2010).



	Site 1276, Leg 210	F. Fonte	Paço d'Ilhas	Ribamar	LVC	Sintra	Sines	Monchique	Loulé
Max	106	93,8	88,0	88,3	72,6	84,0	78,9	72,7	71,8
Min	96,0	93,8	86,8	88,3	72,6	72,0	62,0	68,8	71,8
◇ Avgr	101,0	93,8	87,4	88,3	72,6	78,0	70,5	70,8	71,8

Figure 2.4 – Main occurrences of Late Cretaceous magmatism (Grange et al., 2008; Grange et al., 2010; Miranda et al., 2010).

The overall distribution of these magmatic events shows that these are located mainly in the south-western part of Portugal (South of the Nazaré Fault), and that the first three cycles are associated with the main phases of continental rifting, wheras the fouth cycle is exclusively associated with the post-rift evolution (Ribeiro et al., 1979; Pinheiro et al., 1996; Martins et al., 2010).

Similar and coeval evidence of magmatism are described since the Triassic to the Paleocene on the Newfoundland margin, although in minor extent when compared with West Iberia (Tucholke and Sibuet, 2007).

2.2.4. Post-rift evolution of the West Iberian margin

2.2.4.1. Continental drift

The evolution of the West Iberian margin during the Cretaceous can be subdivided into two main phases with reference to the unambiguous completion of seafloor spreading by late Aptian-Albian times (e.g. Tucholke et al., 2007; Bronner et al., 2011). From this period onwards the entire margin evolved passively and progressively drifted away from Newfoundland (e.g. Srivastava and Verhoeff, 1992). The Late Cretaceous is also marked in northern Iberia by the opening of the Gulf of Biscay, which exerted significant rotational component on the Iberia micro-plate (e.g. Garcia-Mondejar, 1989).

During this period, thermal subsidence, loading and eustasy controlled the deposition throughout the margin that dominantly includes on the proximal sector, alternating successions (both in space and time) of continental, transitional and shallow marine successions of carbonates and siliciclastics (Rey et al., 2006 and references therein). A more detailed description of the lithostratigraphic units and their depositional systems is described in Chapter 2.3.

The Late Cretaceous is marked by significant magmatic activity that includes the intrusion of the alkaline massifs of Monchique, Sines and Sintra, as well as the volcanics, dykes and sills occurring in the Lisbon region and in Loulé (Algarve) (Miranda et al., 2009; Grange et al., 2010). These authors conclude that two main pulses of magmatism occurred throughout the margin (firstly during 94-88 My and secondly during 75-72 My), also suggesting that these pulses resulted from partial melting of a sub-lithospheric source, with Central Atlantic affinities.

2.2.4.2. Inversion of the western iberian margin

The West Iberian margin, similarly to other margins in the North Atlantic underwent through various periods of tectonic inversion (Ribeiro et al., 1990; Masson et al., 1994; Cloetingh et al., 2008; Doré et al., 2008). Inversion of rifted continental margins results from compressional stresses, such as tectono-magmatic and active asthenospheric upwelling, as well as post-breakup compressional and compactional stresses that include plate collision or subduction, ridge-push forces, continental resistance to plate motion, gravity loading, flank enhancement by sediment loading, transfer from orogenic stress, reactivation of pre-existing basement lineaments, plate driving and body forces (e.g. Doré et al., 2008). The deformation styles during inversions are often dependent of the inherited geometry and rheological behaviour of the lithosphere, as well as the intra-plate stress field (Cloetingh et al., 2008).

Throughout West Iberia widespread examples of ancient and recent features of inversion have been described (Boillot et al., 1979; Mougenot et al., 1979; Masson et al., 1994; Alves et al., 2003a; Terrinha et al., 2003; Zitellini et al., 2004; Afilhado et al., 2008; Alves et al., 2009; Neves et al., 2009). Inversion occurred in different periods of the Meso-Cenozoic with the majority and most intensive periods focused from the latest Cretaceous onwards, mainly associated with continental drift and subsequent collision of the Iberian microplate with the European and African tectonic plates (Boillot et al., 1979; Mougenot et al., 1979; Malod and Mauffret, 1990; Srivastava et al., 1990b).

Episodic inversion of the Southwest Iberian margin is firstly recorded during the transition from the Early to the Middle Jurassic, as expressed by the widespread hiatus and angular unconformity of Toarcian-Aalenian age (Oliveira, 1984; Terrinha et al., 2002).

A new event of inversion can be observed throughout the margin, expressed mainly as an angular uniformity and hiatus that ranges (diachronically and in magnitude) from the late Callovian to the mid Oxfordian, immediately preceding the Late Jurassic rift phase (e.g. Wilson et al., 1989; Azerêdo et al., 2002b). The Tithonian-Berriasian uplift and inversion separates the third and the final phase of rifting, which is marked by exposure of parts of the proximal margin (Terrinha et al., 2002).

From the latest Cretaceous onwards nine tectonic phase of shortening, inversion and uplift are recorded (Alves et al., 2003a and references therein). A period of significant shortening and inversion is related with the Late Cretaceous to middle Eocene (Malod and Mauffret, 1990; Srivastava et al., 1990b; Pinheiro et al., 1996), when Iberia was connected to North Africa and the active plate boundary was located at the Bay of Biscay, associated with N-S to NE-SW convergence towards the Pyrenees (Mougenot et al., 1979; Ribeiro et al., 1990; Sainz and Faccenna, 2001). During the latest Cretaceous, the inner proximal margin was also deformed by the intrusion of large igneous bodies of Sines, Sintra and Monchique (e.g. Miranda et al., 2009).

During the Eocene a new episode of inversion is widely expressed throughout the margin, but is more significant on the northern areas of the West Iberian margin, which resulted from the reactivation of NE-SW rift faults (Boillot et al., 1979; Mougenot et al., 1979). On the Galicia margin, compression resulted in large scale buckling of the OCT and limited reverse faulting (e.g. Masson et al., 1994). In the Lusitanian and Peniche Basins, inversion occurs associated with thin-skin tectonics over a shaly-evaporitic Hettangian unit (Ribeiro et al., 1990; Alves et al., 2006).

The most significant period of inversion occurred from the Late Oligocene (Chattian) to Miocene, in relation with the NNE-SSW collision of the Iberian microplate with North Africa, during the Atlas phase of the Alpine orogeny (Ribeiro et al., 1990; Srivastava et al., 1990b; Pinheiro et al., 1996).

Inversion and shortening of the margin continued from the Miocene to the present, resulting in the reactivation of an inherited NE-SW to WSW-ENE architecture as observed from seafloor deformation, faulting and earthquake activity (Ribeiro et al., 1990; Gràcia et al., 2003b; Terrinha et al., 2003; Zitellini et al., 2004; Geissler et al., 2010). In the study area, shortening is dissimilar and reflects the rheology of the distinct crustal domains (Neves et al., 2009; Cunha et al., 2010b). In order to explain the different architectures resulting from compression, Neves et al. (2009) suggest the existence of a deep crustal indentor, thrusting over a mantle detachment.

2.3. Stratigraphy of the Southwest Iberian margin

The West Iberian margin records the complete depositional evolution of the Central-North Atlantic Ocean, since the onset of rifting leading to continental breakup, subsequent drifting and inversion until the present day (e.g. Mougenot et al., 1979; Hiscott et al., 1990; Pinheiro et al., 1996). As part of this broader setting, the Southwest Iberian margin reveals valuable information from outcrops in the regions areas of Sagres, Bordeira, Santiago do Cacém and Sines, as well from boreholes that include the exploration wells Pescada-1 (Pe-1) and Golfinho-1 (Go-1), and the Monte-Paio well (MP) (drilled for non-commercial purposes) (Fig. 2.1).

A summary of the main lithostratigraphic units is presented herein for the Alentejo Basin, based on information from outcrops, wells and dredges, with reference to the regional units described for the Algarve, Lusitanian, Peniche and Porto Basins. Additionally, these stratigraphic units are correlated with the main seismo-stratigraphic sequences interpreted in multichannel seismic data, in order to construct a comprehensive stratigraphic framework that can describe both the tectonic evolution of the margin and their depositional component (Fig. 2.5).

The nomenclature used in this work aims to attain a compromise between recent and old lithostratigraphic names that have been referred in literature, but that still lacks a general consensus and uniformization between industry and academia (e.g. Witt, 1977; Wilson, 1988; Rasmussen et al., 1998; Azerêdo et al., 2003; Rey et al., 2006). In the works of Azerêdo et al. (2003) and Rey et al. (2006) an attempt to consolidate the lithostratigraphic nomenclature for the Lusitanian Basin resulted in fact, in the creation of a vast number of units (and the renaming of previously easily understood formations) that show problematic correlation with those observed in offshore wells and more significantly with the large scale seismic stratigraphic sequences. This in fact hinders a comprehensive analysis and correlation of the depositional units found both onshore and offshore and their distribution along the West Iberian margin. The approach followed throughout the chapters of the thesis does not aim to revise or to propose new formal lithostratigraphic units or nomenclature. It may however, initiate a debate on the regional applicability of some of the formation names recently proposed and a revision of impractical references. Accordingly, Table 2.1 summarises the main lithostratigraphic units referred in this thesis, as well as their dominant lithology and depositional environments.

2.3.1. The pre-rift Palaeozoic basement

In the study area the Palaeozoic underlying the first rift deposits is characterised by moderately to highly deformed outcropping successions of the South Portuguese Zone that in the study area can be grouped in the Southwest Sector and the Cercal-Rio Mira Sector (Oliveira, 1984).

The Southwest Sector comprises from base to top (Oliveira, 1984):

- The Late Devonian deep marine shales and sandstones of the Tercenas Formation;
- The Carboniferous of the Carrapateira Group includes:
    - the Bordalete Formation with metassedimentary black shales and sandstones interbedded with siliceous nodules;
    - the Murração Formation dominantly comprising silts, limestones and black to red schists and shales;
    - The Quebradas Formation is characterised by the occurrence of black schists (often with coal), silts, shales and rare interbedded limestones;
- The Brejeira Formation is characterised by extensive turbidites from the Late Carboniferous.

The Cercal-Rio Mira sector includes (Oliveira, 1984):

- The Volcano-siliceous Complex of Cercal, dated from the Late Devonian to Tournaisian(?);
- The Mira Formation (part of the Flysch do Baixo Alentejo Group), characterised by the occurrence of Namurian (mid Carboniferous) turbidites, conglomerates and patchy interbedded limestones.

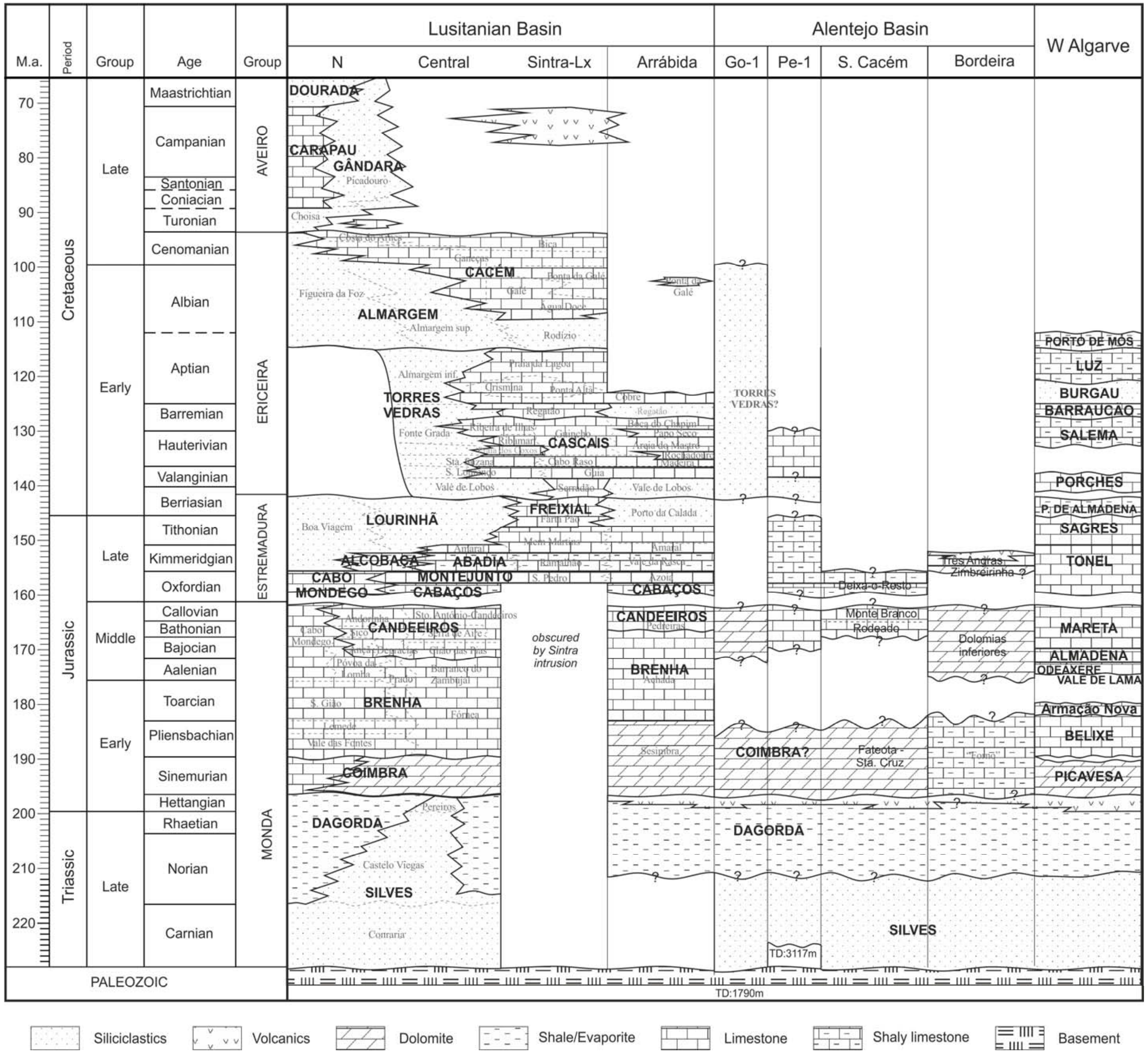


Figure 2.5 – Comparative Mesozoic lithostratigraphy of the Southwest Iberian margin and selected outcrops (Santiago do Cacém and Bordeira) and offshore wells (Go-1 and Pe-1). Principal units are correlated with their counterparts in the Lusitanian and Western Algarve Basins. Lithostratigraphy based on the works of Azerêdo et al. (2003), Rey et al. (2006), GPEP (1986), Inverno et al. (1993), Oliveira (1984), Ribeiro et al. (1987), Ramalho and Ribeiro (1985) and Witt (1977), referring to alternative nomenclature of lithostratigraphic units.

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Table 2.1 - Summary of the informal lithostratigraphic units mentioned in this work, used for the proximal margin of West Iberia (Lusitanian, Peniche and Alentejo Basins), their representative lithologies and overall depositional environment. Based on the works of Witt (1977), GPEP (1986), Wilson (1988), Ellis et al. (1990), Leinfelder (1993), Azerêdo et al. (2003), Rey et al. (2006), and references therein.

Lithostratigraphic unit	Age	Predominant lithologies	Depositional Environment
Moreia	Oligocene?-Miocene to recent	Sandstones, shales, limestones	Shallow to deep marine
Benfica	Late Eocene? - Oligocene	Marls and shales, calcareous conglomerate	Shallow marine
Espadarte	Palaeocene - Eocene	Dolomites, sandstones, shales	Shallow marine
Dourada	Late Campanian – Maastrichtian	Dolomites, sandstones and sandy limestones	Coastal to restricted marine (South); Continental to shallow marine (North)
Carapau	Coniancian - Campanian	Marls, limestones, dolomites; rare sandstones	Shallow marine
Gândara	Turonian - Maastrichtian?	Sandstones, conglomerates, marls and limestones	Continental, alluvial, deltaic
Cacém	Cenomanian – Early Turonian	Limestones, marls; rare dolomites; Argillaceous sandstones	Shallow marine, carbonate platform
Almargem	Aptian - Cenomanian	Sandstones, conglomerates, shales	Continental, fluvial, alluvial; Estuarine
Torres Vedras	Berriasian - Aptian	Sandstones and shales, conglomerates, marls; Rare lignite	Continental, fluvial
Cascais	Barremian - Aptian	Limestones and marls	Shallow marine, open to restricted
Linguado	Tithonian	Sandstones, limestones and marls; occasionally anhydrite	Restricted shallow marine
Freixial	Tithonian	Sandstone, conglomerate, micaceous shale, marl and marly limestone	Open to restricted shallow marine; Lagoonal to lacustrine
Lourinhã	Kimmeridgian - Tithonian	Marls, sandstone, conglomerates, limestones	Continental, fluvial, marginal marine
Alcobaça	Kimmeridgian	Marls and sandstones	Shallow marine and coastal
Abadia	Kimmeridgian	Predominantly marls; turbiditic sandstones, conglomerates and limestones	Deep marine; Axial fans
Três Angras	Lower Kimmeridgian	Limestones and marls, often dolomitic	Shallow marine to lacustrine
Zimbreirinha	Lower Kimmeridgian	Dolomites and marls	Shallow marine and coastal(?)
Cabo Mondego	Late Oxfordian	Argillaceous limestones, fine to coarse sandstones; Occasionally lignites, black shales and marls	Coastal plain to restricted carbonate marine shelf
Montejunto	Late Oxfordian	Limestones, marls, Occasionally conglomerates	Shallow to deep marine; Lagoonal; Axial fans
Cabaços/Deixa-o-Resto	Late Oxfordian	Limestones, marls; occasionally anhydrite;	Restricted to open, shallow marginal marine; Lacustrine to lagoonal
Candeeiros/Monte Branco/Rodeado	Aalenian - Callovian	Limestones, marls, dolomites	Deep to shallow marine carbonate ramp
Brenha	Sinemurian - Callovian	Marly limestones, limestones and black shales	Deep to shallow marine carbonate ramp
Coimbra/Fateota-Sta. Cruz/"Forno"	Sinemurian	Dolomites, limestones, marls and shales	Shallow marginal marine
Dagorda	Norian? - Hettangian	Thick evaporites (halite, anhydrite, gypsum, siderite), interbedded with shales (occasionally black), marls, limestones and dolomites	Continental to restricted marine (?); Sabkha(?)
Silves	Carnian-Hettangian	Red conglomerates, sandstones and shales	Continental, fluvial, alluvial fans

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2.3.2. Syn-rift deposition

2.3.2.1. Carnian to Hettangian – Syn-Rift Phase I

Onset of rift deposition is characterised by the widespread occurrence of Late Triassic fluviatile red beds (and in lesser extent the occurrence of marls and dolomites) of the Silves Formation overlaying a regional angular unconformity over the tightly folded Late Palaeozoic, which can be impressively observed at the Telheiro beach, South of Bordeira (Oliveira, 1984; Ribeiro et al., 1987; Inverno et al., 1993; Azerêdo et al., 2003).

In the Bordeira area, these deposits include fine to coarse red sandstones with oblique stratification subsequently overlain by red shales interbedded with thin grey dolomites (Ribeiro et al., 1987) (Fig. 2.6). In Santiago do Cacém (Fig. 2.7) and Monte Paio well (Fig. 2.8) this unit is characterised by oblique stratification of conglomerates and sandstones (Oliveira, 1984; Inverno et al., 1993). Coeval deposits were drilled in the Pe-1 (Fig. 2.9) and Go-1 exploration wells, both showing similar red siliciclastics (Fig. 2.10) (unpublished reports).

Overlaying the Silves Formation, the extensive but heterogeneous continental unit of the Dagorda Formation - also named "Complexo margo-carbonatado de Silves" in the Algarve (Ribeiro et al., 1987) - is composed of shales, evaporites, dolomites and marls of Norian to Hettangian age (Oliveira, 1984; Inverno et al., 1993; Azerêdo et al., 2003). Its thickness and distribution vary significantly as observed in outcrops of Bordeira and Santiago do Cacém (< 100 m) (Oliveira, 1984; Ribeiro et al., 1987; Inverno et al., 1993) (Figs. 2.6 and 2.7), whereas in the Lusitanian and Peniche Basins, thick successions resulted in significant halokinetic features (Alves et al., 2003c; Alves et al., 2006). In Pe-1 and Go-1, this unit reveals a sabkha to lacustrine environments denoting the inception of the marine influence along the margin, not exceeding 320 m (Azerêdo et al., 2003) (Figs. 2.9 and 2.10).

The Silves and Dagorda Formations, the Megasequences A and B of Soares et al. (1993), are respectively similar and coeval with sequences J1 and J2 interpreted in the Whale Basin (South Newfoundland) and are equivalent to Euridyce and Argo Formations (Hubbard, 1988; Balkwill and Legall, 1989) (Fig. 2.12 and 2.13). Additionally, sequences

Tr1-a and Tr1-b in Essaouira Basin (Morocco) record similar lithostratigraphic units (Hafid et al., 2000) (Fig. 2.12).

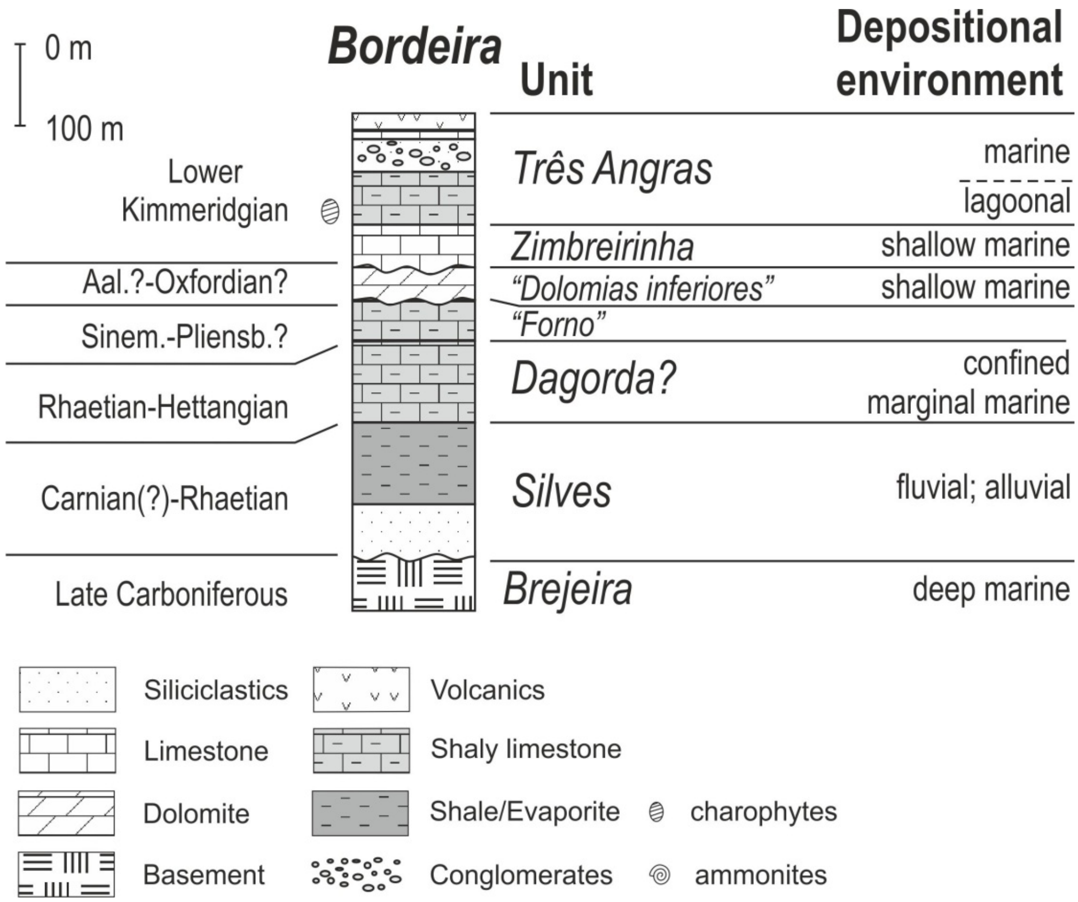

Figure 2.6 – Simplified lithostratigraphy of the Bordeira outcrop.

2.3.2.2. Hettangian to Callovian – Syn-Rift Phase II

Evolution of the Central to North Atlantic in the study area is marked, during the transition to the Early Jurassic, by the installation of widespread shallow marine conditions allowing the formation of the first carbonate successions (e.g. Azerêdo et al., 2003) (Fig. 2.5). On the West Iberian margin and the Alentejo Basin, this event is characterised by the occurrence of extensive low energy dolomitic carbonate ramps of the Coimbra Formation (Azerêdo et al., 2003), timely and lithology equivalent to the Iroquois Formation in Newfoundland (Balkwill and Legall, 1989; Magoon et al., 2005) (Fig. 2.13).

However, in contrast to the Lusitanian Basin, in the Southwest Iberian, the Nova Scotia and the northwest Moroccan margins this early incursion of marine deposits is preceded by the occurrence of magmatics of the CAMP (see section 2.2.3 for details), denoting the initiation of a renewed extensional rift phase initiated by the Rhaetian-Hettangian (Martins et al., 2008; Cirilli et al., 2009). In the Alentejo Basin these volcano-sedimentary units extend from the Sagres area to Santiago do Cacém (~100 m) but also occur in South of Lisbon, in the Arrábida region (~50-70 m) (Azerêdo et al., 2003), and are synchronous to the dykes of the MPFZ across southern Portugal and central Spain (Schermerhorn et al., 1978; Martins et al., 2008) (Fig. 2.3).

In the southwest Iberian margin the dolomitic unit (also referred as “dolomitos em plaquetas” in Bordeira, or as Fateota fm. in Santiago do Cacém) extends unevenly until the Toarcian in Santiago do Cacém and well Pe-1 or the Callovian in the Go-1 well (Ribeiro et al., 1987; Inverno et al., 1993) (Figs. 2.6, 2.7, 2.9 and 2.10). In Bordeira the Early Jurassic is dominantly composed of marls and marly limestones (Ramalho and Ribeiro, 1985; Ribeiro et al., 1987) (Fig. 2.6). In contrast, in the Lusitanian Basin, these dolomites (gradually becoming limestones) are restricted in time and can be found until the Sinemurian in the central and northern areas, whereas in the Arrábida region, these can reach the Pliensbachian (Azerêdo et al., 2003) (Fig. 2.5).

In the Pliensbachian the West Iberian margin experienced a new period of tectonic subsidence (Stapel et al., 1996; Cunha et al., 2009) that resulted in the formation of deep-water facies with the accumulation of black marls and shales with source rock potential in the northern Lusitanian Basin (Brenha Formation) (Wilson, 1988; Azerêdo et al., 2003) and marly limestones in the southern Alentejo Basin (the “Forno” unit in Bordeira) (Oliveira, 1984; Ribeiro et al., 1987). Elsewhere in the Alentejo Basin, the Early Jurassic is dominantly dolomitic (Inverno et al., 1993). This interval is characterised in wells Go-1 and Pe-1 by a major pulse of tectonic subsidence, similarly to wells on the offshore of the Lusitanian Basin (Stapel et al., 1996).

Progressive deepening of the margin associated with a period of relative tectonic quiescence, resulted in the resumed formation of the carbonate ramp throughout the margin, when by the Toarcian-Aalenian a period of regional uplift in southwest Iberia resulted in an durable hiatus (Ribeiro et al., 1987; Inverno et al., 1993; Terrinha et al., 2002). Conversely, this hiatus is absent in the Lusitanian Basin (Azerêdo et al., 2003).

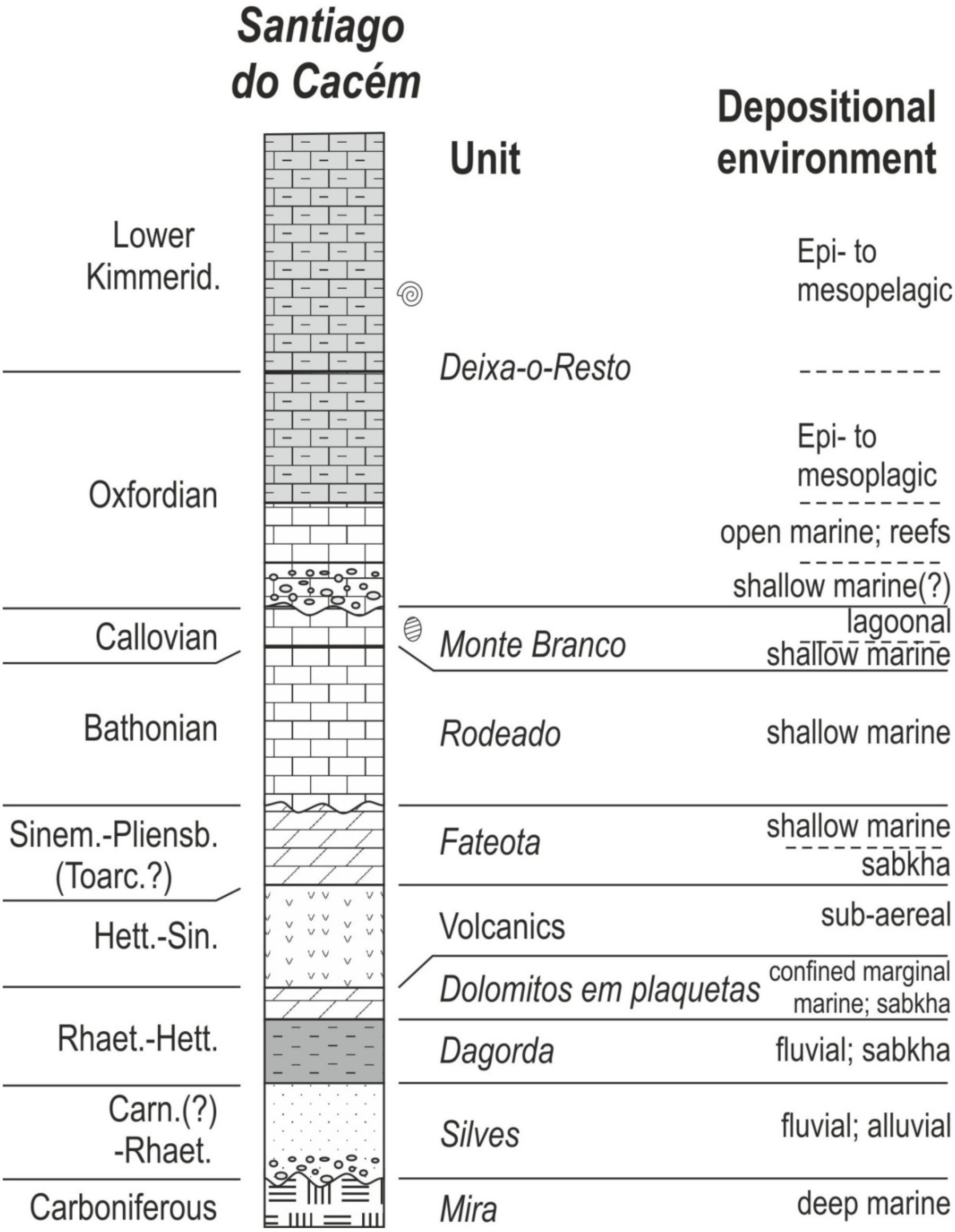

Figure 2.7 – Simplified lithostratigraphy of the Santiago do Cacém. See Fig. 2.6 for explanation of lithological patterns. See Fig. 2.1 for location.

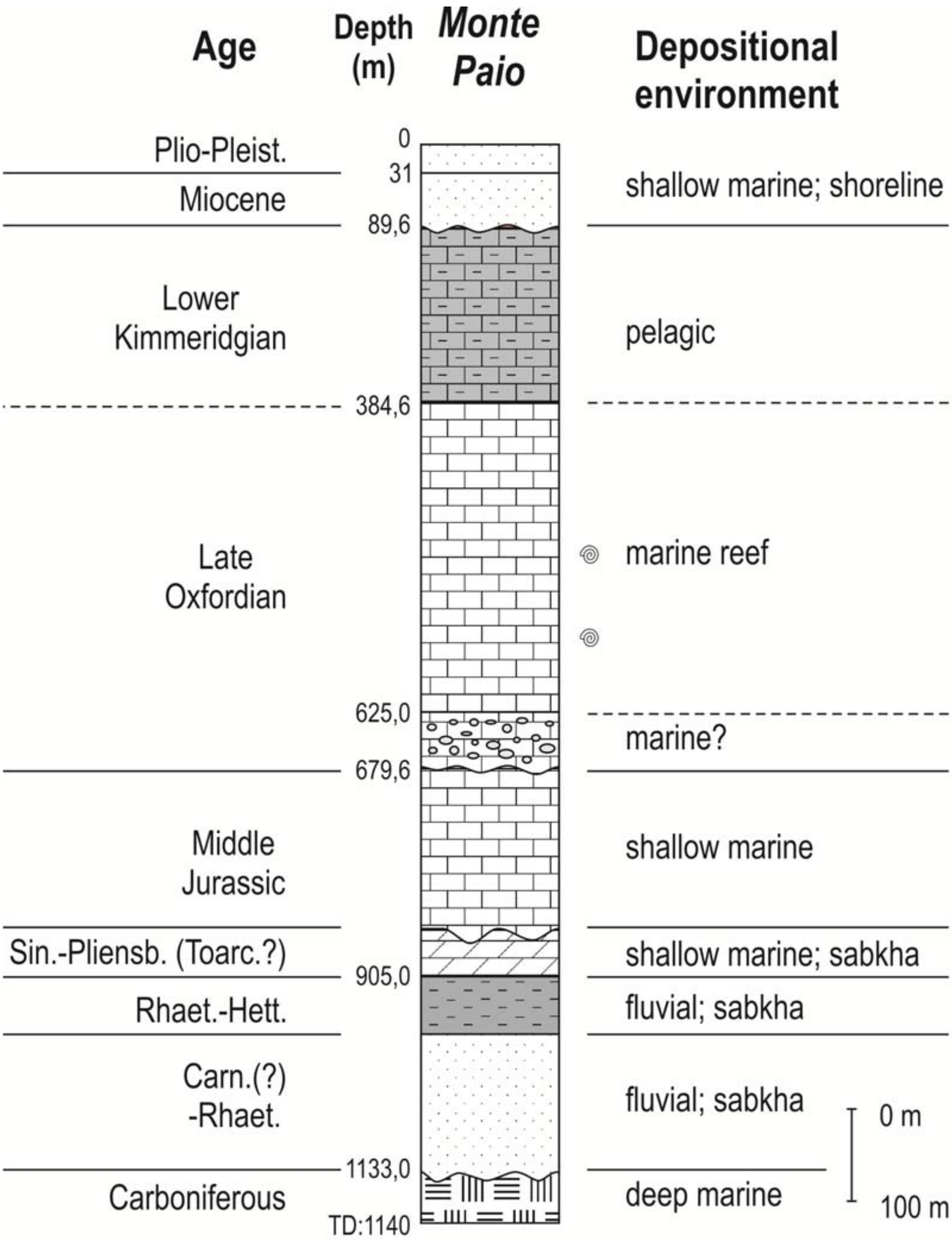

Figure 2.8 – Simplified lithostratigraphy of the Monte Paio borehole. See Fig. 2.6 for explanation of lithological patterns. See Fig. 2.1 for location.

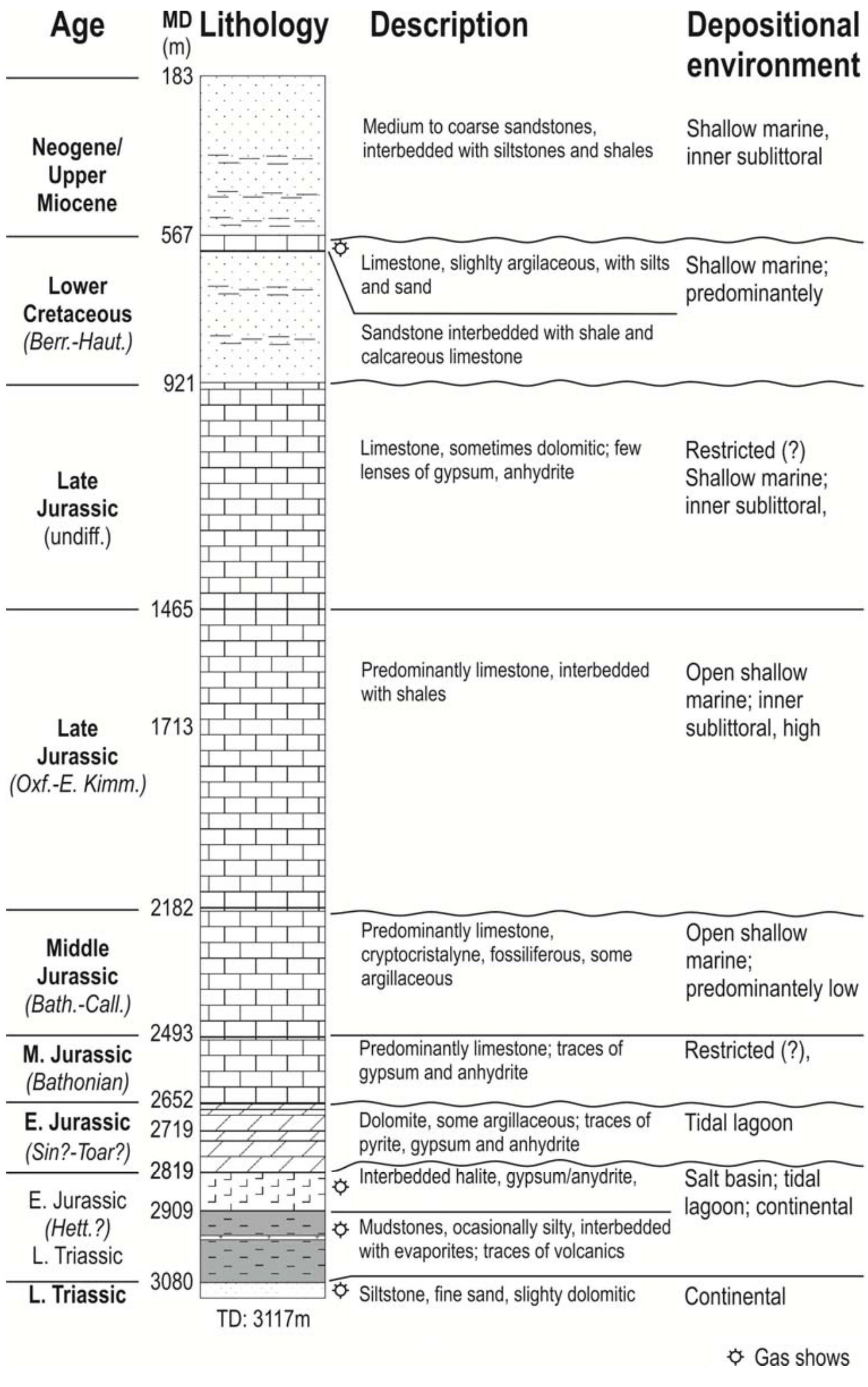

Figure 2.9 – Simplified lithostratigraphy of the Pescada-1 exploration borehole, showing the main unconformities bounding principal lithological units and hydrocarbon shows. See Fig. 2.1 for location.

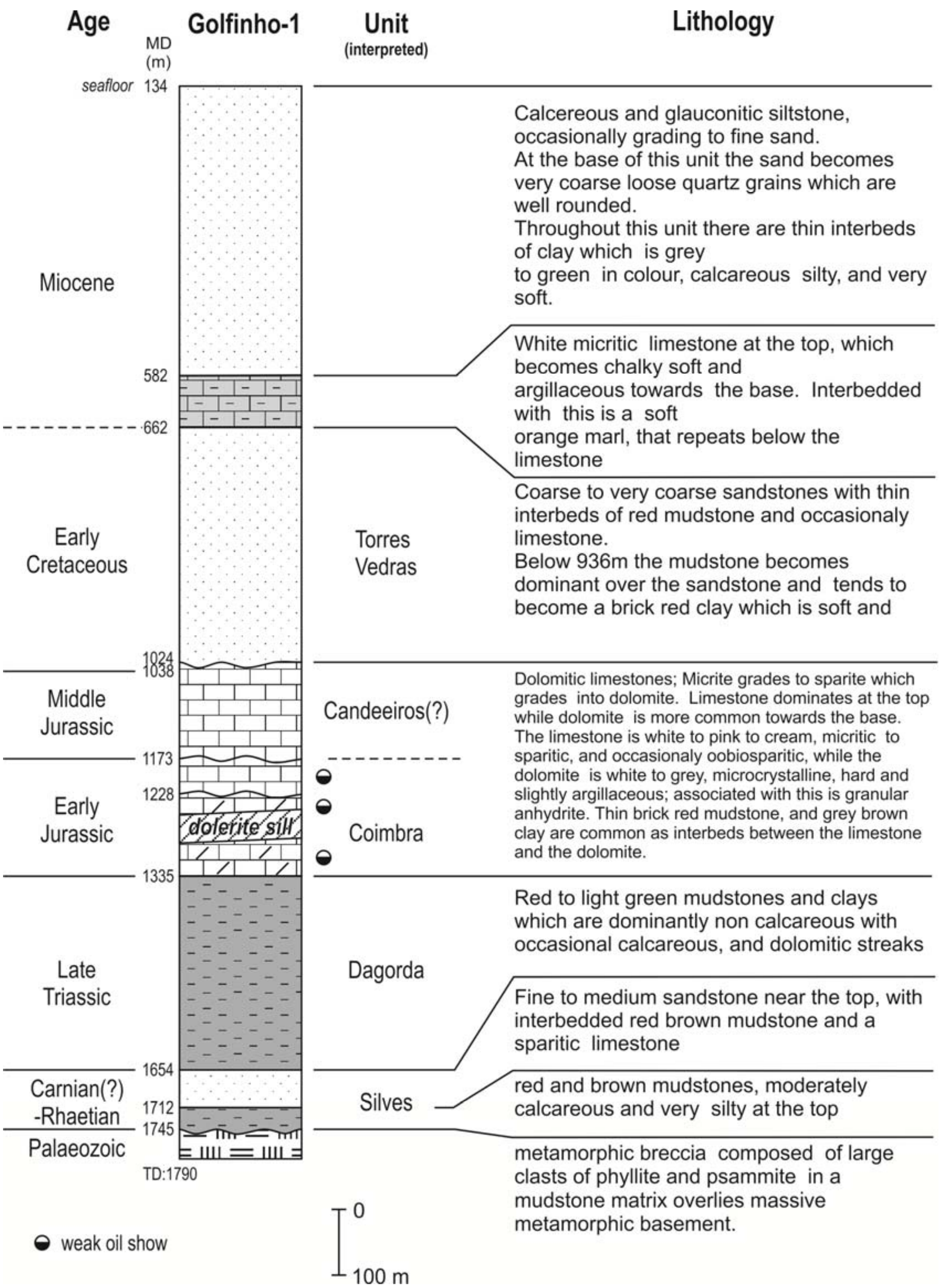

Figure 2.10 – Simplified lithostratigraphy of the Golfinho-1 exploration borehole, showing the main unconformities bounding principal lithological units and hydrocarbon shows. See Fig. 2.1 for location.

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Deposition resumed in the Alentejo and Algarve Basins by the Bajocian and similarly to what was occurring in the Lusitanian Basin (with deposition of the Candeeiros Formation), accommodation space was reduced and the carbonate ramp became progressively shallower, and ultimately the landward domains were uplifted to exposure, resulting in an extensive unconformity that ranges from the mid Callovian to the early Oxfordian (Azerêdo et al., 1998; Azerêdo et al., 2002b; Azerêdo et al., 2003) (Fig. 2.5). The carbonate ramp is characterised in Bordeira (Fig. 2.6) and well Go-1 (Fig. 2.10) by Toarcian?-Callovian dolomites ("dolomias inferiores unit"), whereas in Santiago do Cacém (Fig. 2.7) and Pe-1 (Fig. 2.9), the Bathonian-Callovian interval includes restricted to open shallow marine limestones, interbedded with marls and dolomites (Rodeado and Monte Branco formations) (Inverno et al., 1993).

Deposition throughout the West Iberian margin during this period is distinct from can be observed on the Newfoundland margin, which is dominated deep water facies, including shales of the Downing and Verrill Canyon Formations, interbedded by a prograding Toarcian-Bajocian limestone unit (Whale Mb.) (Fig. 2.11).

The sequence stratigraphy framework this interval is diverse and common surfaces throughout the West Iberian margin are challenging to correlate (Fig. 2.12). Nonetheless, the basal unconformity of the Hettangian, the Toarcian-Aalenian unconformity and the late Callovian-mid Oxfordian unconformity are surfaces that show coeval importance on both sides of the Central-North Atlantic (Fig. 2.11 and 2.12).

2.3.2.3. Oxfordian to Berriasian (?) – Syn-rift Phase III

A new period of marked tectonic subsidence is long recognised in the Late Jurassic of the Lusitanian Basin and the remainder West Iberian margin (e.g. Mougenot et al., 1979; Wilson, 1979; Mauffret et al., 1989b; Hiscott et al., 1990). The base of this sequence that is late Callovian to mid-late Oxfordian in age, is marked by a widespread basinal angular unconformity that can be traced throughout the West Iberian margin (Azerêdo et al., 1998; Azerêdo et al., 2002b; Tucholke and Sibuet, 2007) and Newfoundland (base of the

Abenaki Formation in the Whale Basin and Rankin Formation in Jeanne d'Arc Basin) (e.g. Balkwill and Legall, 1989; Hiscott et al., 1990) (Fig 2.11).

In Santiago do Cacém and the Monte Paio borehole the Oxfordian-Kimmeridgian of the Deixa-o-Resto formation is characterised from base to top by an angular unconformity overlain by a polygenic conglomerate and marine bio-micritic limestones and marls with abundant pelagic fauna (Inverno et al., 1993) (Fig. 2.7 and 2.8). Near Bordeira, the basal unit (probably Kimmeridgian in age) includes the limestones, dolomites and shales of the "Zimbreirinha" that at its base reveals black pebbles, overlain by a rich coral bearing unit of the Três Angras formation, subsequently covered by volcanic tuffs, limestones and conglomerates (Ribeiro et al., 1987) (Fig. 2.6).

The basal Oxfordian units of the Alentejo Basin can be correlated with the Cabaços Formation (lacustrine to shallow marine marls and limestones) and the "brecha da Arrábida" (polymictic conglomerates in a red limestone matrix) in the Lusitanian Basin (Azerêdo et al., 2002b), both marking a renewed period of tectonic subsidence in the margin (Hiscott et al., 1990; Stapel et al., 1996; Manupella et al., 1999; Cunha et al., 2009) (Fig. 2.5).

As extension continued on the margin, a complex suite of interbedded lithologies of late Oxfordian-Kimmeridgian age associated with tilt blocks mark the period of maximum subsidence (Wilson, 1988; Alves et al., 2009). These units include deep-marine to transitional limestones showing high variability in dependence of the position within tilt-blocks (e.g. Ravnås and Steel, 1998) (Fig. 1.9).

In the Alentejo Basin these Late Jurassic deposits are characterised by shallow marine sandstones and pelagic limestones and marls (Inverno et al., 1993), coeval with the fluvial to marginal marine of the Lourinhã Formation, the shallow marine Alcobaça Formation and the deep marine shales and submarine fans of the Abadia Formation (Witt, 1977; Wilson, 1988; Leinfelder and Wilson, 1989) (Fig. 2.5).

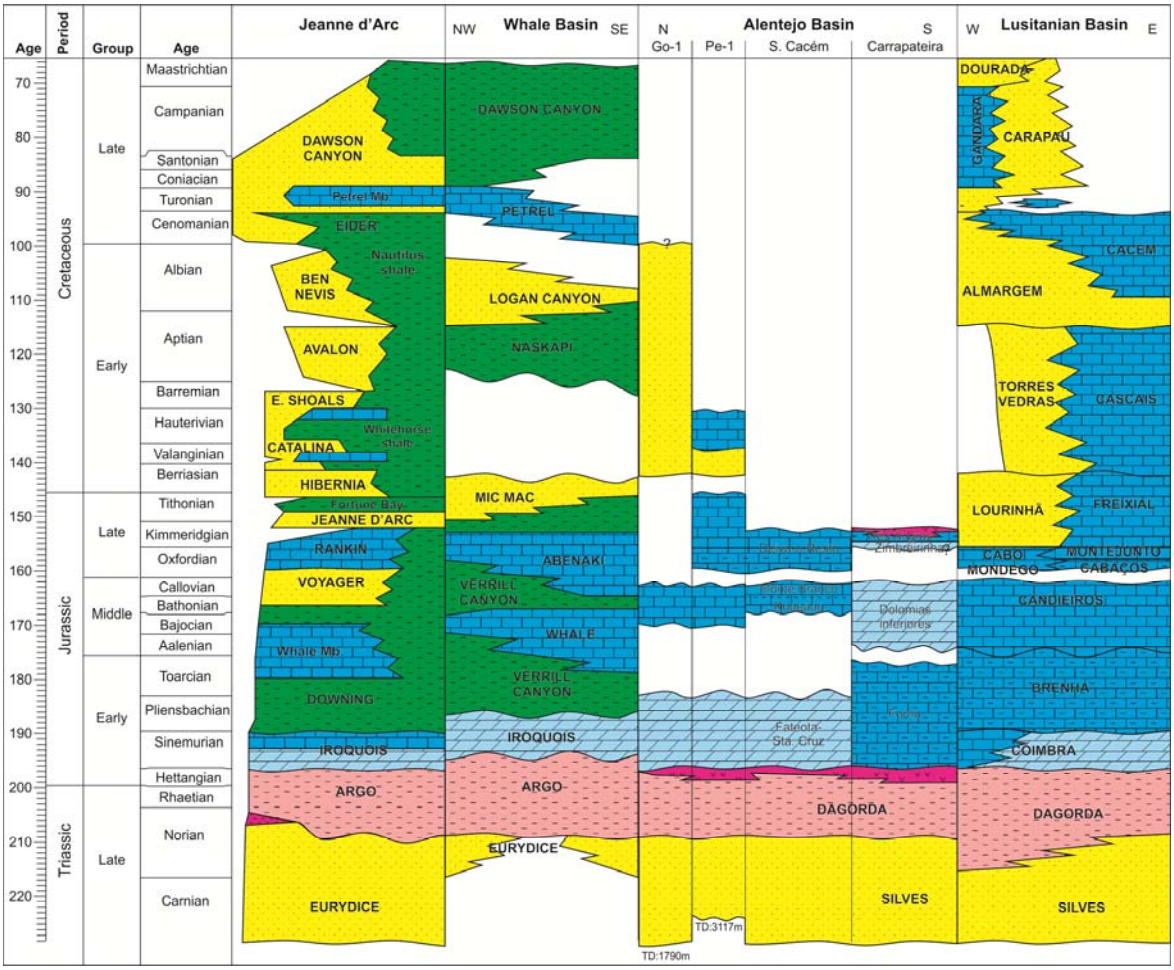

Figure 2.11 – Comparative lithostratigraphy of the West Iberian margin and the Newfoundland, based on the works of Witt (1977), Wilson (1988), Balkwill and Legall (1989), Azerêdo et al. (2003), Magoon et al. (2005), Rey et al. (2006).

The Kimmeridgian of West Iberia similarly to the Jeanne d'Arc Basin (the Rankin Formation, Egret Member) (Magoon et al., 2005) and the North Sea (Kimmeridge Clay) (Ravnås et al., 2000) is associated with source rock potential, although in opposition with the latter cases, in the West Iberian margin no commercial discoveries have been made. In the offshore of the Alentejo Basin, dredges sampled Late Jurassic bioclastic limestones with oil staining (Matos, 1979) (Fig. 2.13).

The late Kimmeridgian to Berriasian interval is absent in the outcrops of Santiago do Cacém and Bordeira, and from offshore exploration wells (Ribeiro et al., 1987; Inverno et al., 1993) (Fig. 2.6 and 2.7). However, offshore dredges recovered shallow marine limestones and dolomites of this age (Baldy, 1977; Matos, 1979; Mougenot et al., 1979). On seismic data of the Southwest Iberian margin Alves et al. (2009) show thick Late Jurassic growth strata, revealing this period as a major subsidence event.

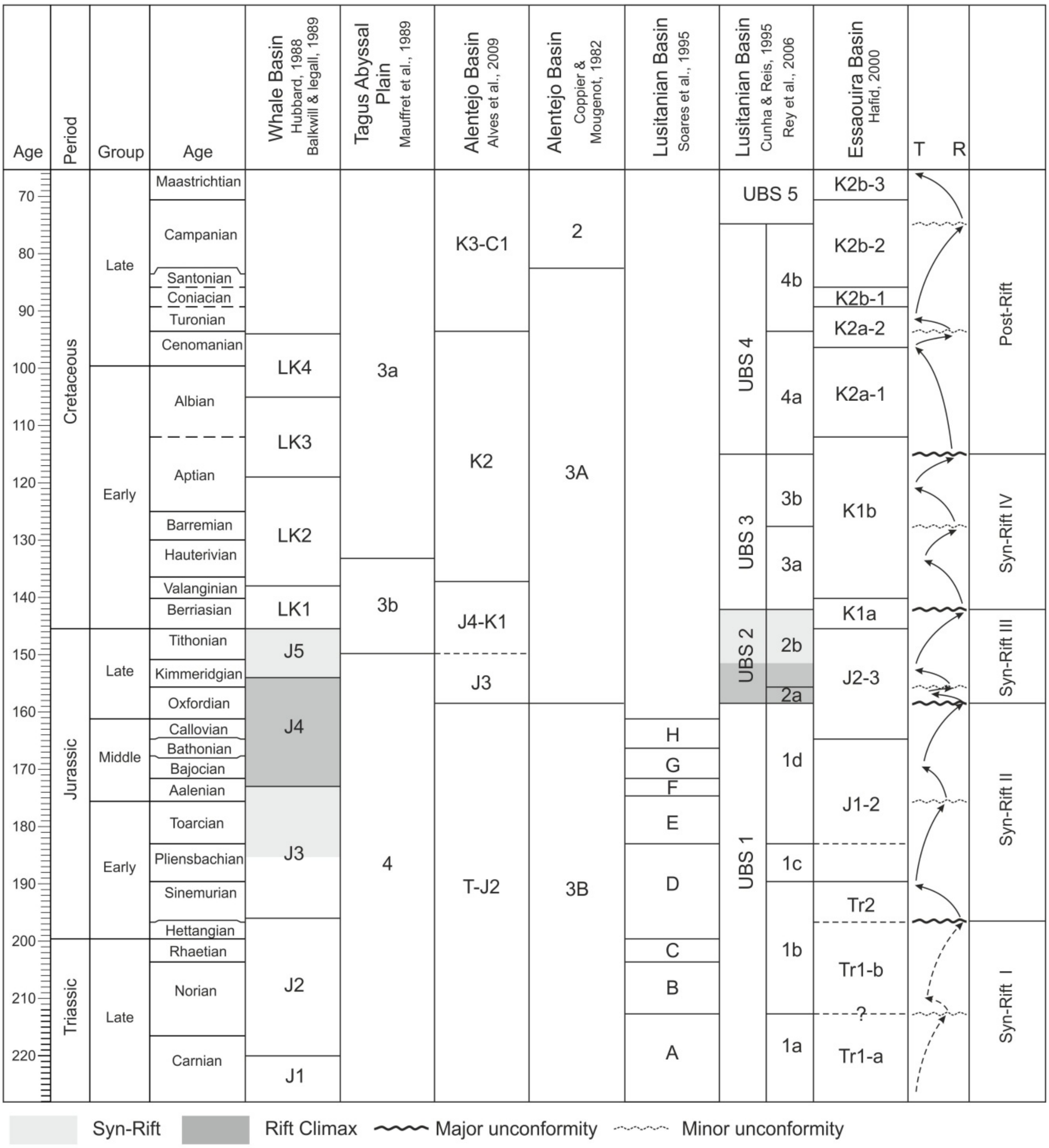

Figure 2.12 – Correlation of seismic stratigraphic sequences on the Iberia, Newfoundland and northern Moroccan margins (Coppier, 1982; Hubbard, 1988; Balkwill and Legall, 1989; Mauffret et al., 1989b; Soares et al., 1993; Hafid et al., 2000; Alves et al., 2009). Shading representing the duration of the main rift phases based on Tucholke and Sibuet (2007).

In the Lusitanian Basin this interval is characterised by the continued deposition of the Lourinhã Formation and in the Lisbon region (revealed as a principal depocentre during this period) by the Freixial formation that dominantly includes shallow marine to lacustrine limestones (Rey et al., 1968; Ramalho, 1971; Wilson, 1988) (fig. 2.5). The top of this depositional cycle is marked by exposure and an widespread angular unconformity of probable Berriasian age (Ramalho and Rey, 1975; Rey et al., 2006), which is broadly coeval with latest Tithonian to mid Berriasian sequence boundaries in the Essaouira (Hafid et al., 2000), Jeanne d'Arc and Whale Basins (Balkwill and Legall, 1989; Hiscott et al., 1990; Magoon et al., 2005) (Fig. 2.12). Mauffret et al. (1989b) consider that during this interval the Tagus Abyssal Plain was achieving seafloor spreading.

2.3.2.4. Late Berriasian to late Aptian – Syn-Rift Phase IV

The Berriasian angular unconformity defines the basal surface that marks a major change in both nature and architecture of depositional units throughout the West Iberian margin, which are dependent on the locus of active rift subsidence during the Early Cretaceous, namely along the principal N-S extensional axis on the margin (Wilson, 1988; Pinheiro et al., 1996; Rey et al., 2006; Alves et al., 2009). Accordingly, during the Berriasian-Aptian interval, rift subsidence was taking place mainly along a rift axis that included the areas West of the Lusitanian Basin and north of the Setubal Canyon towards the Iberia Abyssal Plain (Wilson et al., 2001; Alves et al., 2009). Elsewhere, subsidence was mainly of thermal origin and deposition was broadly controlled by the infill of remaining accommodation space (Rey et al., 2006; Alves et al., 2009).

Deposition during this period is characterised by two-fold end-members that include in the northern areas of the Lusitanian Basin the fluvial to deltaic and shoreline siliciclastics of the Torres Vedras Formation, and to the South by the shallow marine limestones of the Cascais formation (Wilson, 1988; Rey et al., 2006) (Fig. 2.5). In the onshore of the Alentejo Basin this interval is absent but it was intersected by the exploration wells and dredges that revealed siliciclastics and carbonates that can be roughly correlated with these two interbedded units (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Mougenot, 1988) (Figs. 2.9, 2.10 and 2.13).

Seismic data offshore the Alentejo Basin reveals that the Early Cretaceous is characterised by sub-parallel reflections on the proximal margin, although growth strata were interpreted in some areas of the margin (Mougenot et al., 1979; Coppier, 1982; Alves et al., 2009).

In Northwest Iberia, deep-water facies intersected during deep-sea drilling revealed Upper Berriasian to Valanginian chalks, Hauterivian-lower Barremian nannofossil limestones with interbedded mudstones, whereas on the west Galicia margin, shallow water dolomites were found (Tucholke and Sibuet, 2007). These authors additionally refer that the Barremian to Aptian interval shows mainly hemipelagic green and grey mudstones with interbedded coarser-grained turbidites, together with local occurrences of mass-flow breccias derived from the dismemberment of sediments, serpentinites, gabbro and basalts.

Throughout the Iberia-Newfoundland conjugate margin the Berriasian-Aptian depositional unit is characterised at its top by a widespread unconformity that in a simplistic approach can be considered as the "true" breakup unconformity (Driscoll et al., 1995; Tucholke et al., 2007). Additionally, as referred above (Section 1.2.2) the breakup unconformity is sometimes uneven and difficult to be identified with precision, largely as a result of the diachronous tensile efforts of ultimate extensional pulses prior to the onset of seafloor spreading, that in part reflect the exhumation of the serpentinised mantle (Karner et al., 2007; Tucholke et al., 2007; Bronner et al., 2011). From this point onwards the conjugate margins evolved as drifting tectonic plates and deposition is dominantly controlled by eustasy and by punctuated periods of post-rift compression (e.g. Cloetingh et al., 2008).

2.3.3. Albian to Maastrichtian

Subsequently to the complete onset of seafloor spreading on the West Iberian margin, deposition was dominantly controlled by the intricate balance of eustatic base level change and sediment input into the inherited accommodation space.

On the Southwest Iberian margin this period is characterised by simultaneous absence of Late Cretaceous deposits on the proximal sector of the Alentejo Basin (which includes the offshore exploration wells) and by significant accumulation of sediments on the oceanwards domains (Mougenot et al., 1979; Coppier, 1982; Oliveira, 1984; Mauffret et al., 1989b; Alves et al., 2003a; Alves et al., 2009; Neves et al., 2009; Cunha et al., 2010b). Although there is scarce information on the nature of Late Cretaceous deposits, dredges sampled West of Bordeira revealed Cenomanian to Maastrichtian deep-water limestones, some with oil staining (Matos, 1979; Mougenot et al., 1979) (Fig. 2.13).

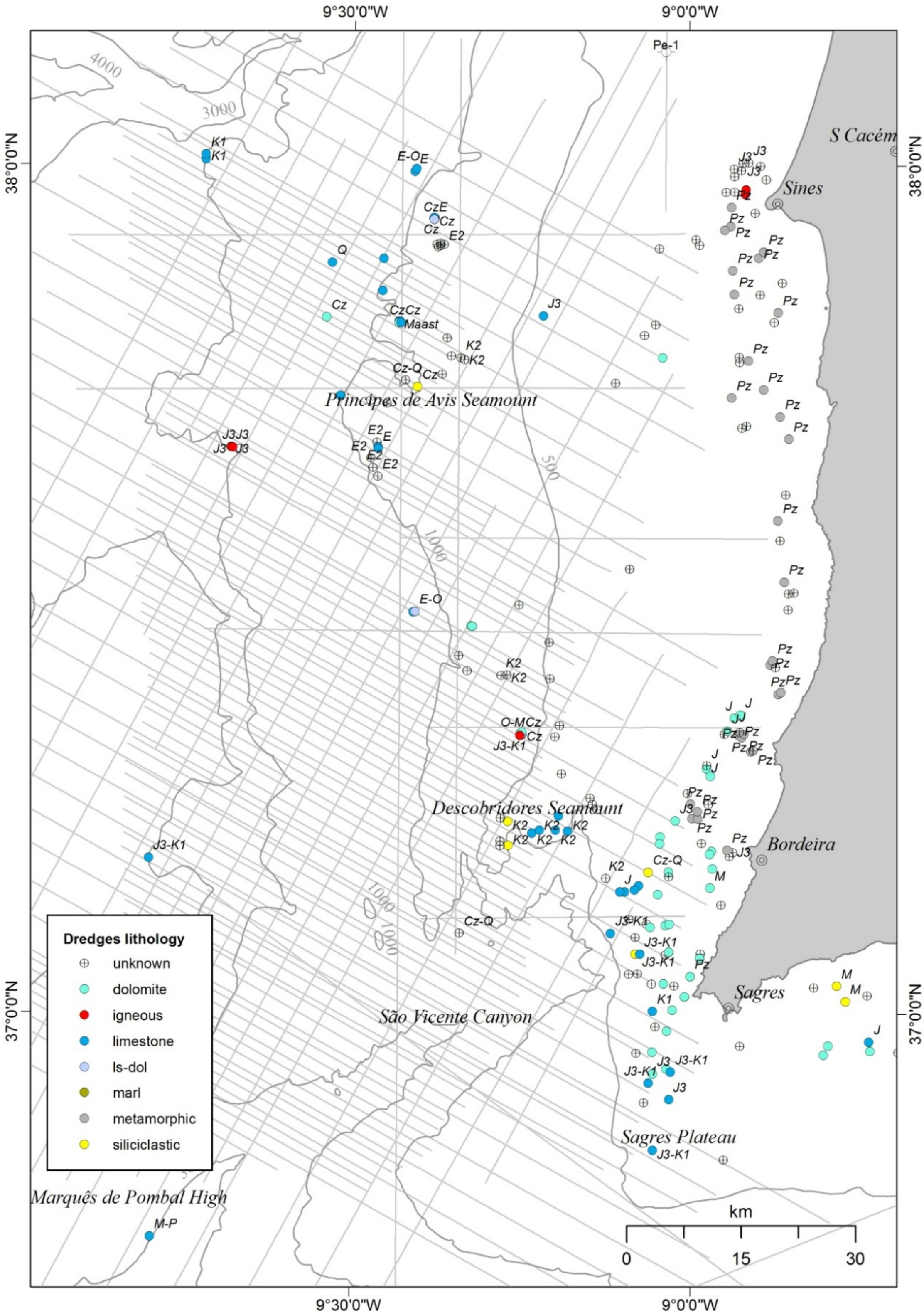

Figure 2.13 – Dredges collected throughout the Southwest Iberian margin in relation with available multichannel seismic data, evidencing both lithology and age (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Coppier, 1982; Mougenot, 1988). Age of dredges: Pz – Paleozoic, J – undifferentiated Jurassic, J3 – Late Jurassic, K1 – Early Cretaceous, K2 – Late Cretaceous, E – Eocene, O – Oligocene, M – Miocene, P – Pliocene, Q – Quaternary, Cz – undifferentiated Cenozoic.

Comparatively, in the Lusitanian Basin, the Albian to Turonian is characterised both by the deposition of fluvio-deltaic siliciclastics of the Almargem Formation and marine limestones of the Cacém Formation (Witt, 1977; Wilson, 1988; Rey et al., 2006) (Fig. 2.5). These deposits are the sedimentary response of the progressive sea-level rise observed throughout the Atlantic, which reached a maximum in the Cenomanian-Turonian, with its deepest facies located in the Lisbon area (Rey et al., 2006; Grange et al., 2010). Coeval units were intersected in offshore wells of the Lusitanian and Porto Basins (Teixeira et al., 1979). Similar carbonate facies can be found on the Canadian margin (Petrel member of the Jeanne d'Arc Basin) (Tankard and Balkwill, 1989) and in deep-sea drilling boreholes that revealed deep water mudstones, some with significant organic matter content (Tucholke and Sibuet, 2007) (Fig. 2.11).

From the Turonian onwards a major unconformity eroded a significant part of the Lusitanian Basin resulting in a hiatus that obliterated or limited deposition on a large portion of the margin (Fig. 2.5). The only deposits from the Turonian-Maastrichtian interval are found in the northern Lusitanian and Porto Basins, both revealing continental fluvio-deltaic siliciclastics of the Gândara formation, the marine limestones of the Carapau formation and the marine siliciclastics of the Dourada formation (Witt, 1977; Rey et al., 2006).

The final period of the Cretaceous (mainly during the Campanian) reveals the important occurrence of magmatism that is most impressive in the intrusions of Monchique, Sines and Sintra that have major impact on the deformation of the country-rocks (Miranda et al., 2009 and references therein) (see Chapter 2.2.3).

2.3.4. Post-Cretaceous deposition

From the Late Cretaceous onwards deposition on the West Iberian margin was largely controlled by the reactivation of inherited Palaeozoic and rift-related faults (Pinheiro et al., 1996), that together with halokynetic and thin-skinned tectonics resulted in the progressive re-organization of existing mini-basins (Ribeiro et al., 1990; Rasmussen et al., 1998; Alves et al., 2003a).

In the Alentejo Basin, Paleogene to Quaternary sediments were mainly sourced from the hinterland and closely related to canyon-related sediment bypass from the main continental Cenozoic depocentres, i.e. the Lower Tagus-Sado Basins and the coastal interior areas of between Sines and Aljezur (e.g. Oliveira, 1984; Alves et al., 2003a). As such, during this period, the Tagus and Setúbal submarine canyons to the North and the São Vicente submarine canyon to the South are considered prominent tectono-depositional features, which together with deep oceanic currents, control sediment input into the margin (e.g. Alves et al., 2003a; Llave et al., 2006; Roque, 2007).

The Paleogene although with limited expression onshore (mainly in the Sado Basin) has been interpreted on seismic data imaging the Alentejo Basin and sampled in dredges (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Coppier, 1982; Oliveira, 1984; Mougenot, 1988; Alves et al., 2000; Alves et al., 2003a; Alves et al., 2009). Deposits from this period include mainly limestones and dolomites as well as continental to shallow marine siliciclastics broadly assigned to the Benfica and Moreia formations (Witt, 1977; Mougenot et al., 1979). It is during the Eocene margin inversion that possible mass-flow deposits were accumulated (Mougenot et al., 1979). These authors also point that during the Oligocene, significant thermal or tectonic uplift of the margin resulted in a widespread erosion surface, ultimately overlain by thick fault-bounded successions resulting from sea-level rise from the Chattian onwards.

The Neogene is characterised by a paroxysmal tectonic phase of inversion during the Burdigalian and the Miocene that resulted in the accumulation of shallow marine siliciclastics, above which Plio-Pleistocene deep-water limestones and marls were deposited (Mougenot et al., 1979). It is during this stage that incision of submarine canyons is most prominent, although its inception can be confidently recognised since the Eocene-Oligocene (Alves et al., 2000; Alves et al., 2003a).

Chapter 3

Data and Methods

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3. Data and Methods

The present study was accomplished using a diverse dataset that includes 2D multichannel reflection seismic, wireline data and reports from hydrocarbon exploration wells, lithological information from a non-commercial well and dredge results. The integration of this information with regional and local data was complemented by fieldwork carried out on outcrops of the western Alentejo and Algarve regions, in order to validate published information and to test preliminary research results.

3.1. Available data

3.1.1. 2D Multichannel reflection seismic

The research work developed in this study was made possible by using three distinct multichannel reflection seismic datasets covering approximately 23.000 km^2 of the shallow to deep offshore of the southwest margin of Portugal (Fig. 3.1 and Table 3.1), namely:

- GSI Geophysical and Texaco (pre-2000, reprocessed 2D multichannel seismic)
- TGS-Nopec 2001
- CGG 2008

These data are protected under confidentiality agreements and therefore, disclosure of selected information is restricted. Nonetheless, permission to publish previously approved seismic lines in journals and conferences was granted and are also used in this thesis.

Table 3.1 – Acquisition parameters of 2D seismic campaigns available in the Alentejo Basin.

<table>
<tr><th>Company</th><th>units</th><th>Pre-2000
GSI, Texaco</th><th>TGS Nopec</th><th>TGS Nopec</th><th>CGG</th></tr>
<tr><td>Ship</td><td></td><td>n/a</td><td>M/V Zephyr-1</td><td>M/V NanHai 502</td><td>CGG Venturer</td></tr>
<tr><td>Acquisition Date</td><td></td><td>n/a</td><td>December 2000 to May 2001</td><td>July 2001 to September 2001</td><td>Aug-Sept 2008</td></tr>
<tr><td>Shotpoint interval</td><td>m</td><td>n/a</td><td>37,5</td><td>25</td><td>25</td></tr>
<tr><td>Cable length</td><td>m</td><td>n/a</td><td>6.100</td><td>6.100</td><td>8.100</td></tr>
<tr><td>Sample rate</td><td>ms</td><td>n/a</td><td>2</td><td>2</td><td>2</td></tr>
<tr><td rowspan="2">Recording Filters</td><td rowspan="2"></td><td>n/a</td><td>low cut 3 Hz @ 6 dB/oct</td><td>n/a</td><td>low cut 3 Hz @ 6 dB/oct</td></tr>
<tr><td>n/a</td><td>high cut 218 Hz @
484 dB/oct</td><td>n/a</td><td>high cut 200 Hz @ 370 dB/oct</td></tr>
<tr><td>Recording delay</td><td></td><td>n/a</td><td>34 ms</td><td>n/a</td><td>n/a</td></tr>
<tr><td>Record Length</td><td>ms</td><td>n/a</td><td>12.288</td><td>12.288</td><td>9.050</td></tr>
<tr><td>Source</td><td></td><td>n/a</td><td>Turned Bolt Array</td><td>Air Gun</td><td>Air Gun</td></tr>
<tr><td>Source Pressure</td><td>psi</td><td>n/a</td><td>2.000</td><td>2.000</td><td>2.000</td></tr>
<tr><td>Source Depth</td><td>m</td><td>n/a</td><td>7,0 ± 1</td><td>7,0 ± 1</td><td>8 to 9</td></tr>
<tr><td>Number of Channels</td><td></td><td>n/a</td><td>480/360</td><td>240</td><td>648+48</td></tr>
<tr><td>Group Interval</td><td>m</td><td>n/a</td><td>12,5</td><td>12,5</td><td>12,5</td></tr>
<tr><td>Cable Depth</td><td>m</td><td>n/a</td><td>9 ± 1</td><td>10 ±1</td><td>8</td></tr>
<tr><td>Near Trace Offset</td><td>m</td><td>n/a</td><td>144</td><td>201</td><td>155</td></tr>
<tr><td>CDP Fold</td><td></td><td>n/a</td><td>80/60</td><td>60</td><td>n/a</td></tr>
<tr><td>Available length of survey</td><td>km</td><td>n/a</td><td colspan="2">~5.045</td><td>3.562</td></tr>
<tr><td>Overall quality of data</td><td></td><td>Poor-good</td><td colspan="2">Good-excelent</td><td>Very good-excelent</td></tr>
</table>

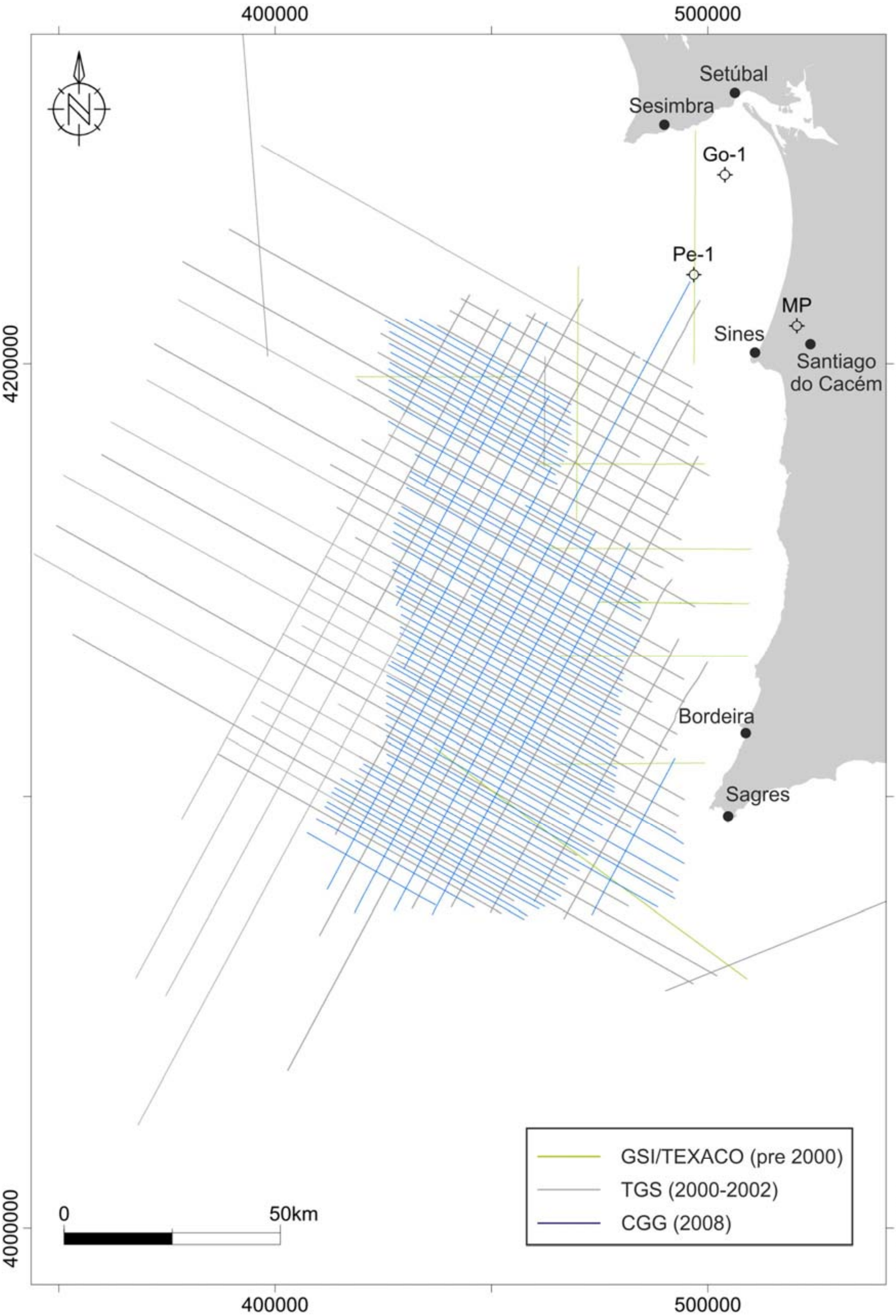

Figure 3.1 – Navigation of available 2D multichannel seismic data used in the interpretation of the study area, in relation with exploration wells and main outcrops.

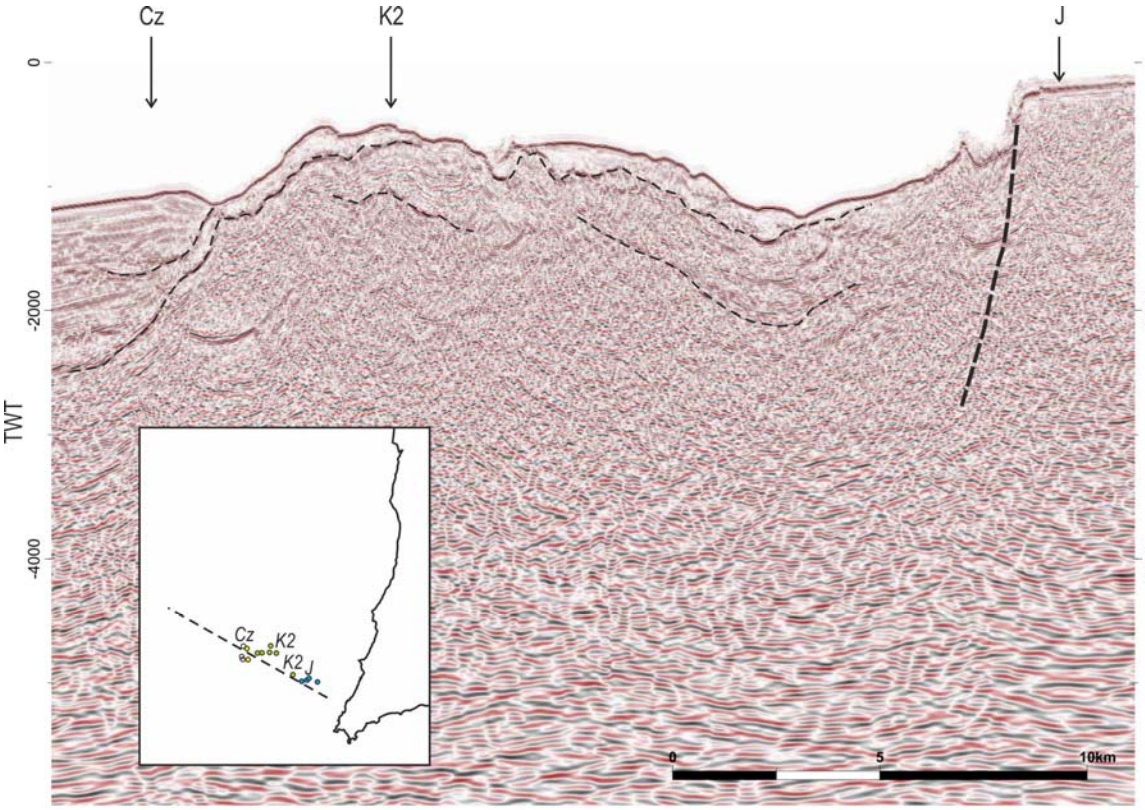

Figure 3.2 – Example of correlation of dredges and seismic data as a base of interpretation (compiled from Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Coppier, 1982). J – undifferentiated Jurassic, K2 – Late Cretaceous, Cz – undifferentiated Cenozoic.

3.1.1.1. Quality control of multichannel seismic data

The quality of seismic data is diverse and reflects not only the date of acquisition, but also the original design and purpose of the survey at the time it was shot (see Table 3.1 for details of acquisition). The available seismic dataset is presented in Two-Way Travel Time (TWT) and Post-stack migration processing was applied. In result, three distinct seismic surveys were made available to the completion of this research, which include data acquired during the 70-80's by Texaco and GSI (later reprocessed by TGS-Nopec), the TGS-Nopec spec survey from 2000-2002, and the infill 2D survey of CGG acquired by the consortium operating the Alentejo Basin acreages (Tullow, Galp and Partex) (Table 3.1).

The pre-2000 surveys were revealed to have dissimilar quality of imaging and poor-good quality can be observed, thus limiting the resolution and therefore the accuracy of interpretation. Poor quality of imaging is mainly located in deeper parts of the seismic sections. Moreover, available seismic lines from these surveys do not cover the totality of study area and a significant portion of the proximal margin could not be interpreted, thus hindering the continuity of interpretation throughout this segment of the margin.

The overall quality TGS-Nopec and CGG data (Table 3.1.) are good to excellent and cover adequately the study area, therefore allowing insightful analysis of subsea structure. However, in shallow water (< 300 m) resolution is significantly decreased and in some deep-water areas seismic imaging does not allow a detailed analysis of depositional features.

Data acquired by CGG is generally of good to excellent quality allowing good analysis of continuity of seismic reflections and their geometry, both in shallow and deeper sequences. However, this dataset does not intersect available wells, which hampers a precise correlation with pre-existing lithostratigraphic data.

Acknowleding some of the uncertainties in the present work associated with limited availability of well information tying with seismic data, additional datasets were included in this analysis, namely by using dredge data, new fieldwork and collection of regional geological information, which are described in the following sections. The integration of these data with seismic stratigraphic analysis (see chapter 3.2.1 for additional information) allows reducing the incertainty deriving of limited lithological and lithostratigraphic control in areas away from well control. Despite possible alternative interpretations of the original dataset, the subsequent chapters aim to present a straightforward description of the data, to present evidence-based interpretations and ultimately, discuss distinct interpretations and build into meaningful conclusions.

3.1.2. Dredge data

Information obtained from dredges was collected from published and unpublished sources (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Coppier, 1982) and integrated into a geographic information system (ArcGIS) and whenever possible, tied to seismic data (Fig. 3.2). Such integration allows assigning an age and lithology to depositional seismic units outcropping the seafloor, thus reducing the uncertainty inherent to seismic stratigraphic interpretation of depositional packages away from well control.

3.1.3. Outcrop information

The Mesozoic of the Southwest Iberian margin is exposed in good quality outcrops mainly in the areas of Sagres, Bordeira and Santiago do Cacém, revealing a nearly continuous record of the Late Triassic to the Early Cretaceous (Oliveira, 1984; Ramalho and Ribeiro, 1985; Ribeiro et al., 1987; Inverno et al., 1993) (Figs. 2. 6, 2.7 and 3.3).

Throughout these areas fieldwork was accomplished in order to:

- Locate areas with good exposure and significant lithostratigraphic information
- Identify and characterise the main regional unconformities that can be correlated on both sides of the Atlantic
- Identify the main unconformities that allow correlation with seismic and well data
- recognise and correlate the main lithostratigraphic units described in literature
- document the overall sedimentological aspects of each lithostratigraphic unit in the context of rift-to-drift deposition

3.1.4. Exploration well data, wireline, reports

In order to investigate the tectono-stratigraphic evolution of the Southwest Iberia margin, selected offshore exploration wells were analysed and re-interpreted, aiming to correlate both regional and local stratigraphy with seismic data imaging the study area (Fig. 3.4).

Data from the exploration wells includes (Table 3.2):

- Well reports;
- Digital wireline data;
- Summary reports from previous companies working in the West Iberian margin.

Well reports used in this study show uneven organization and detail, with lithostratigraphic information often revealing dissimilar methodologies and results. Consequently, the main depositional units were re-interpreted to match the regional lithostratigraphic nomenclature (Witt, 1977; Lomholt et al., 1995; Moita et al., 1996; Azerêdo et al., 2003; Rey et al., 2006) and to allow well correlation throughout the distinct basins (Fig. 2.5). As such, the lithostratigraphic well tops were re-assessed in order to construct a chronostratigraphic approach that could be tied with seismic data.

Wireline data for most of the well includes the typical industry dataset:

- Caliper (CALI)
- Gamma Ray (GR)
- Spontaneous Potential (SP)
- Resistivity logs (with shallow, medium and deep resistivities)
- Density (RHOB)
- Neutron (NPHI)
- Sonic (DT)

3.2. Methods

3.2.1. Seismic stratigraphic interpretation

Interpretation of multichannel seismic data is a fundamental tool in the investigation of depositional sequences. Principles of seismic stratigraphic interpretation have been extensively summarised in literature and their basic concepts date to the early works published in AAPG Memoir 26 (Payton, 1977), subsequently summarised and revised by others (e.g. Emery and Myers, 1996 and references therein; Catuneanu, 2006).

Resolution of reflection seismic data is variable (from a few meters to 10's of meters) and depends mainly of acquisition and processing parameters and ultimately on the wavelength of original acoustic signal and its penetration into the crust, which directly relate the shorter wavelength and higher frequencies to increased vertical resolution (Emery and Myers, 1996; Kearey et al., 2002).

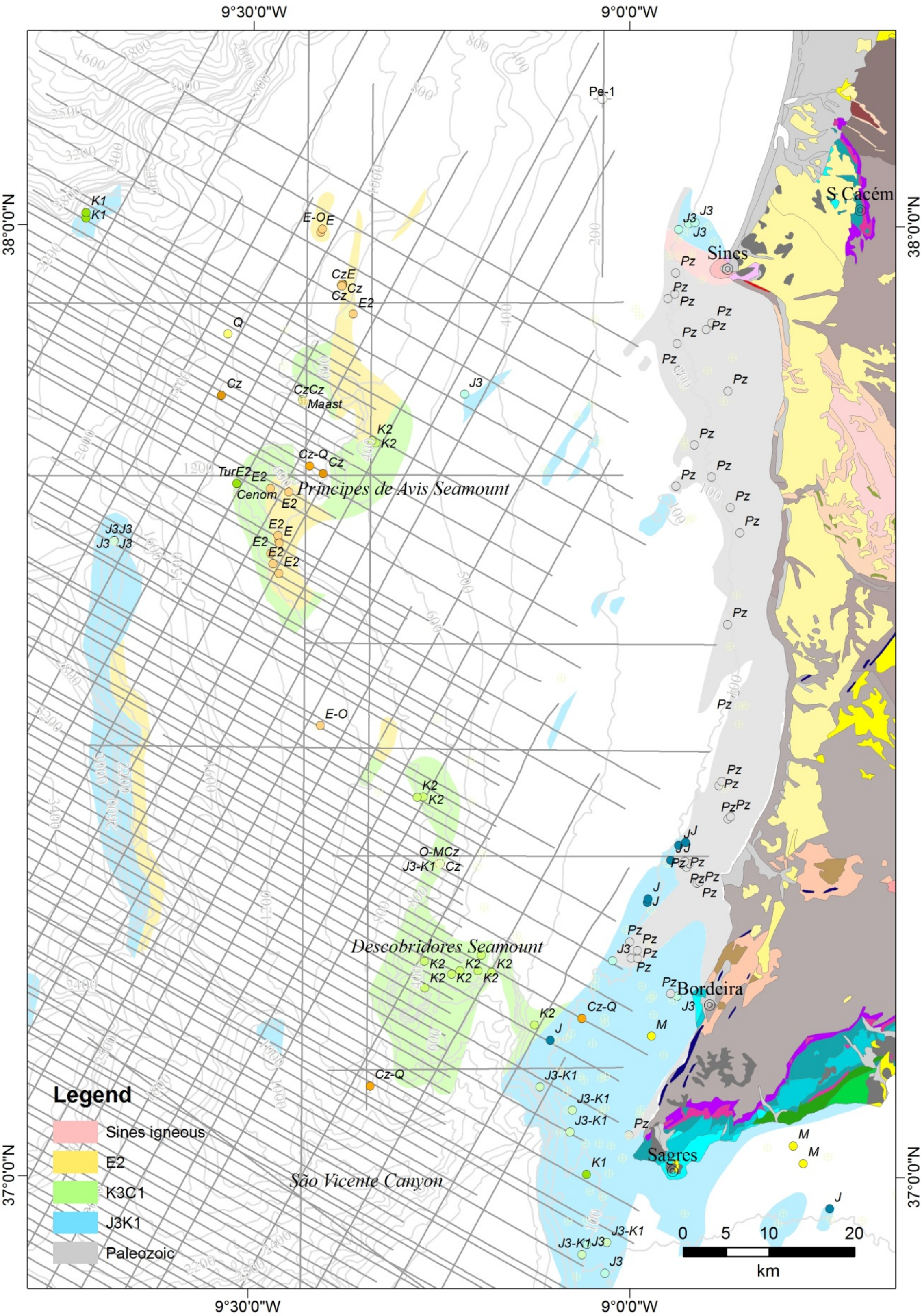

Figure 3.3 – Location of outcropping areas of Sagres, Bordeira, Santiago do Cacém and Sines, with reference to seafloor sampling locations and onshore-offshore geological mapping (modified from Oliveira, 1984). J3K1 – Oxfordian to Albian, K3C1 – Cenomanian to Eocene, E2 – Eocene to Oligocene.

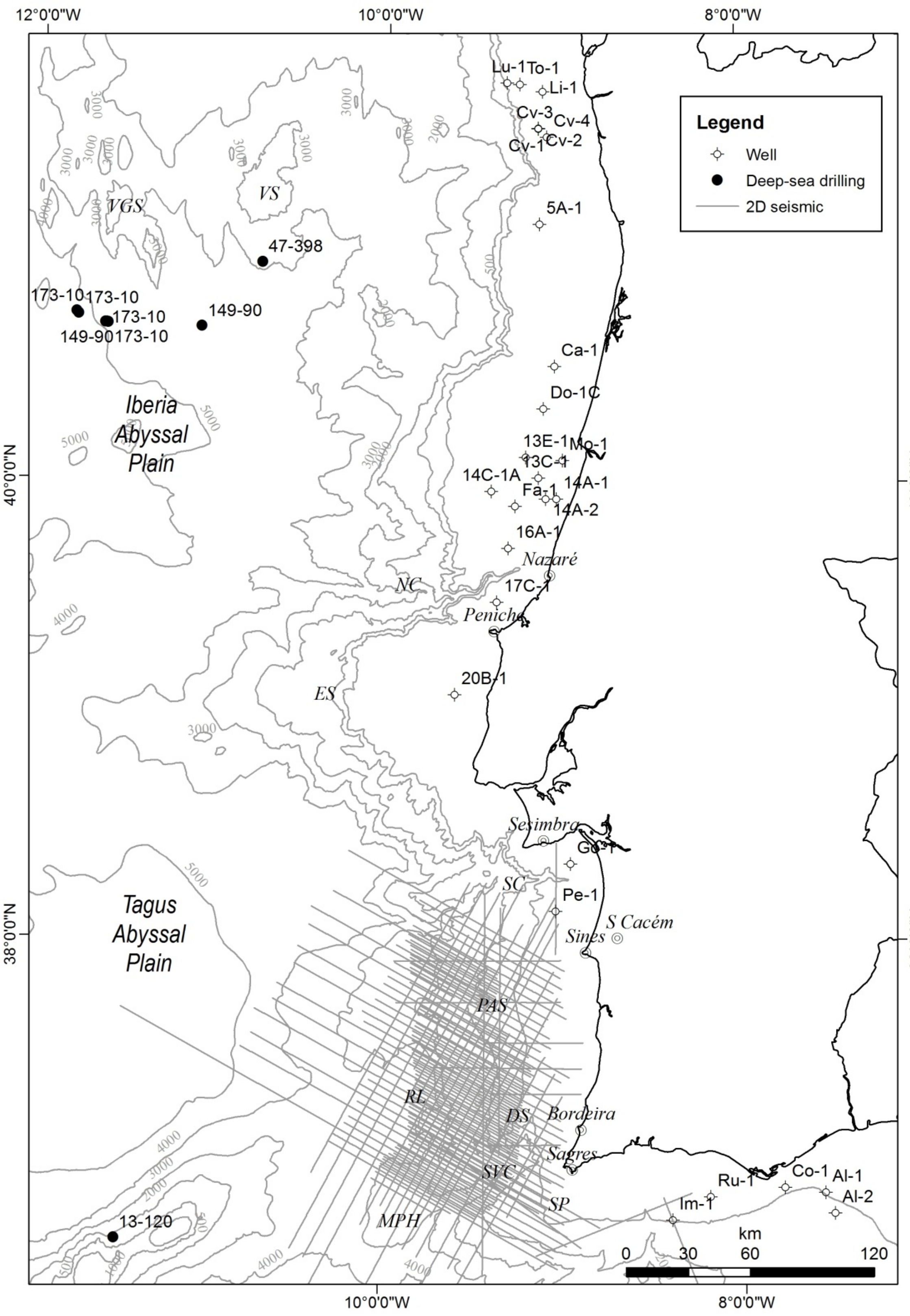

Figure 3.4 – Location of exploration offshore wells and deep-sea drilling boreholes in relation to the study area. GoB – Gorringe Bank, SP – Sagres Plateau, SVC – São Vicente Canyon, DS – Descobridores Seamount, RL – Rincão do Lebre, PAS – Principes de Avis Seamount, SC – Setúbal Canyon, ES – Estremadura Spur, NC – Nazaré Canyon, VS – Vigo seamount, VGS – Vasco da Gama Seamount.

Table 3.2 – Summary of the offshore wells interpreted in this study.

Well name	Abbreviated name	Operator	Spud Year	Total depth (m MD)	Water depth (m)	HC shows	Basin
Sardinha-1	13C-1	Shell	1974	2.801,0	83,0	Gas	Lusitanian
Carapau-1	Ca-1	Esso	1974	2.480,2	69,0	---	Lusitanian
Dourada-1C	Do-1C	Sun Oil	1974	3.668,0	84,1	Gas	Lusitanian
Moreia-1	Mo-1	Sun Oil	1974	2.144,0	44,8	Gas/Oil	Lusitanian
Espadarte-1	14A-1	Shell	1975	2.862,0	43,0	Oil	Lusitanian
Espadarte-1A	14C-1A	Shell	1975	2.142,0	133,0	---	Lusitanian
Cachucho-1	16A-1	Shell	1975	2.655,0	125,0	Oil	Lusitanian
Chicharro-1	17C-1	Shell	1975	2.402,0	104,5	---	Lusitanian
Linguado-1	5A-1	Shell	1975	2.626,0	125,0	---	Lusitanian
Pescada-1	Pe-1	Texaco	1975	3.117,2	149,0	Gas	Alentejo
Ruivo-1	Ru-1	Chevron	1975	2.248,7	91,0	GAS	Algarve
Imperador-1	Im-1	Chevron	1975	2.639,3	370,6	GAS	Algarve
Espadarte-2	14A-2	Shell	1976	2.290,0	67,0	Oil	Lusitanian
Safio-1	20B-1	Shell	1976	2.541,0	88,0	Gas	Lusitanian
Cavala-1	Cv-1	Texaco	1976	1.229,5	84,0	---	Porto
Cavala-2	Cv-2	Texaco	1976	1.700,7	85,0	---	Porto
Cavala-3	Cv-3	Texaco	1976	1.575,8	85,0	---	Porto
Faneca-1	Fa-1	Esso	1976	2.599,9	112,0	---	Lusitanian
Corvina-1	Co-1	Challenger	1976	3.083,0	189,0	---	Algarve
Sardinha-1	13E-1	Shell	1977	2.044,0	107,0	Oil	Lusitanian
Cavala-4	Cv-4	Texaco	1979	2.749,3	92,0	Gas/Oil	Porto
Golfinho-1	Go-1	Texaco	1979	1.790,1	108,0	Gas/Oil	Alentejo
Algarve-1	Al-1	Esso	1981	3.597,0	535,5	---	Algarve
Algarve-2	Al-2	Esso	1982	2242,4	555,0	---	Algarve
Lula-1	Lu-1	Pecten	1985	4.040,0	217,7	Gas/Oil	Porto
Lima-1	Li-1	Neste	1990	2.900,0	110,0	Gas	Porto
Touro-1	To-1	Taurus	1994	2.853,0	131,5	Gas	Porto

As acoustic signal propagates through the rocks, velocity of waves is accelerated or slowed, thus recording the transition between distinct rock units of different nature and their boundaries in space, which therefore makes this method suitable for the investigation of the continuity of geological strata (Emery and Myers, 1996; Kearey et al., 2002). Accordingly, these surfaces (seismic reflections) are then considered to represent relatively concise periods of time and can ultimately be used as time lines bounding seismic packages of identical signal.

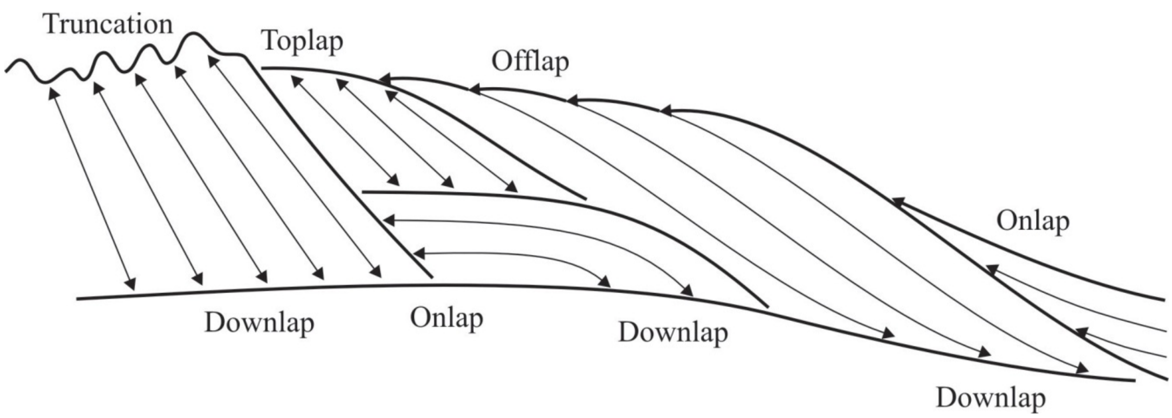

Figure 3.5 – Types of reflection termination (Catuneanu, 2006).

The identification of such depositional seismic packages are given through the interpretation of the continuity and termination of reflections, commonly termed onlaps, downlaps, toplaps or offlaps, each with its genetic significance (Fig. 3.5) (Mitchum et al., 1977b; Emery and Myers, 1996).

Reflection termination and their continuity within major depositional packages often show similar architecture and can broadly be grouped into main types of internal reflections, such as parallel, sub-parallel or divergent and also can be used to describe the configuration of clinoforms (Mitchum et al., 1977a) (Figs. 3.5, 3.6 and 3.7).

A detailed methodology for the analysis of seismic stratigraphy can be found in Emery and Myers (1996) and comprises the following steps:

1. Define the vertical and horizontal scale of the section;
2. Divide the seismic data into discrete stratigraphic packages by marking reflections terminations;
3. Define seismic surfaces based on consistent reflection terminations;
4. Analyse and describe the packages bounded by seismic surfaces;
5. Characterise the seismic facies of each package.

Recognition of these aspects of seismic data allows the interpretation of the main seismic stratigraphic surfaces that whenever possible should be tied to well data or other significant geological information (Emery and Myers, 1996). Consequently, these surfaces can then be assigned to the main regional geological events in order to represent sequence boundaries, i.e. significant erosional unconformities and their correlative conformities (sensu Mitchum et al., 1977b). However, sequence boundaries vary from model to model (both in space and time) and their expression on seismic can differ in nature and significance (Catuneanu et al., 2009).

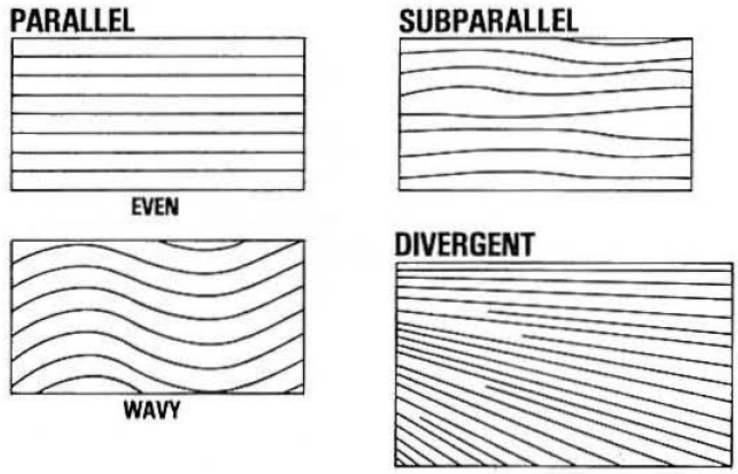

Figure 3.6 – Types of internal seismic reflection configurations (Mitchum et al., 1977a).

The term "sequence", as originally defined by Mitchum et al. (1977b) is a "stratigraphic unit composed of a relatively conformable succession of genetically related strata bounded at its top and base by unconformities or their relative conformities". However, different approaches to sequence analysis and characterization resulted in a vast number of concepts and criteria for interpretation should be disclosed in every investigation (Catuneanu et al., 2009).

The present study applies the notion that depositional sequences are bounded by major unconformities often coinciding with widespread erosional surfaces, along with the correlative facies changes bounding the major depositional sequences thus defining Megasequences (Vail et al., 1977; Hubbard et al., 1985a; Hubbard, 1988; Posamentier et al., 1988).

The application of these principles allows constructing a meaningful framework, by defining main seismic stratigraphic packages with base level variation affinities and relative shift in shoreline directions, i.e. the depositional systems tracts (Emery and Myers, 1996; Catuneanu, 2006).

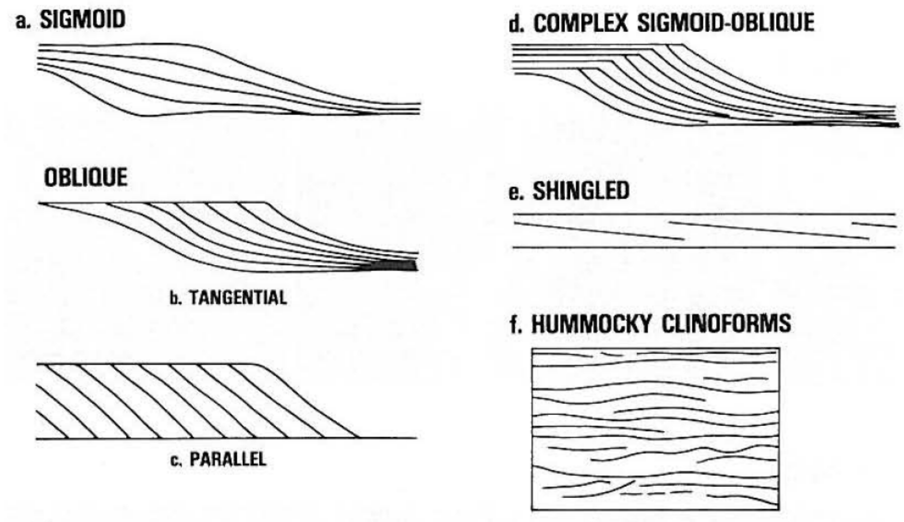

Figure 3.7 – Types of seismic reflections in prograding clinoforms (Mitchum et al., 1977a)

Despite the different approaches that allow addressing sequence stratigraphy of depositional units, an intense debate still continues, regarding the unification of criteria and terminology (e.g. Catuneanu et al., 2009). Thus the present summary adopts a more classical approach to the analysis of depositional systems tracts, which include the use of Lowstand Systems Tract (LST), the Transgressive Systems Tract (TST) and the Highstand Systems Tract (HST) (e.g. Emery and Myers, 1996 and references therein) (Fig. 3.8) (see Chapter 1.2.2 for additional information).

However, as referred in Chapter 1.2.2 the application of sequence stratigraphy concepts to extensional continental basins and their growth strata is often complex and consequently, the basis for the construction of the tectono-stratigraphic framework consists of Megasequences that show regional significance (sensu Hubbard et al., 1985a; Hubbard, 1988), thus allowing to correlate the major unconformity bounded sequences throughout not only across West Iberia, but also on the Iberia-Newfoundland conjugate margins (e.g. Hiscott et al., 1990).

The framework resulting from this analysis is afterwards refined and growth strata is interpreted on the basis of the identification of the main tectonic systems tracts (sensu Prosser, 1993) and ultimately the main tectono-stratigraphic events and their megasequences were grouped into the Rift Initiation, Rift Climax and Late Rift depositional packages (Prosser, 1993; Nøttvedt et al., 1995; Ravnås et al., 1997; Ravnås and Steel, 1998) (See section 1.2.2 for concepts).

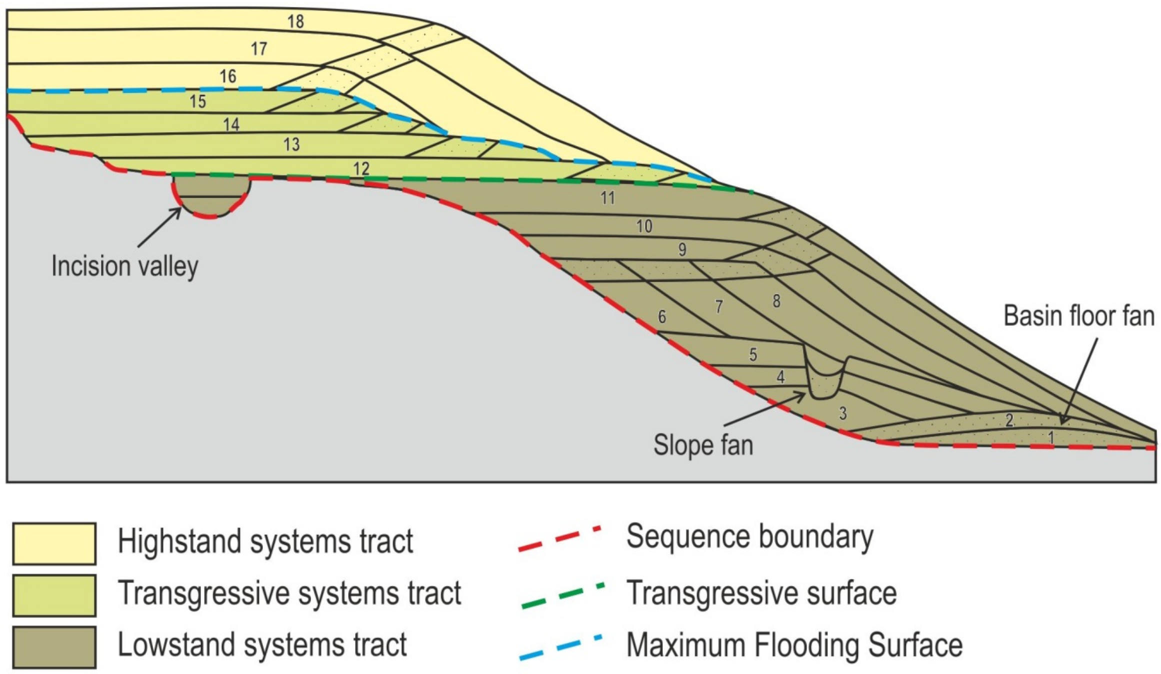

Figure 3.8 – Conceptual cross section of unconformity-bounded sequences and their related depositional systems tracts (modified from Emery and Myers, 1996). Numbers indicate sequence of deposition.

Criteria that allow identifying the breakup unconformity follows the approach of Driscoll et al. (1995) (see section 1.2.2 for detailed description).

3.2.2. Wireline interpretation and well correlation

Wireline data comprises the information retrieved from a group of sensor positioned along a string of logging tools pulled (or pushed) along the borehole and transmitted to a recorder at the surface. Such data traditionally includes the Gamma Ray (GR), the Spontaneous Potential (SP), a suite of resistivity measurements (informally named deep, medium, shallow and microresistivity), the bulk Density log (RHOB), the Neutron log (NPHI) and the sonic (DT) that are both used for well correlation, stratigraphic analysis and for petrophysical analysis (such as porosity, water saturation, lithology and mineral abundance) (Emery and Myers, 1996; Asquith and Krygowski, 2004).

The combination of these logs, together with other geological well information and outcrop or regional calibration (unconformities, palaeontological content, depositional environments, etc.), allows investigating the depositional sequences intersected in a borehole, as they broadly responds to the lithological and facies variations of sedimentary successions (Emery and Myers, 1996; Asquith and Krygowski, 2004). As such, the recognition of trends along the log records allows identifying at multiple scales the principal expression of prograding, retrograding or aggrading trends that ultimately allow the characterization of depositional systems tracts (Fig. 3.9).

The identification of depositional systems tracts on wells, similarly to seismic data is based on the unconformities identified along the borehole and by recognizing the patterns and changes in depositional sequences (Emery and Myers, 1996).

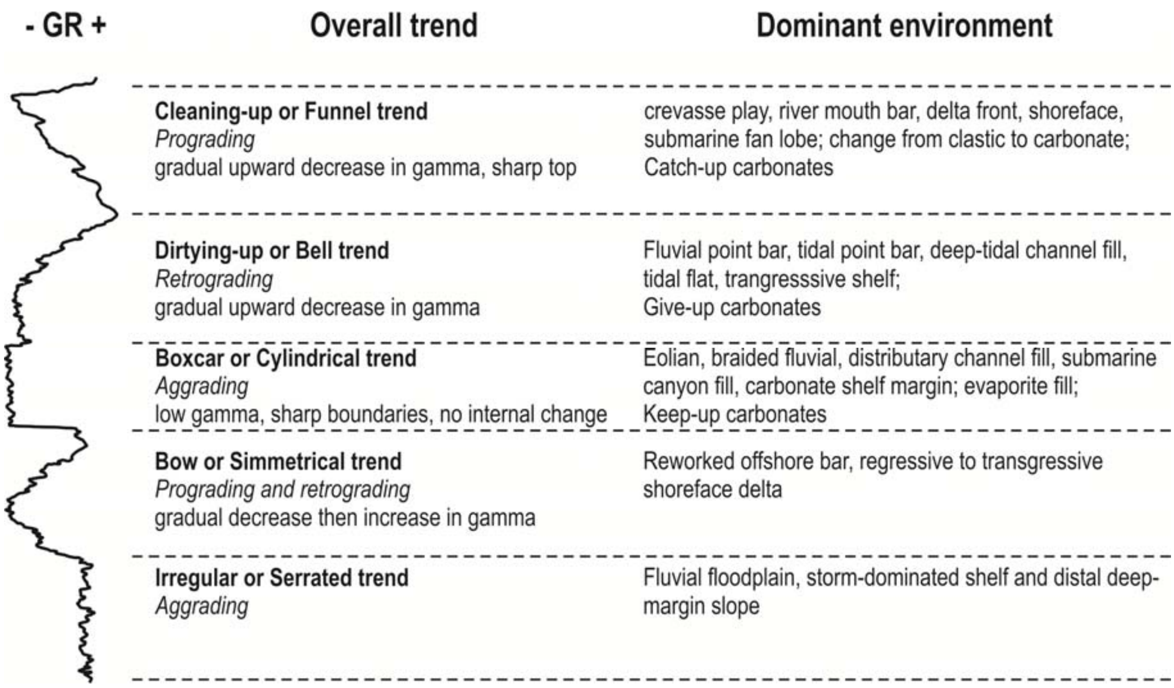

Figure 3.9 – Schematic gamma ray (GR) log trends and their associated depositional environments. Modified from Emery and Myers (1996) and Kendall (2012).

3.2.3. Burial history modelling

Backstripping and burial history modelling are analytical tools used to investigate tectonic subsidence and uplift of sedimentary basins, which has been used both by industry and research, in order to explain not only the evolution of margins through the complex interplay of eustasy, tectonics, continental lithosphere thermal regime, sediment accumulation and erosion, but also to assess their impact on the generation, migration and accumulation of hydrocarbons (e.g. Watts and Ryan, 1976; Parnell, 1992; Baur et al., 2010).

Backstripping models assume that sediment and water load are compensated by isostatic Airy-type crust or flexural loading of a rigid crust (Watts and Ryan, 1976).

Moreover, this method accounts for sediment porosity loss and bulk density variations during burial and therefore, present-day vertical succession of strata can be reconstructed to the time of deposition (Steckler and Watts, 1978; Baur et al., 2010). Backstripping, and consequently burial history modelling, also consider the effects of continental lithosphere thermal evolution (through Heat Flow estimation) and stretching (β), by applying isostatic equilibrium to the crust in order to reconstruct the tectonic subsidence of basins (McKenzie, 1978; Cunha, 2008).

Burial history models are typically constructed using data from wells (1D models), but technological advances also allow the creation of 2D and 3D models through the use of dedicated software. The present study uses PetroMod 1D (Schlumberger-IES) freeware license to investigate subsidence and uplift throughout the Southwest Iberian margin.

The construction of 1D burial history models requires the input of well data, such as lithology, chronostratigraphy of depositional units and their related erosional events, estimation of the eroded thickness, and a group of boundary conditions that include palaeowater depth (PWD), seawater temperature variation through time and the regime of crustal heatflow (HF) of subsiding basins.

Lithology input is required to account for compaction of sediments during stacking of successive depositional units, which along with the control of the age of deposition allows constraining the main events of basin infill in relation to the accommodation space generated during rift subsidence.

The identification of the eroded thickness during periods of uplift allows to account for the removed sections of the stratigraphic record, which can be derived from well data (e.g. maturation of vitrinite, Ro%), regional studies or from depth converted seismic data.

Palaeowater depth can be estimated mainly from the palaeontological record or from sedimentological studies and analogues.

Heatflow values can be found on literature, although in the case of missing information, PetroMod includes a specific built-in tool derived from McKenzie (1978) that allows the construction of a subsidence model.

In the present work, data used in the construction of burial history models is based on the interpreted lithology, ages and hiatuses of non-exclusive well reports, on previous subsidence analysis made with commercial wells from the onshore and offshore West Iberian margin (Stapel et al., 1996; Cunha et al., 2009) and on the regional chronostratigraphic control of the main depositional events (e.g. Witt, 1977; Azerêdo et al., 2003; Rey et al., 2006).

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Chapter 4

Margin segmentation prior to continental break-up: a seismic-stratigraphic record of multiphased rifting in the North Atlantic (Southwest Iberia)

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4. Margin segmentation prior to continental break-up: a seismic-stratigraphic record of multiphased rifting in the North Atlantic (Southwest Iberia)

Abstract

A dense grid of multichannel (2D) seismic profiles, tied to borehole, dredge and outcrop data are used to analyze the multiphased rifting, structural architecture and rift-locus migration across the southwest Iberian margin. In the study area, three distinct sectors show different structural evolution from the Late Triassic to the Late Jurassic-earliest Cretaceous. The three structural sectors are distinguished by: 1) the presence of incipient tilt-blocks on the inner proximal margin, which denotes limited syn-rift subsidence; 2) developed tilt-blocks on the outer proximal margin; 3) evidence of significant fault-related subsidence on the outer proximal margin during the Middle Jurassic, followed by an Oxfordian-Tithonian/Berriasian(?) rift phase leading to seafloor spreading; and 4) marked crustal stretching on the distal margin, where highly-rotated tilt-blocks overlain by thick Late Triassic to Late Jurassic units are observed. This chapter demonstrates that significant subsidence occurred in Southwest Iberia several millions of years prior to the latest Jurassic-earliest Cretaceous extensional episode leading to continental breakup. The magnitude of early-subsidence episodes approaches that of the last subsidence pulse preceding continental breakup. Across the southwest Iberian margin the observed structural sectors differ from each other in terms of the age of rift climax of syn-rift strata. This study also shows that he multiple extensional pulses recorded in Southwest Iberia result not only from continental rifting between Iberia and Newfoundland, but also between Nova Scotia and Morocco. Thus, it is considered that pre-breakup units in the deep-offshore basins of Iberia comprise multiple rift-related sequences whose distribution and relative thickness depends on local subsidence rates, on the diachronous northward-migration of rifting, and on the relative crustal stretching experienced by individual sub-basins.

4.1. Introduction

The southwest Iberian margin is a scarcely studied region, rarely included in palaeogeographic reconstructions of the North Atlantic Ocean (e.g. Tankard and Balkwill, 1989; Hiscott et al., 1990) (Fig. 4.1). However, Southwest Iberia is crucial to better understand the initial episodes, geometry and timing of continental rifting between Iberia and the Newfoundland Grand Banks (Northeast Canada). It also records any relationships between the latter margins and the west Tethyan provinces of Northern Africa (e.g. Rovere et al., 2004). Until now, efforts to describe the geometry and evolution of the western Iberian margin have addressed key issues on the timing of rift episodes (Mauffret et al., 1989b, a; Hiscott et al., 1990; Alves et al., 2009 and references therein), the age(s) of breakup of the North Atlantic (Pinheiro et al., 1996; Srivastava et al., 2000; Tucholke and Sibuet, 2007), and the decoupling of structural domains in response to rift locus migration (Manatschal and Bernoulli, 1998, 1999; Wijk and Cloetingh, 2002; Manatschal, 2004; Nagel and Buck, 2004). Nevertheless, difficulties still exist in what the understanding of the relative magnitude and age of major rift-related events along West Iberia are concerned, mostly due to the limited information yet available on the southwest and central Iberian margins (Alves et al., 2003a; Rovere et al., 2004). Other aspects still not addressed comprise the structural differences among southwest Iberia, the Galicia and Newfoundland Margins, as well as the impact of these differences on the pre-breakup evolution of the North Atlantic Ocean.

The main aspect to be addressed concerns the validity of the published models for the evolution of non-volcanic passive margins, which are mostly based on seismic data from the Galicia Margin and analogue outcrops from the Alps (Manatschal and Bernoulli, 1998, 1999). The models recognize the existence of proximal to distal domains on continental margins, and are based on borehole and geophysical data from the Iberia Abyssal Plain, mostly acquired in regions close to where continental breakup occurred. Thus, the proximal margin is marked by limited tilt-block rotation, and records the early stages of extension and fragmentation of the continental crust (Manatschal and Bernoulli, 1998, 1999). The distal margin is characterized by deeply rooted, highly rotated tilt blocks overlying a major detachment surface (the ‘S’ or ‘H’ reflector), developed in association with high β factor and with the exposure of serpentinised mantle (e.g. Pérez-Gussinyé et al., 2001; Wilson et al., 2001). Despite the existence of comprehensive data sets from distal and proximal margin areas, scarce information has been published on continental-slope basins. This limitation has so far caused problems when attempting the reconstruction of the first stages of ocean spreading and continental breakup in the North Atlantic. It also hinders any input from continental slope basins, in which sedimentary units spanning the entire rift-to-drift evolution of the margin are better preserved, to the evolutionary models proposed for non-volcanic margins (Alves et al., 2006; Alves et al., 2009). In addition, no systematic structural characterization of the southwest Iberian proximal margin has been attempted. Published work on Southwest Iberia has been mainly focused on post-rift sequences and the evolution of the proximal margin (Baldy, 1977; Mougenot et al., 1979; Coppier and Mougenot, 1982; Mauffret et al., 1989b; Alves et al., 2000; Alves et al., 2003a).

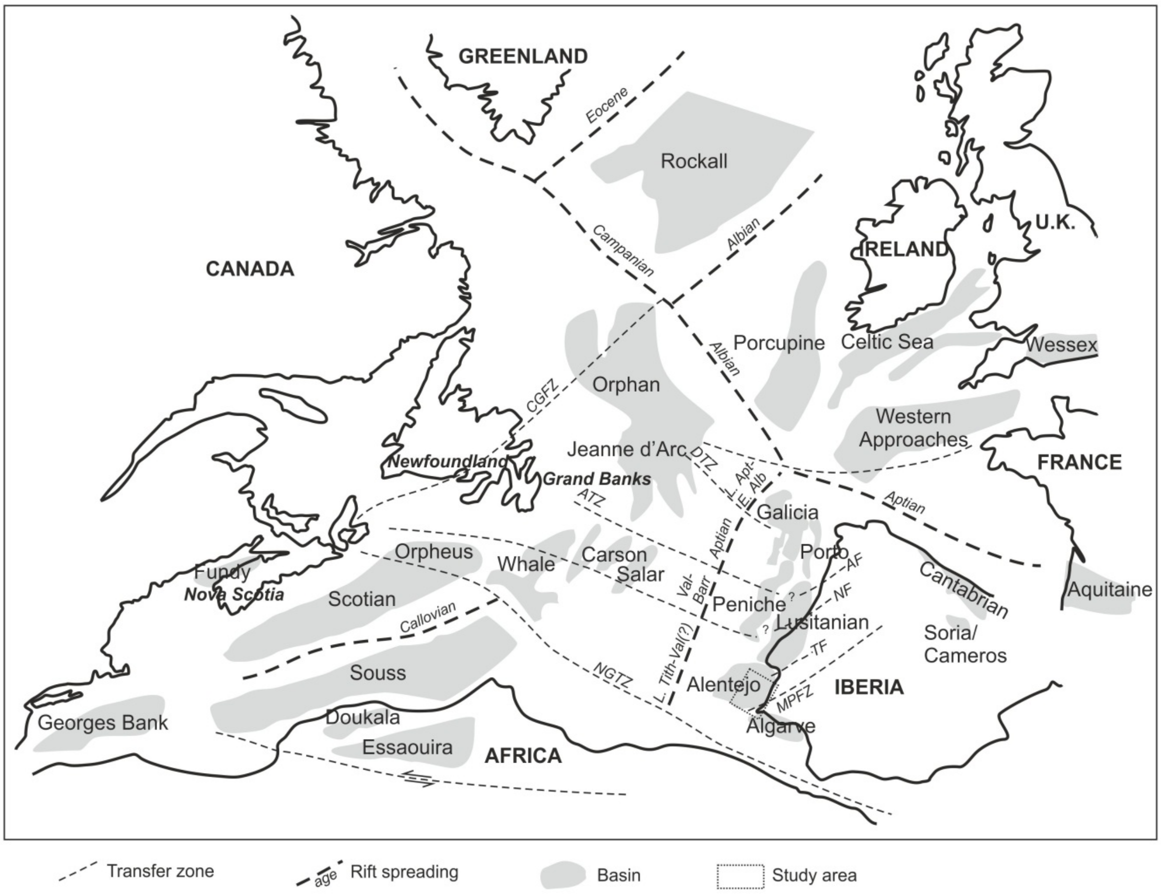

Figure 4.1 - Palaeoreconstructed position of the Iberian margin and major Mesozoic sedimentary basins of the North Atlantic (modified from Hiscott et al., 1990). Age of seafloor spreading from Hiscott et al. (1990). NGTZ - Newfoundland-Gibraltar Transfer Zone, NF - Nazaré Fault, TF - Tagus Fault, ATZ – Avalon Transfer Zone, DTZ – Dominion Transfer Zone, CGFZ – Charlie-Gibbs Fracture Zone.

In order to address some of the latter gaps in knowledge, this chapter presents new data on the southwest Iberian margin, comparing it with other Iberian basins, namely the Lusitanian, Peniche and the Galicia Margin, where proximal to distal margin models have been presented to explain the Mesozoic extension of the North Atlantic (Manatschal and Bernoulli, 1998, 1999; Manatschal, 2004; Alves et al., 2009) (Fig. 4.2). It also provides new information on the Mesozoic syn-rift geometry and evolution of the southwest Iberian margin by: a) identifying seismic (syn-rift) Megasequences in distinct sectors of the margin, correlating them with outcrop, borehole and dredge data; b) describing the syn-rift structural styles that occur from the proximal to the distal margin, as extension evolves from continental rifting to seafloor spreading; and c) identifying the main syn-rift episodes in the study area, correlating them to those recorded in neighbouring margins. Additionally it presents a comprehensive description of the structural architecture of the southwest Iberian margin. This chapter shows evidence of persistent multiphased rifting episodes in Southwest Iberia prior to sea floor spreading, which followed a marked westward migration of the main rift locus. In such a setting, distinct extensional syn-rift phases have the potential to form distinct depositional megasequences (sensu Hubbard et al., 1985b), as described for the eastern Brazilian rift system (Chang et al., 1992; Moreira et al., 2007). Therefore, the concept of "continental rifting" used herein refers to the complex processes of thinning and breaking of continental crust through multiple extensional episodes, a process culminating in the formation of oceanic crust.

4.2. Methods

The interpreted dataset includes over 5000 km of 2D multichannel seismic profiles (courtesy of TGS-Nopec), plus additional confidential seismic data imaging ~23,000 km^2 of the southwest Iberian margin (Fig. 4.2). Older non-exclusive 2D reprocessed seismic data acquired on the continental shelf were also used (Fig. 4.2). Borehole data include two exploration wells located to the northeast of the study area, Pescada-1 (Pe-1) and Golfinho-1 (Go-1) (Fig. 4.2). The two wells drilled through sedimentary units ranging from the Late Triassic to the Cenozoic (Fig. 4.3). The dataset available from these wells includes wireline data, completion reports and regional summary reports (Lomholt et al., 1995) providing information on main depositional sequences, lithology and time-depth correlations. Additional information was obtained from dredge data (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Oliveira, 1984) (Figs. 2.13 and 3.3). At outcrop, the Upper Triassic to Upper Jurassic strata can be observed at Santiago do Cacém (Oliveira, 1984; Inverno et al., 1993), Bordeira (Ramalho and Ribeiro, 1985; Ribeiro et al., 1987) and Sagres (Rocha et al., 1979) (Figs. 4.2 and 4.3).

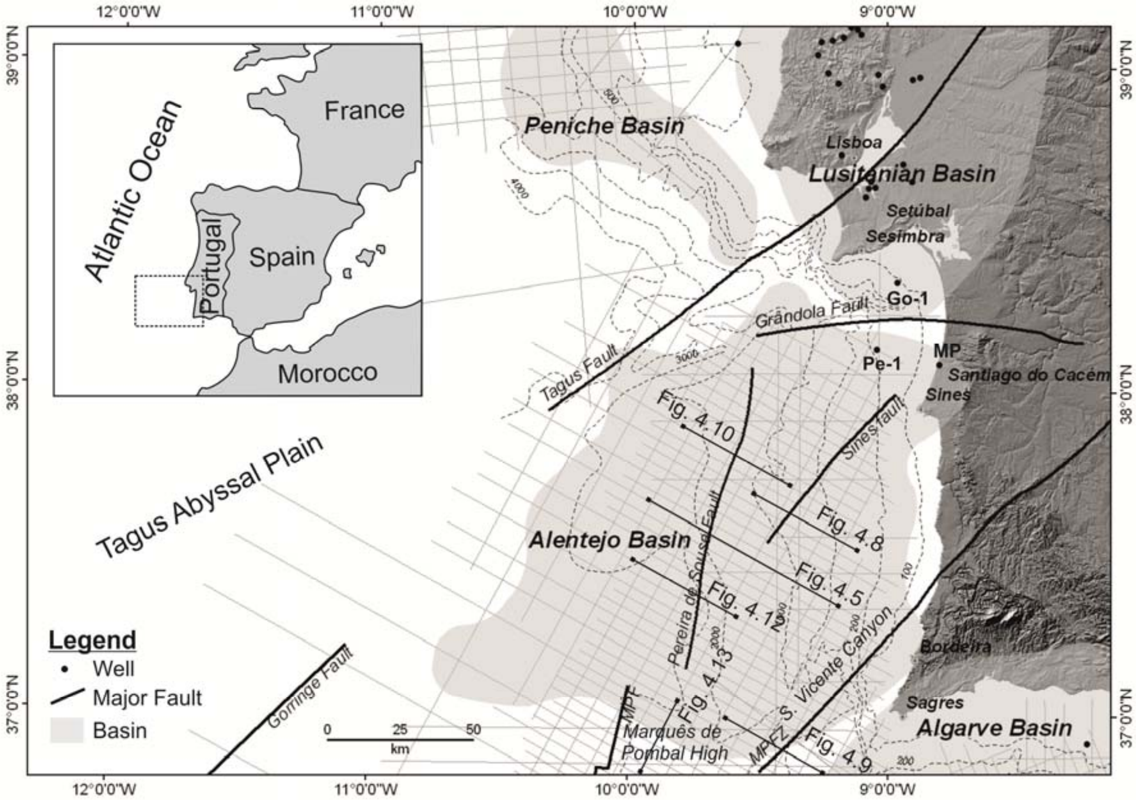

Figure 4.2 - Map of the study area showing the location of seismic lines discussed in text. MPFZ - Messejana-Plasencia Fault Zone; MPF - Marquês de Pombal Fault. Bathymetry in meters.

4.3. Geological Setting

The North Atlantic conjugate margins of Iberia and Newfoundland are considered a typical example of a non-volcanic asymmetric rift (Tucholke and Sibuet, 2007). Continental extension was initiated as early as the Triassic and evolved northwards in relation to the opening of the Morocco-Nova Scotia conjugate margins in the Early to Middle Jurassic (Hiscott et al., 1990; Tucholke et al., 2007). This process ultimately led to Early Cretaceous continental breakup between Galicia and the Orphan Basin (e.g. Tucholke et al., 2007) (Fig. 4.1).

During the late Mesozoic, Southwest Iberia recorded multiple events of extension, which are expressed at outcrop, borehole and multichannel seismic reflection data.

4.3.1. Continental rifting and subsequent break-up

Two main phases of continental extension preceding seafloor spreading are described on the western Iberian and Newfoundland margins (Tucholke and Sibuet, 2007): 1) Late Triassic to the earliest Jurassic, and 2) Middle Jurassic to the Early Albian. This second phase of continental extension can be subdivided into three major pulses, as extension migrated northwards; a Middle Jurassic-Berriasian pulse, a Valanginian-Barremian pulse, and a Barremian to Late Aptian-Early Albian pulse (Hiscott et al., 1990; Pinheiro et al., 1996; Tucholke and Sibuet, 2007). This subdivision is supported by estimates of tectonic subsidence from various basins across the North Iberia-Newfoundland conjugate pair of margins (Lusitanian, Galicia and Jeanne d'Arc Basins) (Hiscott et al., 1990; Stapel et al., 1996; Cunha et al., 2009). In contrast to the latter basins, prolonged Early to Late Jurassic subsidence is detected on the proximal margins of southwest Iberia namely by exploration well Pe-1 (Stapel et al., 1996; Cunha et al., 2009). Early to Middle Jurassic subsidence is also described in the southern Newfoundland basins (Whale, Carson and Salar Basins (Hubbard, 1988; Balkwill and Legall, 1989; Tucholke and Sibuet, 2007), offshore northern Morocco (Schettino and Turco, 2009) and in Nova Scotia (Withjack et al., 2009 and references therein).

Based on magnetic data and seismic profiles, Mauffret et al. (1989b, a) interpreted continental breakup in Southwest Iberia to have occurred in Kimmeridgian times. Recent interpretations suggest both Tithonian (magnetic anomalies M20-M11) (Hiscott et al., 1990; Srivastava et al., 2000) or Late Valanginian-Early Hauterivian (M10-M8) ages for this same event (Pinheiro et al., 1992; Pinheiro et al., 1996; Tucholke et al., 2007; Tucholke and Sibuet, 2007). To the north of the study area, in the Lusitanian Basin-Jeanne d'Arc conjugate, the age of breakup has been dated as Barremian (Whitmarsh and Miles, 1995; Wilson et al., 2001). Further north, an intra Aptian to earliest Albian age has been proposed for continental breakup offshore Galicia (Tucholke and Sibuet, 2007). After continental breakup, distinct compressive events controlled the geometry and evolution of the western Iberian margin (e.g. Boillot et al., 1979; Ribeiro et al., 1990).

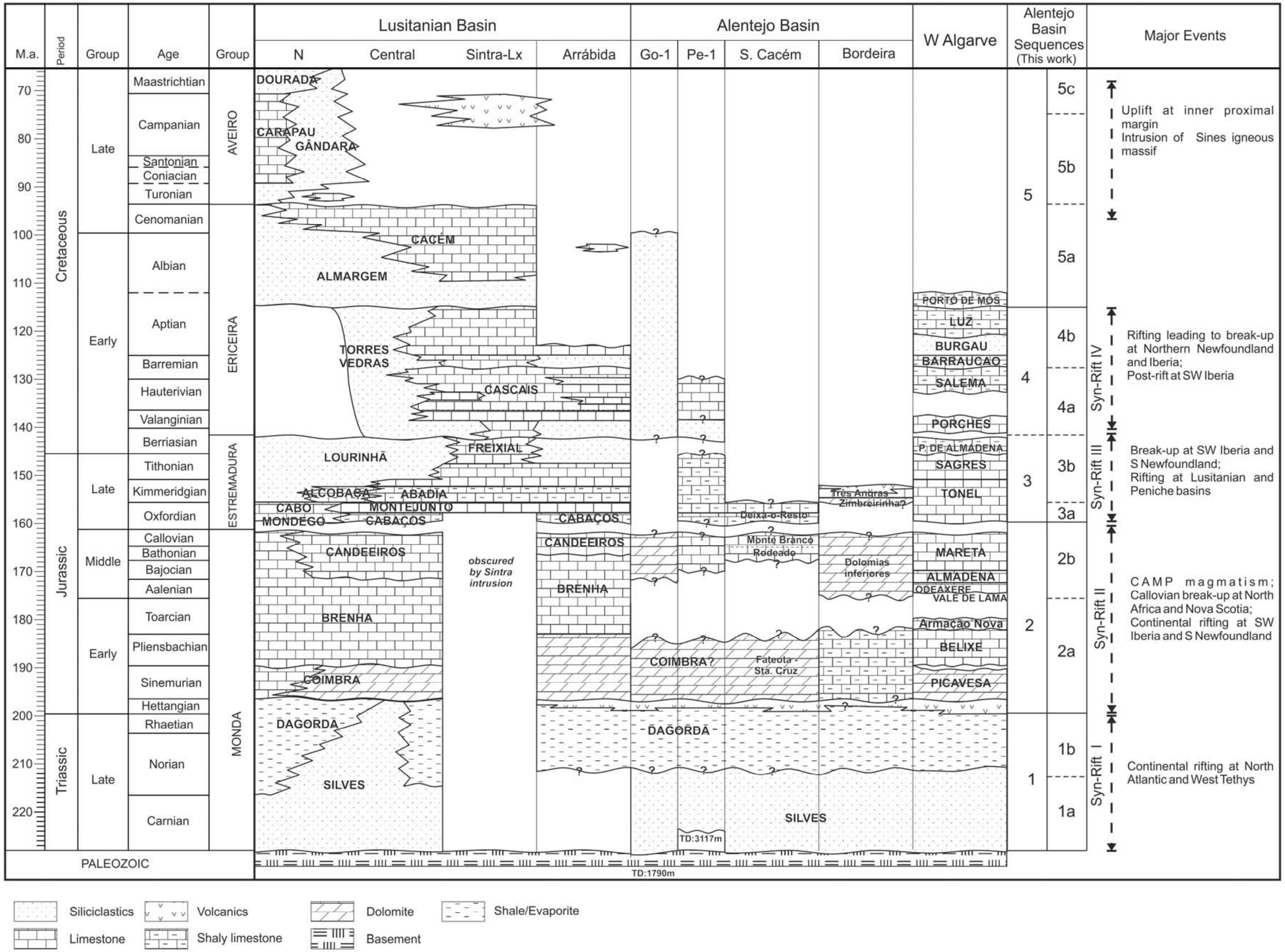

Figure 4.3 - Simplified lithostratigraphic column showing the main Mesozoic units at outcrop and offshore wells (Go-1 and Pe-1). Principal units are correlated with their counterparts in the Lusitanian and Western Algarve Basins. Lithostratigraphy based on the works of Witt (1977), Ramalho and Ribeiro (1985), GPEP (1986), Ribeiro et al. (1987), Oliveira (1984), Inverno et al. (1993), Azerêdo et al. (2003) and Rey et al. (2006).

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Table 4.1 - Summary of principal features in seismic Megasequences from the proximal to distal margins of Southwest Iberia. IPM - inner proximal margin, OPM - outer proximal margin and DM - distal margin.

Mega-sequence	Probable Age	TWT Thickness (ms)			Internal character	Probable lithology
		IPM	OPM	DM		
5	Middle Aptian-Maastrichtian (Paleocene?)	0-1100	0-400	0-1000	Sub-parallel to chaotic reflections, often downlapping incision surfaces; prograding wedge with transparent to chaotic reflections	Shallow siliciclastics to fluvial (?), carbonates (?) at proximal margin; deep siliciclastics at distal margin (?)
4	Berriasian(?) - middle Aptian	0-800	0-400	0-1200	Sub-parallel to chaotic reflections, downlapping syn-rift	Shallow marine siliciclastics, interbedded with carbonates at the proximal margin; deep siliciclastics (turbidites?)
3	Oxfordian-Berriasian (?)	0-700	0-1000	0-1400	Wedge reflectors thickening towards master faults; sub-parallel at inner proximal margin; chaotic reflections	Syn-rift siliciclastics at distal domains; carbonates to siliciclastics at proximal margin
2	Sinemurian (?) -Callovian	0-600	0-1000	0-1200	Sub-parallel to wedge reflectors; growth towards master faults	Shallow to deep (?) marine carbonates and syn-rift siliciclastics (?)
1	Carnian (?) - Hettangian (?)	<500 (?)	<1000 (?)	<1400 (?)	Sub-parallel to chaotic reflections; local growth strata	J1: subaerial volcanics (?); shallow to deep marine carbonates T-J1: Continental to shallow marine (?) siliciclastics; evaporites and shales

4.3.2. Structure of the southwest Iberian margin

The study area is bounded to the south by the Messejana-Plasencia Fault Zone (MPFZ) and to the north by the Grândola fault (Fig. 4.2). The MPFZ is a major crustal feature with a northeast-southwest trend along Portugal and Spain and a length in excess of 530 km (Schermerhorn et al., 1978; Cebriá et al., 2003). The MPFZ is a structure inherited from the late Variscan Orogeny, when it acted as a sinistral strike-slip suture, later reactivated as a major transtensional fault zone (Schermerhorn et al., 1978; Cebriá et al., 2003; Ortas et al., 2006; Silva et al., 2008). Magmatism along the MPFZ is related to the Central Atlantic Magmatic Province (CAMP) (Martins et al., 2008).

The southwest margin of Iberia reveals distinct extensional domains, which include a continental domain (with crustal thickness in excess of 25 km), a thinned domain (with crustal thickness approaching 15-25 km), the transitional domain (crust with approximately 5 to 15 km) and the oceanic domain (less than 5 km thick) (Afilhado et al., 2008) (Fig. 4.4). In a similar manner to Galicia and northern Newfoundland, the syn-rift evolution and segmentation of the southwest Iberian margin reveal that the continental domain was ultimately thinned to breakup (Mauffret et al., 1989a; Pinheiro et al., 1992; Rovere et al., 2004).

Subsidence onshore and on the continental shelf occurred from the Upper Triassic to the end of the Jurassic (Wilson et al., 1989). Major basin-bounding structures comprise rift-shoulder faults limiting rotated tilt-blocks, and a suite of transfer faults limiting the distinct segments of the margin (Tucholke and Sibuet, 2007; Alves et al., 2009). Rift-related extensional faults controlled the geometry and subsidence history of discrete sub-basins, with the major extensional episodes being expressed in seismic, outcrop and well data (Wilson et al., 1989; Alves et al., 2003b; Alves et al., 2003c; Alves et al., 2006).

Sediments filling the rift-related basins include from base to top, continental late Triassic siliciclastics red beds, shales and evaporites (e.g. Azerêdo et al., 2003) (Fig. 4.3). Overlaying these units, the Lower to Middle Jurassic is dominated by thick marine carbonate sequences (e.g. Azerêdo et al., 2003). Late Jurassic carbonates record deposition at the later stages of rifting (Oliveira, 1984; Inverno et al., 1993; Azerêdo et al., 2003).

In an attempt to add more information on the tectono-stratigraphic evolution of the Iberian continental slope basins, Alves et al. (2009) suggested six stratigraphic markers to date the diachronous segmentation of the west Iberian Margin. In essence, six major regressive events can be recognized on stratigraphic units described both by industry and academia for the Peniche and Lusitanian Basins, Southwest Iberia and the western Algarve Basin (Witt, 1977; GPEP, 1986; Ribeiro et al., 1987; Alves et al., 2003b; Alves et al., 2003c; Azerêdo et al., 2003; Rey et al., 2006; Alves et al., 2009). The Callovian-Oxfordian and the Tithonian-Berriasian unconformities are marked by typical continental micropalaeontological content, marking the regressive events throughout the west

Iberian margin (Ramalho, 1971; Rey, 1972; Azerêdo et al., 2002a; Pereira et al., 2003; Pereira et al., 2010).

After continental breakup, Iberia experienced several compressional episodes since the Late Cretaceous to the Holocene. These compressional episodes are related to the rotation and collision to both Eurasia and the North African plate (Srivastava et al., 1990b).

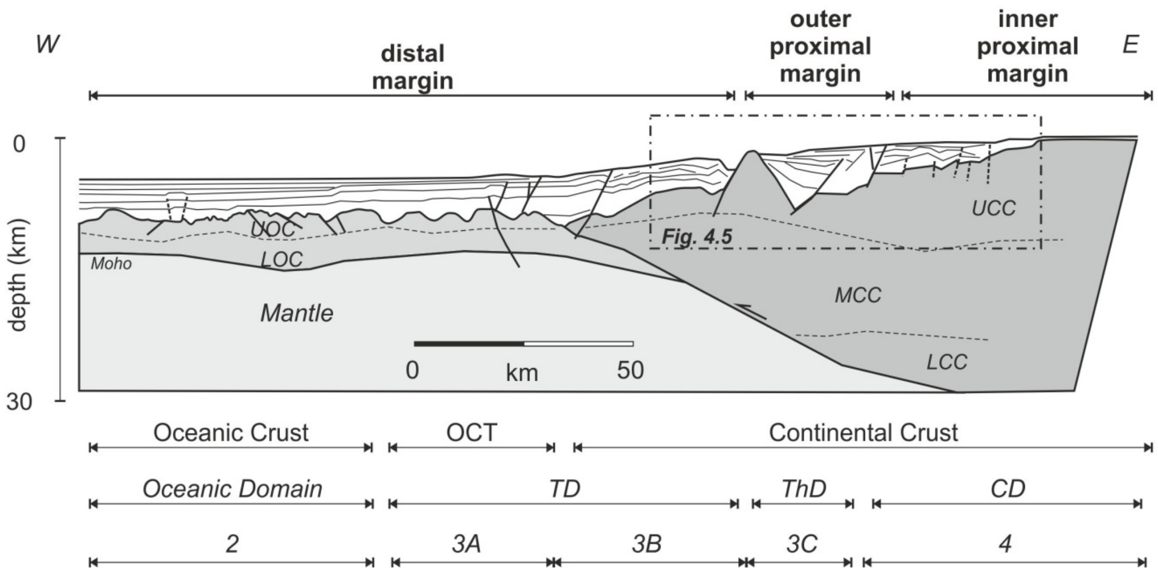

Figure 4.4 - Schematic reconstruction of the deep structure and crustal domains of the southwest Iberian margin, based on interpreted seismic velocity model (modified from Afilhado et al., 2008). The crustal domains of Afilhado et al. (2008) are compared to the sectors adopted in the present work. CD - continental domain, LCC - lower continental crust, LOC - lower oceanic crust, MCC - middle continental crust, OCT - ocean-continent transition, OD - oceanic domain, TD - transitional domain, ThD - thinned domain, UCC - upper continental crust, UOC - upper oceanic crust. Figure also presents the compressional domains 2, 3 and 4 of Neves et al. (2009). Vergence of the continental crust indentor from Neves et al. (2009).

During the Cenozoic, post-rift compression of the margin occurred mainly during the Eocene and the Oligocene-Miocene and continues to the present day (Boillot et al., 1979; Mougenot et al., 1979; Ribeiro et al., 1990). In Southwest Iberia, Miocene to post-Miocene compression resulted in differential shortening throughout the margin (Neves et al., 2009). These authors suggest that dissimilar shortening inversion structures are the result of interaction between different crustal domains, in association with the presence of a middle-upper crust indentor over a mantle detachment surface (Fig. 4.4).

4.4. Syn-rift and post-rift megasequences

The interpretation of seismic reflection profiles from the proximal to distal margins of Southwest Iberia reveals a suite of superimposed growth strata, bounded by distinct major unconformities. In some areas of the margin, growth strata denote continuous rifting spanning from Late Triassic to the latest Jurassic-earliest Cretaceous. The principal megasequences, their features and estimated lithology are summarized at Table 4.1. The significance of superimposed syn-rift megasequences in the study area, their geometry and timing in the context of the evolution of the Central and North Atlantic are discussed in detail in the following sections.

In the absence of well control in the distal margin, the acoustic basement was assumed to depict the boundary between highly deformed Palaeozoic successions and the Mesozoic syn-rift units (Fig. 4.5). Above the acoustic basement, discrete growth strata can be identified in different sectors of the margin (Fig. 4.5). The basement is subdivided into distinct sectors of rotated crustal blocks, creating a suite of sub-basins aligned along master faults broadly striking to the northeast. They dip towards the west in the distal margin, whereas on the proximal margin faults dip both to west and to the east (Fig. 4.6A).

The outer proximal and distal margins show significant block rotation and thick syn-rift sequences reaching up to 2.4 s two-way time (TWT) (Fig. 4.6B).

4.4.1. Upper Triassic to lowermost Jurassic (Megasequence 1)

The basal megasequence comprises sub-parallel to chaotic internal reflections observed above the Palaeozoic basement (Fig. 4.5). On seismic data this sequence thickens towards master faults and at outcrop, suggesting that significant and widespread subsidence has occurred during the Late Triassic-earliest Jurassic. Basal deposits from this sequence are related here to those exposed onshore and intersected from wells Pe-1 and Go-1, which include Carnian(?)-Norian continental red sandstones and shales of the Silves fm. (Sequence 1a, Fig. 4.3).

Over the Silves fm., the shaley-evaporitic unit of the Dagorda fm. (Sequence 1b) was deposited in a sabkha environment, an evidence for ongoing subsidence and progressive evolution to increasingly marine dominated successions.

Megasequence 1 represents the onset of the continental rifting on a wide rift mode, where fault-bounded depocenters accommodate deposits resulting from the degradation of the Palaeozoic relief (Fig. 4.5A).

4.4.2. Lower to Middle Jurassic (Megasequence 2)

On the proximal margin, the base of Megasequence 2 is recognized at outcrop and exploration wells by the occurrence of extrusive volcanic rocks and, onshore, by intrusive dolerites at the MPFZ. The presence of volcanic rocks is associated with the northernmost branch of the CAMP (Martins et al., 2008). On the outer proximal margin downlapping and divergent reflectors at the base of this megasequence (Fig. 4.5A), suggest an unconformity coeval with the igneous event. This volcano-sedimentary unit, absent in the northern basins of West Iberia, occurs from the Sesimbra-Setúbal region to the western part of the Algarve Basin. It comprises volcanic tuffs and lava flows of mafic composition (Azerêdo et al., 2003), similar and synchronous to those occurring in the Carson and Salar Basins (Wielens et al., 2006) (Fig. 4.3). Doleritic dykes associated with the MPFZ were intruded at approximately 200 M.a. (Cebriá et al., 2003) and are contemporaneous with volcanic units interbedded with Hettangian-Sinemurian evaporites exposed at outcrops in Santiago do Cacém, Bordeira and the Algarve Basin (Martins et al., 2008).

Sequence 2a (Hettangian?-Toarcian) is characterized by parallel to sub-parallel reflections downlapping Megasequence 1 (Fig. 4.5A).

This sequence is equivalent to the first successions outcropping around Santiago do Cacém and in wells Pe-1 and Go-1. Sequence 2a comprises dolomitic carbonate ramp deposits of Sinemurian to Toarcian(?) age (Coimbra fm.). Similar carbonate ramp deposits can also be observed in the Lusitanian Basin and in western Algarve (Inverno et al., 1993; Azerêdo et al., 2003). At Bordeira, the equivalent Early Jurassic sediments (J1-Lias? of Ribeiro et al. (1987)), are essentially marly limestones (Ramalho and Ribeiro, 1985). In the

Alentejo and Algarve Basins this Sequence 2a is bounded at the top by the Toarcian(?)-Aalenian unconformity and hiatus (Terrinha et al., 2002; Azerêdo et al., 2003).

Sequence 2b (Aalenian?-Callovian) is characterized by wedge shape deposits and divergent reflectors thickening towards major faults, which are most evident at the deeper domains of the proximal margin (Fig. 4.5A). On seismic, the base of this sequence is marked by a strong reflector, similar to that described from outcrops and Pe-1, likely associated with the Toarcian(?)-Aalenian event (Terrinha et al., 2002). At Santiago do Cacém and Pe-1, this sequence is characterized by the occurrence of limestones, whereas at Bordeira and Go-1, sediments are mainly dolomitic (Oliveira, 1984; Ribeiro et al., 1987; Azerêdo et al., 2003). Along the west Iberian and West Algarve margins, Sequence 2b is topped by a Late Callovian hiatus and corresponding unconformity, extending in some areas to the middle(?) Oxfordian (Azerêdo et al., 2002a; Azerêdo et al., 2002b). This hiatus is interpreted as a response to the end of a rift-climax cycle mainly expressed south of the Tagus Fault, i.e. segment 1 of Alves et al. (2009). Sequence 2b is timely coeval to the increased extension initiated from the Bajocian (unit J4) reported at Whale Basin (Hubbard, 1988; Balkwill and Legall, 1989; Tucholke and Sibuet, 2007). This similarity suggests that subsidence at the southernmost segment of the Iberia-Newfoundland is initiated early, prior to the main rift climax of the Oxfordian-Kimmeridgian.

4.4.3. Upper Jurassic to lowest Cretaceous (?) (Megasequence 3)

A widespread hiatus of Late Callovian to middle Oxfordian age defines the base of this unit (Azerêdo et al., 2002b), which reflects a new extensional event affecting the central segment of the North Atlantic (e.g. south Lusitanian and Jeanne d'Arc Basins). The hiatus and corresponding angular unconformity are less evident offshore with sparse downlapping reflections being observed on top of Megasequence 2.

Megasequence 3 is characterized in the study area by syn-rift wedge reflectors, thickening towards west-dipping master faults. These are best developed in the distal margin, but at the proximal margin these assume a late rift geometry (e.g. Prosser, 1993), with sub-parallel reflectors onlapping the previous sequence (Fig. 4.5A).

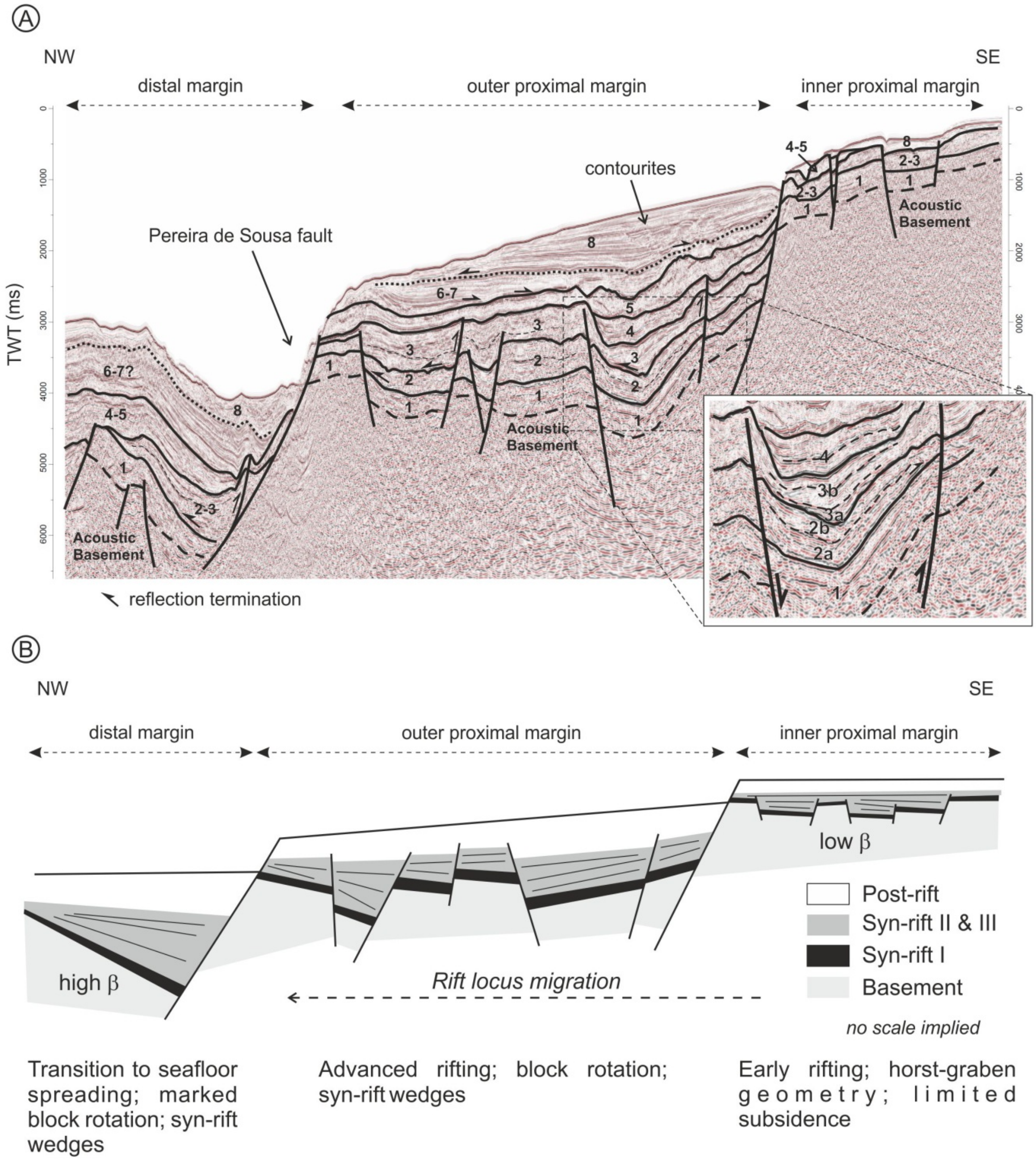

Figure 4.5 - Syn-rift segmentation of the proximal to distal margins of the Alentejo Basin. A - Migrated multichannel seismic section along a dip line evidencing superimposed growth strata. Megasequence 1 (Late Triassic-earliest Jurassic) thickness at the outer proximal margin. Megasequence 2 (Early to Middle Jurassic) showing syn-rift wedge seismic packages, evidencing significant subsidence prior to the final extension episode. Megasequence 3 (Late Jurassic to earliest Cretaceous), shows thick growth strata both on the outer proximal and distal margin. Megasequence 4 (Berriasian to Aptian); Megasequence 5 (latest Aptian to Maastrichtian-Palaeocene); Megasequence 6 (Palaeocene to mid Eocene); Megasequence 7 (mid Eocene to latest Oligocene-Miocene); Megasequence 8 (late Oligocene-Miocene to recent). B - Schematic representation of the syn-rift segmentation across the margin of Alentejo Basin.

Outcrops at Santiago do Cacém (Deixa-o-Resto fm.) and Arrábida (Sesimbra region) show polymictic conglomerates resting on an angular unconformity above the Middle Jurassic, and record the first high energy response to a renewed rifting event (Inverno et al., 1993).

By the same time at Bordeira, dolomites (Zimbreirinha fm.) and limestones (Três Angras fm.) are deposited and ultimately covered by volcanics (Ribeiro et al., 1987) (Fig. 4.3). Rift-related strata of Kimmeridgian to Berriasian age (Megasequence 3) are represented at Pe-1 well and on the interpreted seismic data. In the Lusitanian Basin, a depositional package equivalent to Megasequence 3, with siliciclastics and carbonates, is observed. In the Algarve Basin this same sequence is dominated by carbonate deposition. Megasequence 3 is truncated by a significant unconformity of Berriasian age, recognizable in the Lusitanian and the Algarve Basins as well as in the southwest Iberian margin. The final depositional sequences of the Tithonian to Berriasian reveal exposure and continentally influenced carbonate deposits with continental microfossils (Ramalho, 1971; Rey, 1972; Pereira et al., 2010) while at the same time, siliciclastic fluvial strata are documented to the North.

The syn- to post-rift seismic stratigraphic units defined in this work depict the transition from continental extension to a passive margin setting, and allow a preliminary correlation with major transgressive-regressive events defined by Montenat et al. (1988) and Rey et al. (2006) (Fig. 4.7). Consequently, the megasequences defined herein for the Alentejo Basin can be correlated with sequences interpreted for the Whale Basin (Hubbard, 1988; Balkwill and Legall, 1989), the Tagus Abyssal Plain (Mauffret et al., 1989b) and the Lusitanian Basin (Cunha and Reis, 1995; Rey et al., 2006) (Fig. 4.7). Such a correlation reveals the general synchronicity of major tectonic events during the Late Triassic to the Late Jurassic, especially between the conjugate margins of South Newfoundland (represented by the Whale Basin), and Southwest Iberia, a character addressed in section 4.6.

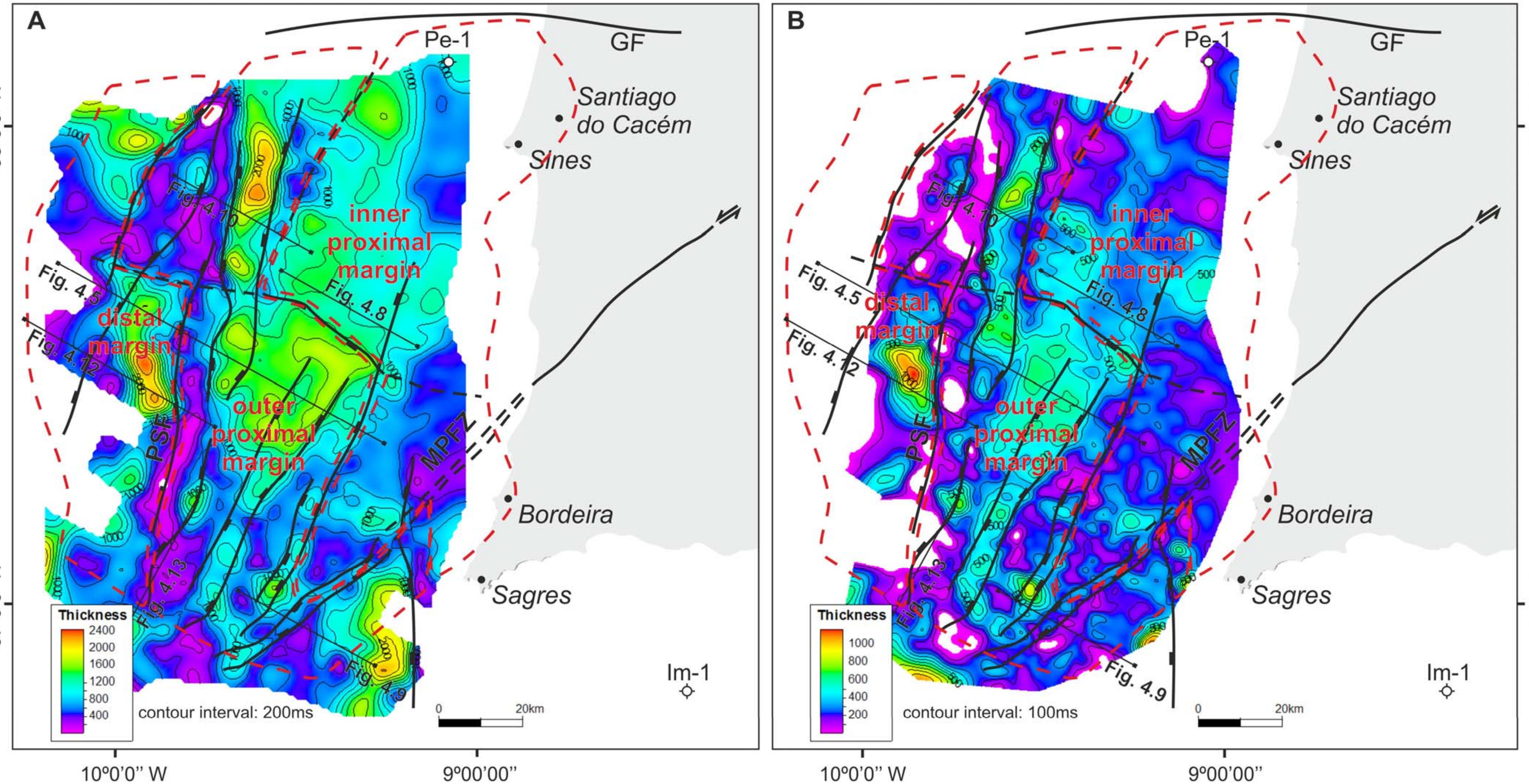

Figure 4.6 - Two-way time (TWT) isochron map of syn-rift Megasequences (1, 2 and 3) evidencing basement highs controlling deposition. B - Isochron TWT map of Megasequence 2 (Sinemurian-Callovian) showing thickness variation induced by subsidence. MPFZ - Messejana-Plasencia Fault Zone, PSF - Pereira de Sousa Fault, GF - Grândola Fault.

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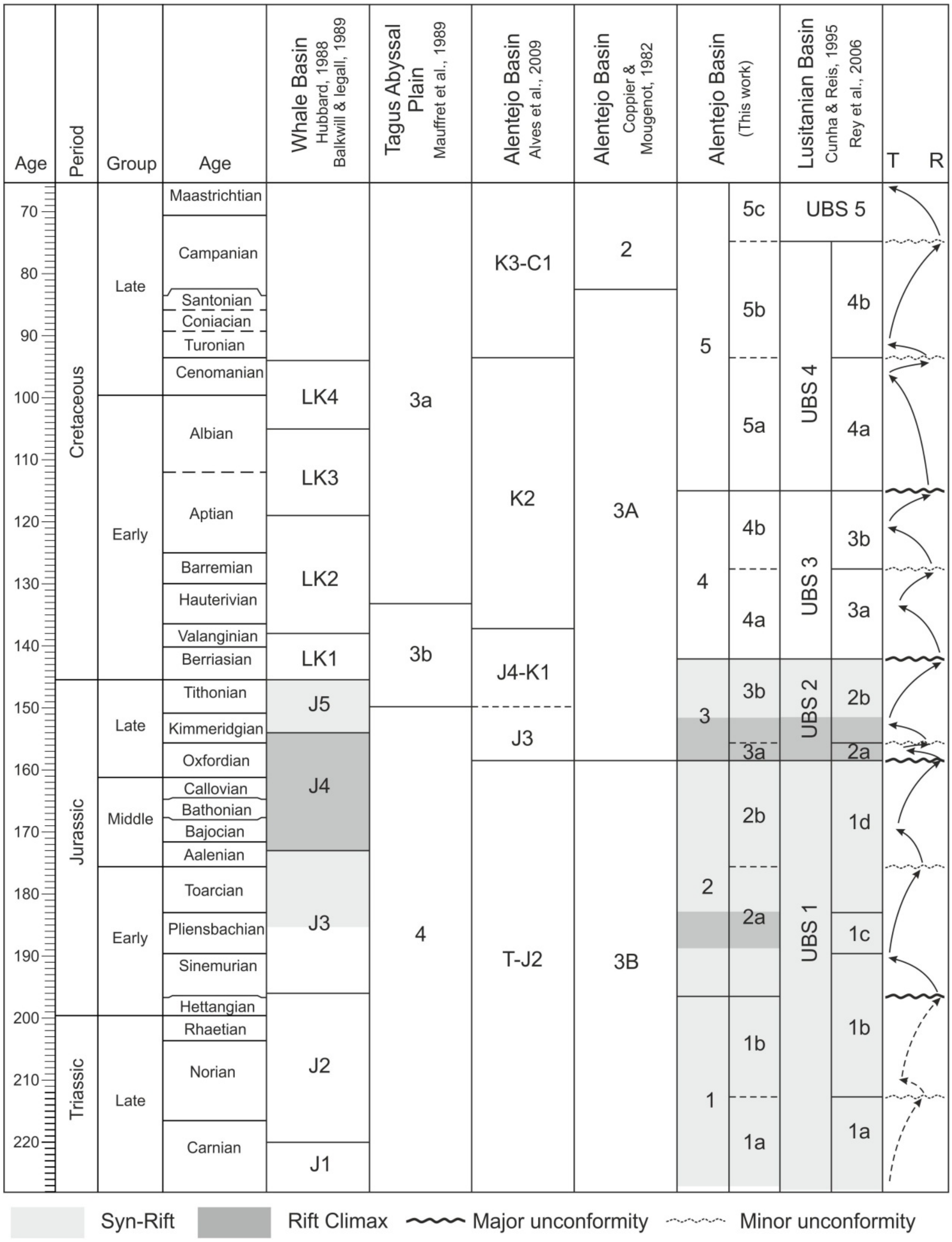

Figure 4.7 - Correlation of seismic-stratigraphic sequences in the Alentejo Basin with those from Lusitanian Basin, Tagus Abyssal Plain and Whale Basin. Schematic transgressive-regressive curves based on Montenat et al. (1988) and Rey et al. (2006). Syn-rift and rift climax shading adapted from Tucholke and Sibuet (2007).

4.5. Post-rift Megasequences

Overlying the syn-rift growth strata described above (Megasequences 1, 2 and 3), the post-rift is initiated at Southwest Iberia by the deposition of Early Cretaceous (Megasequence 4) and subsequent Late Cretaceous Megasequence 5 (Fig. 4.3), prior to the onset of compressive events governing the each of the main Cenozoic Megasequences (6, 7 and 8).

Seismic data from Megasequence 4 show prograding reflections overlapping the syn-rift growth strata (Fig. 4.5A). This Megasequence reveals two distinct units expressed differently across the margin.

Sequence 4a (Berriasian-Barremian) can be recognized nearly across the entire margin by chaotic to sub-parallel reflections and was intersected by dredges and exploration boreholes (Pe-1 and Go-1). Sequence 4b (Barremian-Aptian) occurs mainly on the outer proximal and distal margins and is expressed by sub-parallel to chaotic reflections. In Southwest Iberia, the “Aptian unconformity” bounding the top of Sequence 4b is not widely identified across the margin. On the distal margin it is characterized at by a strong reflector likely equivalent to a paraconformity, with an equivalent breakup unconformity in northwest Iberia.

The last Mesozoic unit represented in the southwest Iberian margin (Megasequence 5, Late Aptian-Maastrichtian) occurs only to the base of the continental slope. This Megasequence is expressed on seismic sections as a series of prograding reflections, including canyons and local erosion surfaces. Reflections within this sequence are mainly sub-parallel but include channel-fill and chaotic reflectors (Fig. 4.5A). In the study area, Sequence 5a (Late Aptian to Cenomanian) has been reported from Go-1 exploration well. Dredge data and seismic data interpretation point to the existence of the later sequences from the proximal to distal margins. Sequences 5b and 5c, extending from the Cenomanian to the Maastrichtian (and probably into the Paleocene), are absent from local outcrops and boreholes, but are described from dredge data and interpreted to occur on outer proximal and distal margins. The absence of late Cretaceous sediments on the inner proximal margin is likely related to the emplacement of the igneous batholith of Sines, assumed to have uplifted and eroded the continental shelf.

Cenozoic Megasequences 6, 7 and 8 can be broadly grouped into three major unconformity bounded units, which are expressed differently across the margin. The lowermost unit (Megasequence 6, Paleocene to middle Eocene) is likely absent on the inner proximal margin, as testified from exploration wells and dredge data. On the proximal margin, such deposits drape the Late Cretaceous-earliest Paleocene(?), showing downlaps over an interpreted erosional unconformity (Fig. 4.5A). On the distal margin this sequence is thicker (up to 1.2 ms TWT), showing sub-parallel reflectors. Late Eocene to latest Oligocene-earliest Miocene strata (Megasequence 7), were scarcely dredged on the inner proximal margin, and are deposited unconformably over the underlying strata. This sequence is characterized on the distal margin by sub-parallel reflections. The final depositional unit, Megasequence 8 (Miocene to recent), occurs widely across the margin and has been intercepted in exploration wells and dredges. This last Megasequence was, deposited unconformably over an erosional surface, is characterized by sub-parallel reflectors and contourite deposits (Fig. 4.5A).

4.6. Structural segmentation of the SW Iberian margin

The analysis of seismic reflection data from the southwest Iberian margin revealed distinct structural styles defining three major syn-rift sectors that characterize the Mesozoic rift evolution of the southernmost domain of the North Atlantic (Fig. 4.5).

4.6.1. The Inner proximal margin

The inner proximal margin broadly corresponds to the present day continental shelf and shows moderately developed half-graben geometry with syn-rift Mesozoic deposits providing evidence of limited subsidence. In this sector of the margin, continental crust is approximately 30 km thick (Neves et al., 2009), with total sediment thickness up to 1.5 s TWT. Sequences from syn-rift Megasequence 2 can reach approximately 0.5 s TWT (Fig. 4.6).

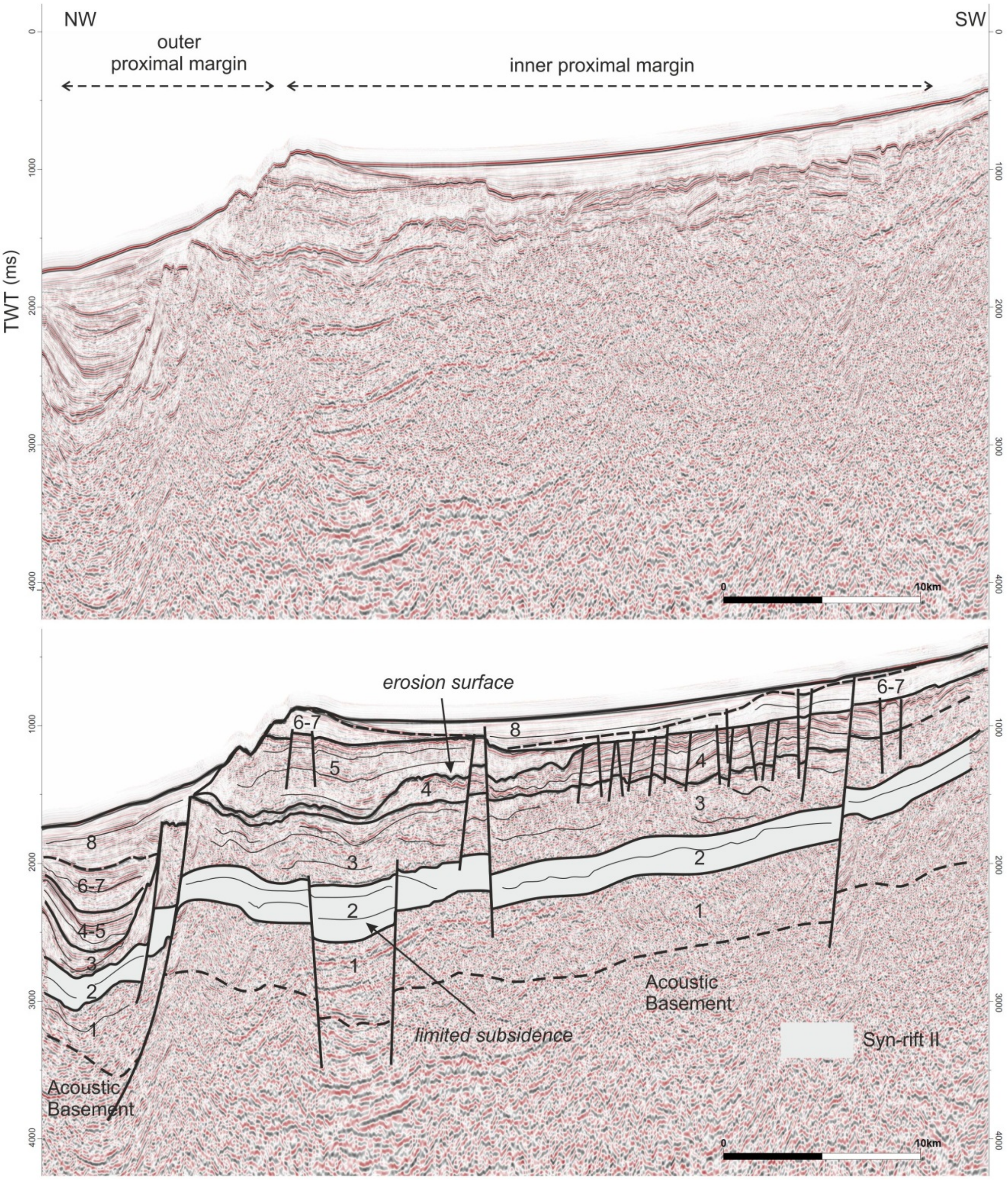

Figure 4.8 - Migrated multichannel seismic line showing limited syn-rift subsidence across inner proximal margin. Megasequence 2 (Early to mid-Jurassic) reveals downlapping reflections overlaying the previous unit and some degree of thickness variation. Post-rift Megasequence 4 (Early Cretaceous) downlaps the syn-rift growth strata and is crosscut by a late Cretaceous incision surface.

Faults affecting this segment are dominantly extensional, aligned NE-SW and dip both to the West and to the East (Fig. 4.6), bounding minor sub-basins with little rotational component (Fig. 4.8). Minor faults affect mainly the Cretaceous sequences and segment the margin in closely- spaced tilt-blocks. This area illustrates the structural architecture of the margin during rift initiation, generated from early lithospheric necking of the continental crust. Reverse faults associated with the Cenozoic compression can be observed, some affecting the seafloor.

Mesozoic sequences deposited from the Upper Jurassic onwards (as seen on exploration wells, Pe-1 and Go-1, dredge information and outcrops), generally thin to the East and are gently tilted to the southwest. To the south of the southwest Iberian margin the continued activity of the MPFZ records a complex structural evolution.

Syn-rift growth strata recognized below a major unconformity (earliest Cretaceous?) are greatly affected by intense segmentation probably associated with oblique extension (Fig. 4.9).

4.6.2. The Outer Proximal margin

This sector is characterized by a thinned continental crust, segmented by normal faults inducing continued half-graben subsidence from the Late Triassic to the latest Jurassic-earliest Cretaceous, with a total syn-rift sediment thickness of up to 2.4 s TWT (Figs. 4.6 and 4.10).

Strata deposited during Syn-rift II megasequences reveal approximate thickness up to 1 s TWT (Fig. 4.6). Faults in this sector define tilt blocks aligned NNE-SSW to NE-SW, dipping either to the West or to the East, with half-graben geometries and successive syn-tectonic rotational sedimentary wedges. East-dipping faults often limit syn-tectonic depositional sequences with divergent reflectors thickening to the West, suggesting Middle Jurassic subsidence (Fig. 4.4, 4.10). West-dipping faults affect deposits from Megasequences 2 and 3 (Figs. 4.5A, 4.6, 4.10 and 4.11). Late Jurassic strata are overlain by an unconformity representing continental breakup and subsequent seafloor spreading occurring westwards, separating the southern Grand Banks of Newfoundland and the southwest Iberian margin.

The geometry of the outer proximal margin is broadly similar to that described from the outer proximal margin of the Galicia Bank and Interior Basin, Porto Basin (Murillas et al., 1990; Manatschal, 2004) and the Moroccan margin (Hafid et al., 2000; Le Roy and Piqué, 2001), but differs by presenting distinct syn-rift intervals with significant stratal growth (Fig. 4.10).

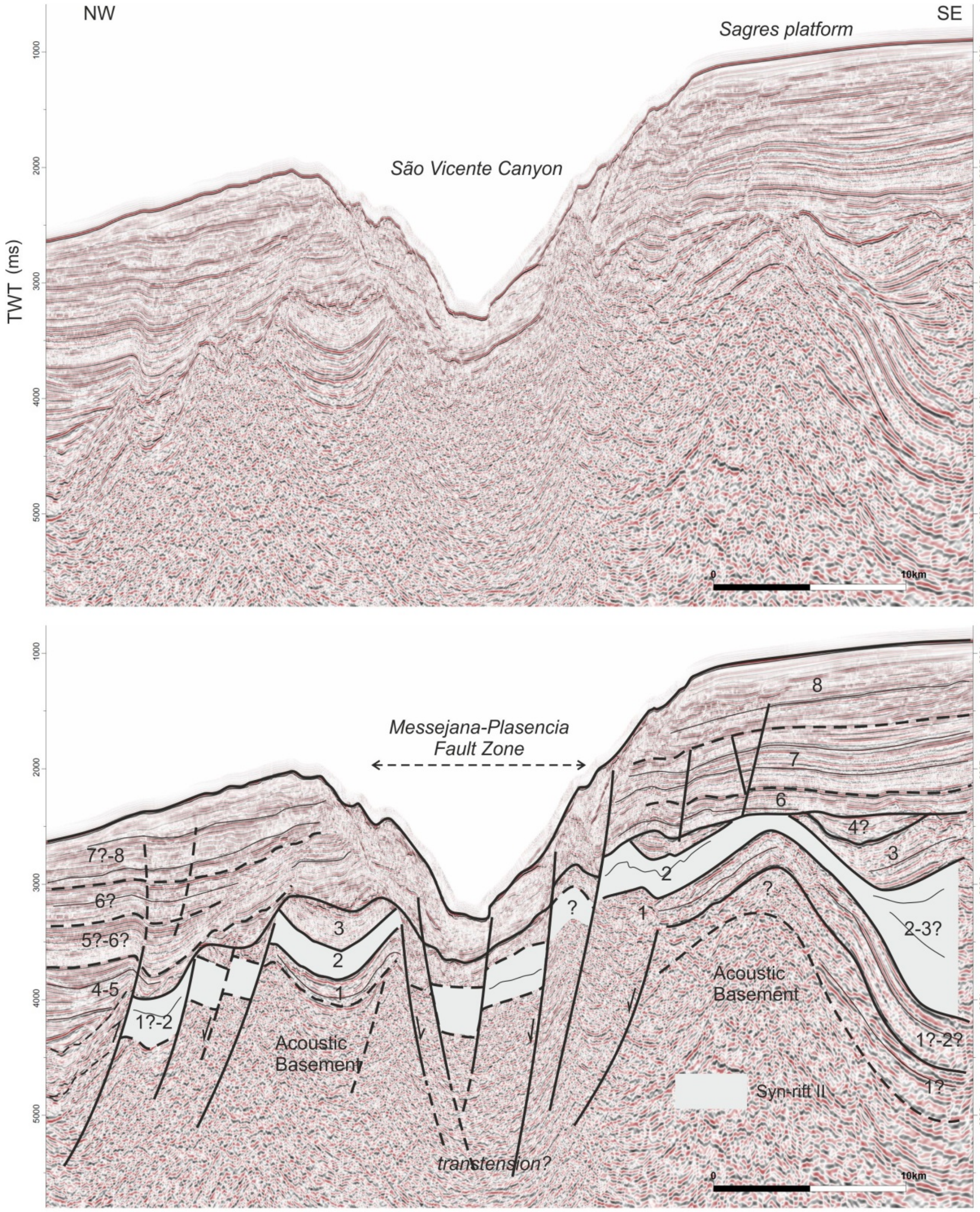

Figure 4.9 - Migrated multichannel seismic line across the S. Vicente canyon and the offshore expression of the Messejana-Plasencia Fault Zone. Note thickness variation of syn-rift strata from Megasequence 2 (Early to Middle Jurassic) and Megasequence 3 (Late Jurassic-earliest Cretaceous. Syn-rift sequences are overlain by the Oligocene (?) angular unconformity and post-rift "parallel" reflections (Megasequences 6 to 8).

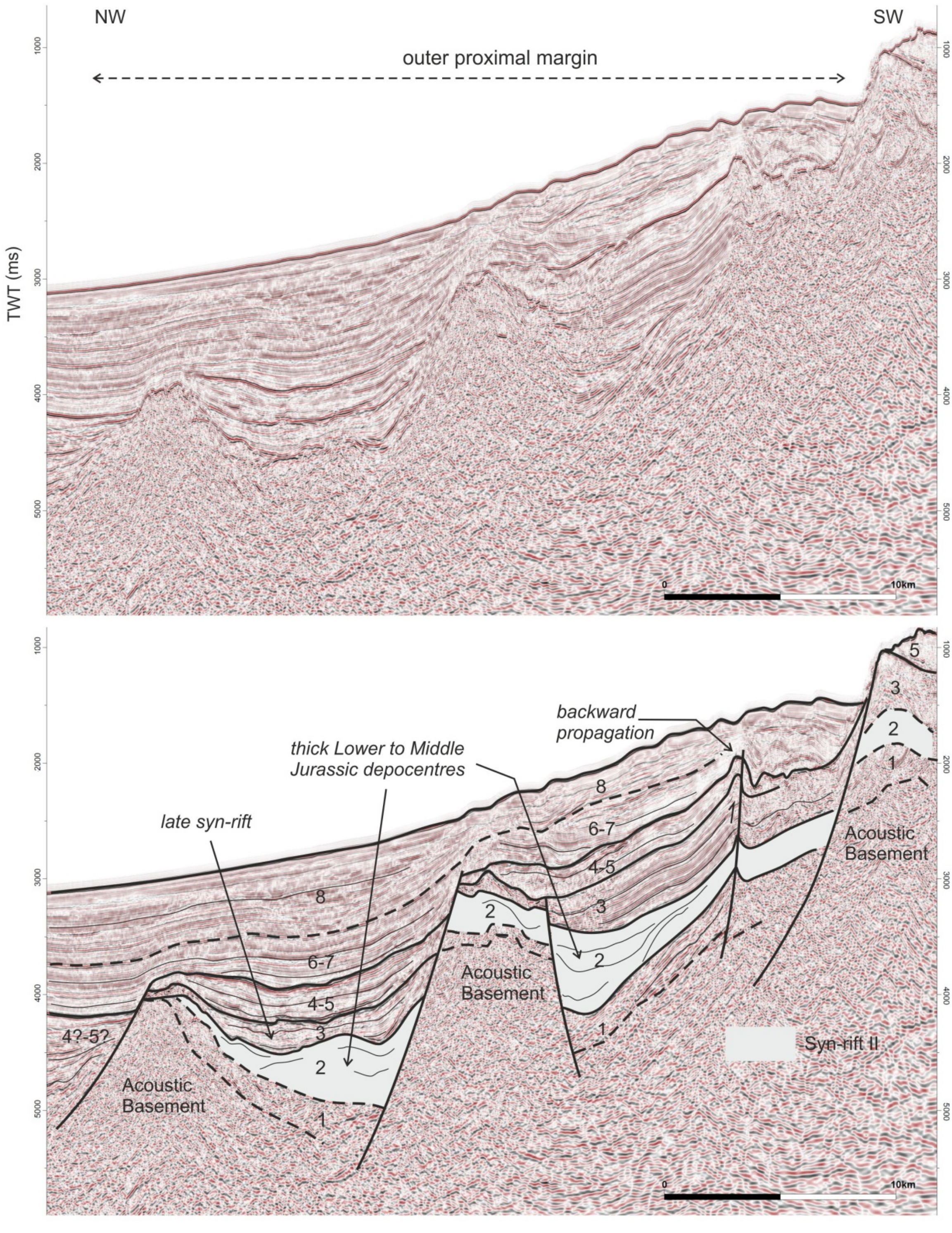

Figure 4.10 - Migrated multichannel seismic line across outer proximal margin, evidencing superimposed syn-rift megasequences (1, 2 and 3) from the Late Triassic to the Late Jurassic-Early Cretaceous. Post-rift reverse faults, likely rooted on shaley-evaporitic deposits, crosscut the Mesozoic and the Early Cenozoic deposits.

This sector, can be recognized from the shallow platform to the continental slope rupture to the West (Figs. 4.5 and 4.6). Inversion features at this sector are marked by localized footwall thrusting of Meso-Cenozoic sequences forming short-spaced anticlines and reverse faulting generated as backward propagation (sensu Hayward and Graham, 1989) (Fig. 4.10).

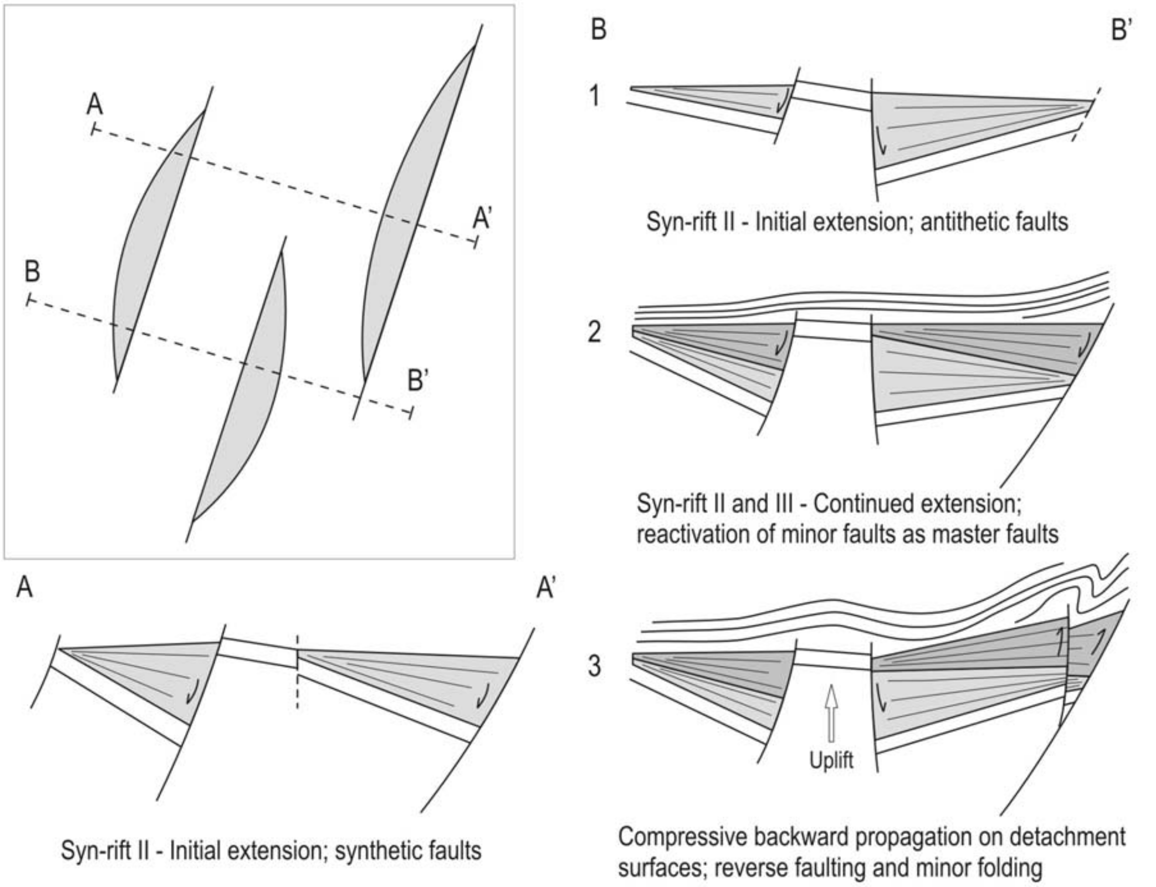

Figure 4.11 - Schematic model depicting the multiphased rift evolution of the outer proximal margin, from extension to compression at distinct subsiding sub-basins A and B. Subsidence in section A shows typical synthetic faults forming sub-basins. Section B shows subsidence across the outer proximal margin with distinct tilt block rotation during Syn-rift II and III. Post-rift compression results in reverse faulting, likely rooted at deep shaley-evaporitic deposits from Megasequence 1.

4.6.3. The Distal Margin

The distal margin is characterized by significant tilt-block rotation, which led to significant subsidence in distinct sub-basins (Fig. 4.12).

Most faults within this area intersect the seafloor (e.g. Pereira de Sousa Fault) and limit sub-basins up to 30-50 km in extension (Fig. 4.6A). Faults bounding these sub-basins are oriented broadly NNE-SSW, dip to the west and record the major extensional effort of the rift. This sector was formed in the last extensional episode leading to seafloor spreading and master faults within this sector are likely rooted at deep crustal levels similar to the S reflector described from the distal margin of northwest Iberia (Tucholke et al., 2007).

The distal margin is underlain by a thinned continental crust and extends from the shelf-edge toward the base of the continental slope. In this sector, reverse faults affect the syn- to post-rift sequences. These are likely rooted at late syn-rift Sequence 1b, where evaporitic and shaley successions likely work as detachment surfaces (Fig. 4.12).

The distal sector extending oceanwards from the base of the continental slope, reveals highly rotated tilt-blocks bounded by faults deeply rooted at upper crustal detachments, aligned generally N-S along the margin (Fig. 4.6). This same sector also presents high-amplitude anticlines resulting from compression during the Cenozoic (Fig. 4.13). Compression reactivated previous syn-rift highly rotated fault blocks forming broad anticlines with seafloor expression, suggesting a buttress effects similar to those described by Mitra and Mount (1998) for colliding crustal segments.

4.7. Discussion

4.7.1. Evidence of multiphased rifting in Southwest Iberia

Based on the interpreted geometry of superimposed syn-rift sequences, discrete Mesozoic extensional events are interpreted to have contributed to the structural segmentation of Southwest Iberia. Accordingly, evidence for three distinct syn-rift episodes are presented (Syn-rift I, II and III) occurring from the Late Triassic to the latest Jurassic-earliest Cretaceous (Fig. 4.3). Syn-rift phase I was initiated in the Late Triassic (Carnian? to Rhaetian), as widespread continental segmentation created sub-basins showing limited subsidence subsequently filled by fluvial siliciclastic red bed and evaporitic deposits.

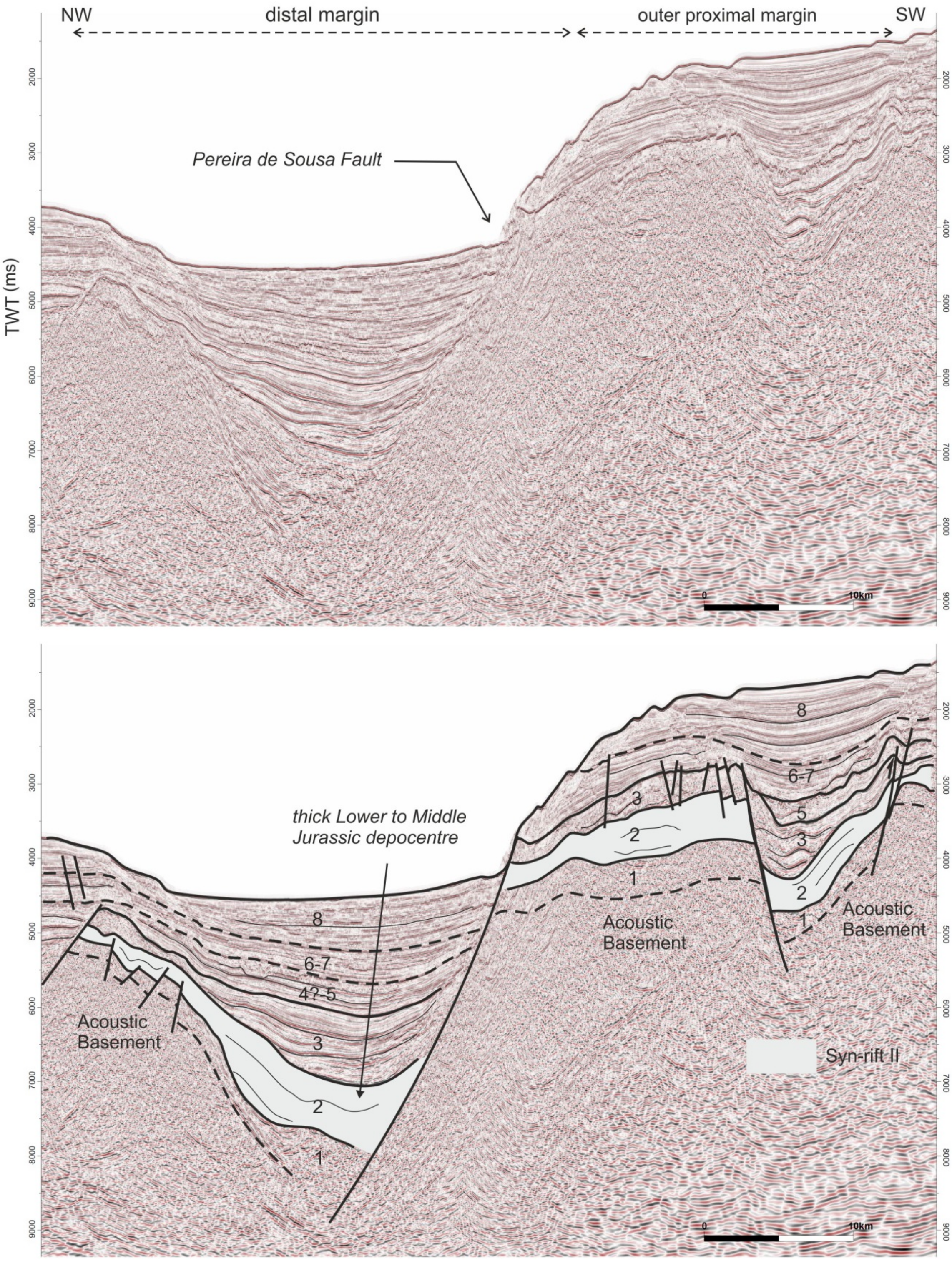

Figure 4.12 - Migrated multichannel seismic line across the outer proximal to the distal margins evidencing superimposed growth strata (Megasequences 1 to 3). Syn-rift II phase denotes significant Middle Jurassic subsidence, prior to Late Jurassic-Early Cretaceous transition to seafloor spreading. Seafloor deformation west of the Pereira de Sousa Fault suggests subsidence subsequent to the latest rift episode and present day clockwise rotation of the thinned continental crust.

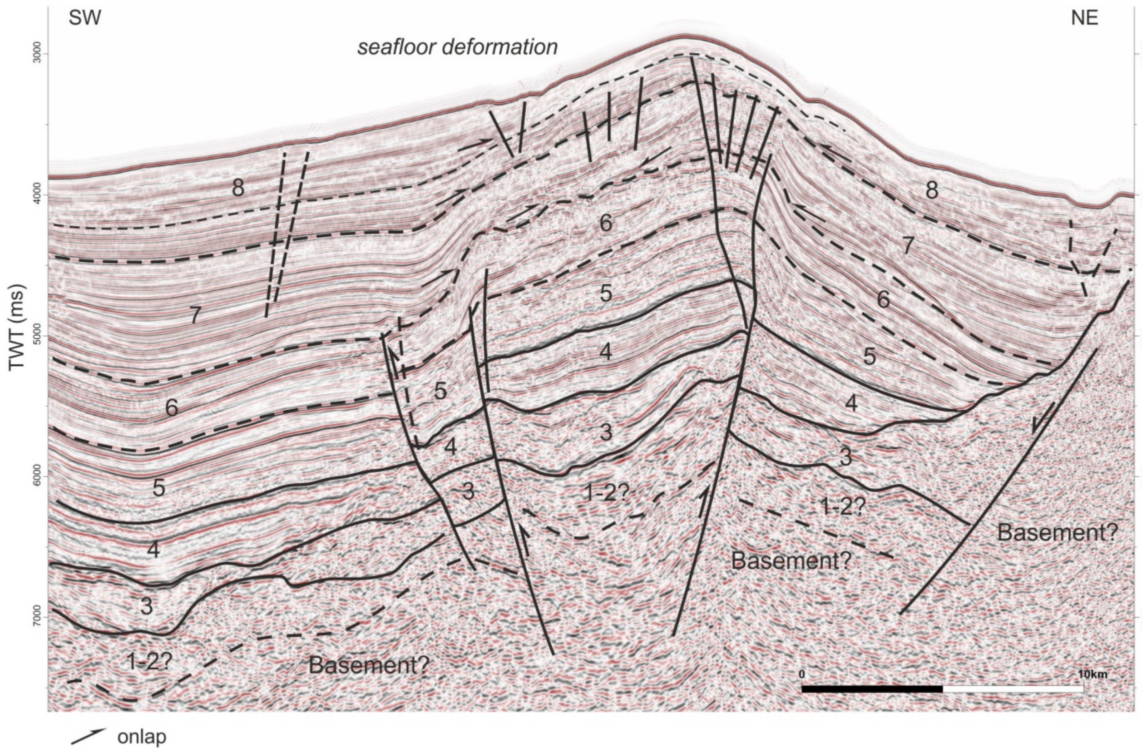

Figure 4.13 - Migrated multichannel seismic line across the distal margin showing post-rift compression across the Marquês de Pombal High, inversion of syn-rift megasequences and present-day seafloor deformation. Note the reflection terminations towards the Oligocene to Eocene-Miocene anticline.

The initiation of a second phase of extension (Syn-rift II) is marked by the occurrence of CAMP related magmatism at Southwest Iberia, as well as the associated intrusive dolerites of the MPFZ.

Subsequently, this phase is marked by increased subsidence during the Sinemurian to the Pliensbachian, during which marine dolomites and limestones (some with high organic matter contents associated with proven source rock potential (GPEP, 1986)) denote persistent extension of the margin.

This episode extends to the Toarcian(?)-Aalenian and ultimately up into the Callovian, when renewed subsidence is recorded at the southwest Iberian margin by growth strata accumulating on mid-Jurassic depocenters. This Early to mid-Jurassic episode is synchronous with extension leading to breakup of the northern Central Atlantic (Morocco-Nova Scotia conjugate margins). Syn-rift phase II is best observed in the outer proximal and distal margins of the southwest Iberian margin (Fig. 4.4), where thick growth strata from Megasequence 2 occur (Fig. 4.5B). This episode reveals Southwest Iberia as a northern Central Atlantic influenced domain.

The third and final extensional episode (Syn-rift III) is focused at the distal margin of the southwest Iberian margin (Fig. 4.4), the Tagus Abyssal Plain as well as in the Lusitanian Basin, where marked subsidence South of the Nazaré fault enabled the deposition of significant syn-rift deposits (Wilson et al., 1989). This episode initiated in the Oxfordian with paroxysmal subsidence in the Kimmeridgian ended by latest Jurassic-earliest Cretaceous time. On the outer proximal and distal margins, Syn-rift III is represented in seismic data by thick growth strata bounded at the top by the Late Tithonian-Berriasian(?) breakup unconformity (Figs. 4.5A, 4.10, 4.12).

Syn-rift extension from the earliest Cretaceous to the middle Aptian (Syn-rift IV) is expressed mainly in the northern basins (Peniche and Lusitanian). It represents the last extension phases leading to seafloor spreading between Iberia and Newfoundland. By this time, the proximal to distal margins of Southwest Iberia, evolved as a passive margin as evidenced by the post-rift Cretaceous Megasequences 4 and 5 (Figs. 4.5, 4.10, 4.12).

4.7.2. Rift locus migration during continental extension

The identification of distinct structural styles in the study area and the occurrence of discrete (but diachronous) Mesozoic growth-packages on the proximal to the distal margin, indicate multiphased continental rifting on the non-volcanic passive margin of Southwest Iberia (Fig. 4.14). However, the structural sectors observed on the southwest Iberian margin do not correlate directly with the broader evolutionary model presented for the Galicia margin. The models presented for Galicia mainly address the evolution of the distal margin and its relation to the deep crustal detachments, lacking significant information from strata older than the upper Jurassic.

A contrasting aspect between the two margins is the relatively minor expression of marginal highs in Southwest Iberia, when compared with those described from the Galicia Bank. In contrast with the distal Galicia margin, the Southwest Iberia margin shows near-continuous subsidence of continental-slope tilt-blocks, and denotes a multiphased rifting over a relatively long period (Late Triassic to latest Jurassic-earliest Cretaceous, approximately 90 M.a.).

These facts suggest an important impact of the deep crustal structure on the subsidence histories of parts of the southwest Iberian margin. As a result, continental break-up occurred very close to the present-day continental slope, hindering the formation of extensive marginal highs as those offshore Galicia.

The distinct structural sectors identified in Southwest Iberia are related with the relative westwards migration of the rift locus during the syn-rift (Fig. 4.14). During syn-rift phase I, extension on a wide rift mode has induced the formation of early sub-basins chiefly dominated by continental deposition.

As extension continued during Syn-rift II (Sinemurian? to Callovian-Oxfordian), extensional stresses became concentrated on the outer proximal and distal margins inducing increased subsidence, tilt block rotation and larger accommodation space for mid to late Jurassic sub-basins (Fig. 4.14). Growth strata from Megasequence 2 are observed on the transition to an advanced rifting phase dominated by simple shear extension. Growth strata at the outer proximal margin show Megasequence 2 thickening either to the west or the East, whereas syn-rift Megasequence 3 deposits thicken to the East (Figs. 4.10, 4.11). The thickening of Megasequence 2 (Sinemurian to Callovian-Oxfordian) towards master faults, occurring mainly on the outer proximal and distal margins clearly contrasts to the limited occurrence of growth strata in the Peniche Basin presented in Alves et al. (2006). In this work, this character is considered an evidence of continued continental extension from the early to middle Jurassic in Southwest Iberia.

From the Oxfordian to the Tithonian-Berriasian, a renewed pulse of extension (Syn-rift III), focused mainly at the distal margin of Southwest Iberia and segments to the north, reactivates existing faults, inducing strong subsidence and a thick syn-rift depositional Sequence 3 (Figs. 4.12 and 4.14). Faults of this phase predominantly dip westwards, typically characterizing a transition to breakup and seafloor spreading, as evidenced by highly rotated fault blocks occurring mainly at the distal margin. These faults, planar to listric in geometry are likely rooted at upper crustal detachments, similar to those from northwest Iberia. Figure 4.14 illustrates the evolution of the proximal to distal margins in relation to the rift phases and relative rift locus migration, from initial continental segmentation to the transition to seafloor spreading.

At the southern domain of the study area, structural styles such as those described above are not clearly expressed. The original rift geometry is largely modified by the offshore extension of the MPFZ and the effects of Alpine compressive events. In contrast with the transpressive features the MPFZ observed onshore, the offshore continuation is characterized by multiple normal faults broadly aligned NE-SW, suggesting transtension (Fig. 4.2). At the southern domain of study area, in the vicinity of the MPFZ, seismic data reveal thick growth strata, suggesting extension since the Triassic (?) to the Upper Jurassic (Fig. 4.9). On the outer proximal margin, these sequences are covered by post-rift successions from the Early Cretaceous onwards.

4.7.3. Southwest Iberia in the context of the Central and North Atlantic rifting

It is considered herein that each unconformity-bounded megasequence, observed either at outcrops or their expression on seismic data, depicts discrete coeval events potentially recorded on the conjugate and neighbouring margins. Each unconformity is a response to major tectono-stratigraphic event, which makes them suitable for large scale margin correlation. Examples of such synchronicity between the conjugate margins of the southern North Atlantic are the major unconformable events recorded during the Toarcian-Aalenian, the Callovian-Oxfordian and ultimately the Tithonian-Hauterivian event expressed in the Whale Basin. These events coincide with the principal sequence boundaries in southwest Iberia and are ultimately coeval to other events recorded both in Iberia and Newfoundland.

The widespread Syn-rift phase I (Carnian-Hettangian), corresponds to the wide rift mode continental segmentation along the West Tethys, Central and North Atlantic. CAMP magmatism occurring at southern Iberia by the Hettangian marks a new pulse of continental extension and the transition to marine influenced deposition. It defines the onset of Syn-rift II, synchronous to the seafloor spreading at the North African segments ending by the Callovian. This phase is characterized by significant growth strata thickening towards master faults, best expressed at the outer proximal and distal margins, evidencing early subsidence of the southwest Iberian margin and the relative migration of the locus for subsidence. This phase is also reported from South Newfoundland (e.g. Whale Basin) where mid Jurassic growth strata are described. Such event represents the northern Africa-Nova Scotia influenced domain.

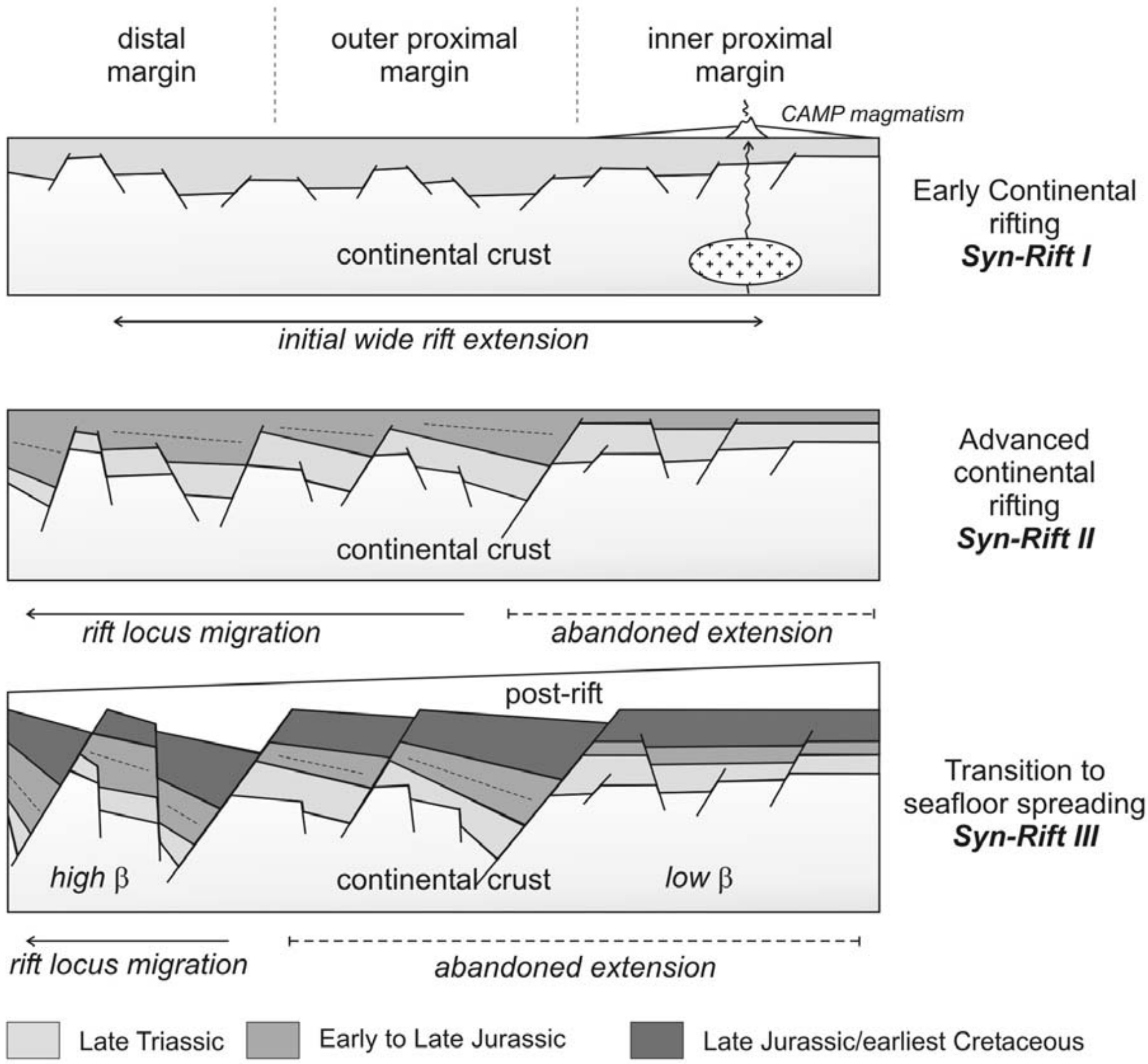

Figure 4.14 - Schematic evolution of distinct structural sectors of the proximal to distal margins in response to three rift phases at Southwest Iberia' from early continental rifting to seafloor spreading. Major subsidence at different sectors of the margin denotes relative rift locus migration across the margin.

During the Callovian(?)/Oxfordian-Tithonian, a new rift phase (Syn-rift III) is recorded. On the proximal margin it is characterized on seismic data by downlapping reflectors towards an unconformity and/or hiatus, overlain by subsequent late rift tectonic system tract, whereas on the distal margin, it is characterized by thick growth strata showing typical rift climax tectonic system tracts. This same event is expressed on outcrops, revealing an angular unconformity overlain by basal conglomerates. Extension at the Southwest Iberia proximal margin culminates by the Tithonian-Berriasian (?) and is expressed on seismic as a breakup unconformity, overlain by Early Cretaceous post-rift deposits. This event is correlated to the extension at southern proximal margin segments of Lusitanian, Peniche and Jeanne d'Arc Basins, where marked subsidence was occurring as a result of continental rifting, which is identified here as an early North Atlantic extensional phase.

Syn-rift IV, occurring at northern segments of the Iberia-Newfoundland conjugate margins, culminates in an Aptian (early Albian) event. By this time, an assumed coeval unconformity is expressed in the post-rift sequences of the proximal margin of the southwest Iberian margin. This event is the expression of the northwards migration of the Atlantic spreading, later culminating by the Albian breakup at northern Newfoundland and Galicia.

The data presented herein strongly suggest that the last rifting episode in Southwest Iberia (leading to the deposition of Megasequence 3) relates to the advanced rifting and transition to seafloor spreading stage and immediately precedes continental break-up west of the Tagus Abyssal Plain. The observed multiphased rifting agrees partly with the interpretation of Srivastava et al. (2000), which considers that breakup west of the Tagus Abyssal Plain should have occurred by the late Tithonian to Berriasian (magnetic anomalies M20-M17). Assuming this latter age as the onset of seafloor spreading, and considering a 30 to 50 M.a. interval for initiating an extension phase, an estimated Sinemurian-Aalenian period (172 to 192 M.a.) should correlate with the onset of a new rift event. If the lowermost limit for initial extension is positioned approximately at 192 M.a. (i.e. Sinemurian), this same event is broadly coincident to the early extension recorded outcrop and borehole data in Southwest Iberia and in the Lusitanian Basin. This rifting event chiefly coincides with the widespread unconformity and hiatus expressed from the proximal margin of Southwest Iberia (base of Syn-rift II).

4.8. Conclusions

The present chapter documents the continued segmentation of the southwest Iberian margin during the Mesozoic rifting, by describing the different structural styles, seismic-stratigraphic features of syn-rift sequences and the relative migration of the main locus of rift-related subsidence.

Across Southwest Iberia, three distinct structural sectors characterize the geometry of the margin: 1) the inner proximal margin; 2) the outer proximal margin and 3) the distal margin.

Syn-rift I, best observed on the inner proximal margin, is characterized by generalized short spaced faulting of the continental crust when the initial tensile forces, created wide accommodation areas for Late Triassic to earliest Jurassic continental siliciclastics and evaporites.

A second episode (Syn-rift II) is initiated by the Hettangian-Sinemurian and evidenced by the emplacement of CAMP related volcanics and the dykes from the Messejana-Plasencia Fault Zone.

After a Toarcian(?)-Aalenian major hiatus, continued subsidence and extension are recorded on the outer proximal and distal margins. Syn-rift sequences in these sectors are characterized by growth strata assigned to the mid-Jurassic. It is therefore suggested that this event is coeval to the extension leading to seafloor spreading between Nova Scotia-Morocco conjugate margins.

The third and final episode (Syn-rift III) coincides with the principal episode of extension in the Lusitanian Basin and its conjugate from Newfoundland. Subsidence continues until the Tithonian-Berriasian when seafloor spreading suggestively occurred in the Tagus Abyssal Plain. This event is shown on the outer proximal on the distal margins, as thick syn-rift strata infilling renewed accommodation space generated by increased subsidence from master faults.

The variation in syn-rift geometry and thickness of the three megasequences interpreted in Southwest Iberia reveals a relative westward migration of major subsiding areas during continental extension prior to breakup, an evidence of rift locus migration.

From the Early Cretaceous onwards, seismic data reveals post-rift megasequences onlapping Megasequences 1 to 3. This event is coeval to the Syn-rift IV occurring in northwest Iberia.

Chapter 5

Post-rift compression on the SW Iberian margin (eastern North Atlantic): a case for prolonged inversion in the ocean-continent transition zone

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5. Post-rift compression on the SW Iberian margin (eastern North Atlantic): a case for prolonged inversion in the ocean-continent transition zone

Abstract

An extensive grid of 2D seismic reflection data imaging the non-volcanic continental margin of SW Iberia is used to investigate the post-rift compressional evolution in the transition zone between continental and oceanic crust. Tectonic compression affected the margin almost continuously since the latest Cretaceous, but was predominantly focused during the mid-Eocene and the late Oligocene–mid-Miocene. The detailed interpretation of post-rift structures and their adjacent strata shows that crustal shortening in the various sectors of the margin is neither synchronous nor similar in style. Main post-rift structures include: (1) thick-skinned transpressional deformation on the distal margin; (2) localized basin shortening on the outer proximal margin; (3) limited reverse faulting and inversion on the inner proximal margin. The location and magnitude of crustal shortening are dependent on the inherited syn-rift geometry, the existence of evaporite (or clay-rich) detachments at depth, the rheological behaviour of previously extended continental crust and the position of the ocean–continent transition zone. The mechanisms of compression are mainly dominated by plate collision associated with the south-eastern migration of the Iberian microplate during the Alpine orogeny and with recent westward convergence with the oceanic domain.

5.1. Introduction

The Mesozoic margin of Iberia comprises a non-volcanic rifted margin that experienced compression after the Late Cretaceous (e.g. Boillot et al., 1979; Ribeiro et al., 1990; Pinheiro et al., 1992; Pinheiro et al., 1996; Srivastava et al., 2000; Wilson et al., 2001; Manatschal, 2004; Tucholke et al., 2007). In a manner similar to that for other margins in the North Atlantic (e.g. Cloetingh et al., 2008; Doré et al., 2008), tectonic compression controlled the evolution of Iberia soon after continental breakup between Iberia and Newfoundland. Compressional stresses affecting passive margins are the result of tectono-magmatic and active asthenospheric upwelling, post-breakup compressional and compactional stresses (Schlische et al., 2003; Doré et al., 2008). The latter stresses include plate collision or subduction, ridge-push forces, continental resistance to plate motion gravity loading, flank enhancement by sediment loading, transfer from orogenic stress, reactivation of pre-existing basement lineaments, plate driving and body forces (Doré et al., 2008). The deformation styles of deeper crustal layers and overlying deposits are, therefore, controlled by the rheological behaviour of the lithosphere, the inherited geometry prior to compression and the regional intra-plate stress field (Cloetingh et al., 2008).

West Iberia is traditionally considered to be a passive continental margin (e.g. Wilson et al. 2001). However, multiple examples of tectonic compression along this margin have been described in the literature (Boillot et al., 1979; Mougenot et al., 1979; Masson et al., 1994; Terrinha et al., 2003; Péron-Pinvidic et al., 2008; Neves et al., 2009). The variable styles and timings of inversion raise some questions concerning their tectonic significance in the context of the Pyrenean and Alpine orogenies and their relation with the syn-rift geometry of the continental crust. Thus, Southwest Iberia is revealed here as a key province to understand the intricate rift-to-drift evolution of the southernmost segments of the North Atlantic and their relationship to the Western Tethys and North Africa (Fig. 5.1). Several workers addressed some of the tectonic features resulting from compression (Mougenot et al., 1979; Alves et al., 2003a; Terrinha et al., 2003; Rovere et al., 2004; Zitellini et al., 2004; Afilhado et al., 2008; Alves et al., 2009; Neves et al., 2009), but a more systematic approach to describe the distribution and significance of compression is still to be accomplished.

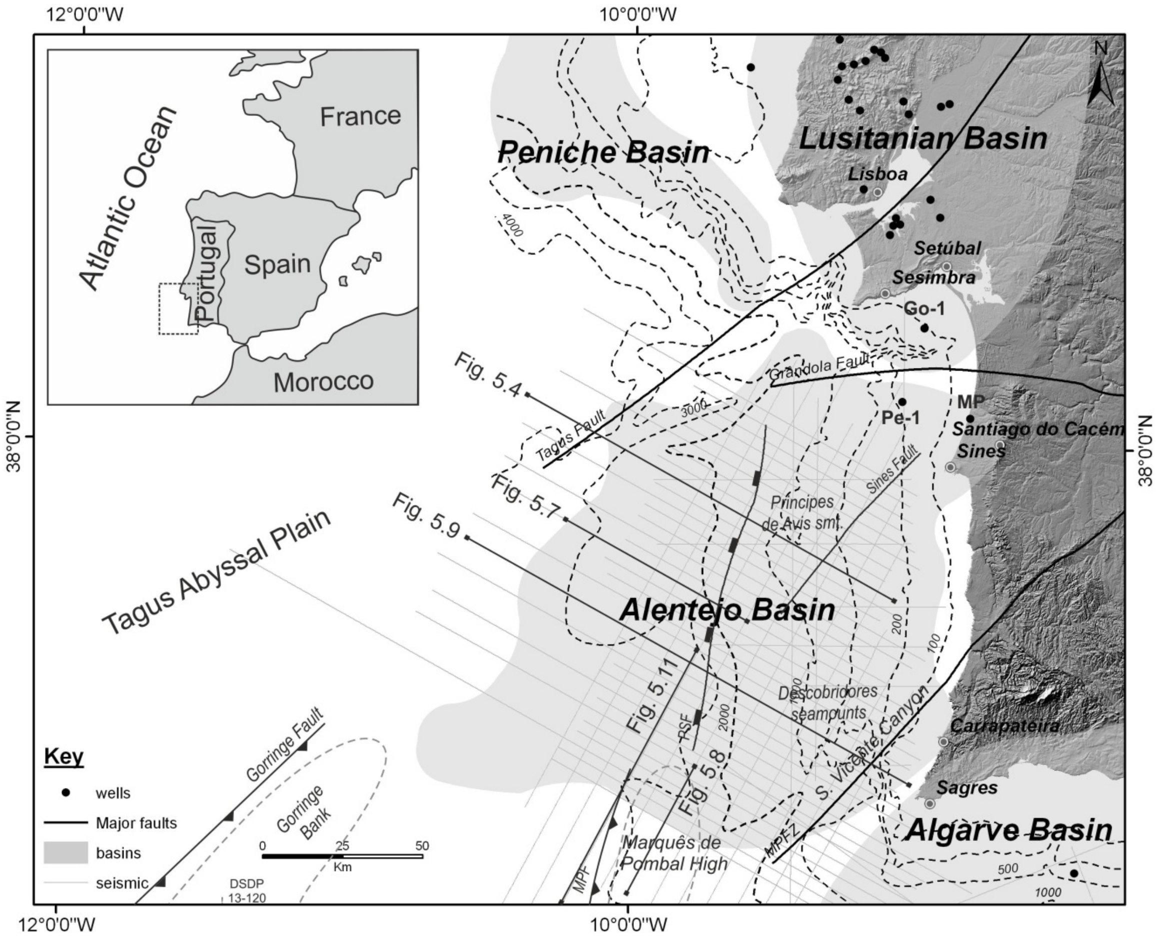

Figure 5.1 - Location of the study area and main physiographic features on the SW Iberian margin. PSF, Pereira de Sousa Fault; MPFZ, Messejana–Plasencia Fault Zone.

This chapter presents an overview of the evolution of the SW Iberian margin in the context of the opening of the North Atlantic and westernmost Tethys (i.e. during continental extension and subsequent basin inversion). The mechanisms and relative timings of tectonic compression throughout the margin are investigated. This chapter presents: 1) a seismic-stratigraphic interpretation of syn- to post-rift strata deformed by compressive events; 2) a description of the distinct post-rift structural styles; 3) a description of the effect of Cenozoic compression from regions of thick continental crust to the thinned distal margin. The results are used to estimate the onset and duration of compressive events across the Southwest Iberian margin, where contour currents, low sedimentation rates and canyon erosion predominate. Moreover, this chapter investigates the mechanisms of compression controlling crustal shortening on the proximal and distal margins. Results based on the interpretations of the discrete structural sectors allow, for the first time, a comprehensive data analysis of structural styles in the ocean–continent transition (OCT) zone of Southwest Iberia.

5.2. Data and Methods

This work uses extensive 2D multichannel seismic datasets from Southwest Iberia, imaging the area east of the Tagus Abyssal Plain (Fig. 5.1). Seismic data were tied to the exploration well Pescada-1 (Pe-1), dredge data (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Oliveira, 1984) (Fig. 2.13 and 3.3) and outcrop information from Santiago do Cacém, Bordeira and Sagres (Oliveira, 1984; Ramalho and Ribeiro, 1985; Ribeiro et al., 1987; Inverno et al., 1993). On the distal margin, away from well control and dredge information, the seismic stratigraphy criteria of Mitchum et al. (1977a) were applied to identify main sequence boundaries. The seismic-stratigraphic criteria of Prosser (1993) and Ravnås and Steel (1998) were used to characterize syn-rift units. The interpretation of sedimentary responses to tectonic compression followed the work of Cartwright (1989) and Hayward and Graham (1989).

The stratigraphic framework proposed here was based on information from outcrops and exploration boreholes from west Iberia (Witt, 1977; GPEP, 1986; Wilson, 1988; Azerêdo et al., 2003; Rey et al., 2006) (Fig. 5.2). The integration of these datasets allowed the recognition of the principal megasequences (sensu Hubbard et al., 1985a) characterizing the syn-rift to post-rift evolution of Southwest Iberia (Alves et al., 2009; Pereira and Alves, 2011) (see chapter 4).

5.3. Geological framework

5.3.1. Physiography and structure of the SW Iberian margin

The Southwest Iberian margin extends from the offshore prolongation of the Messejana-Plasencia Fault Zone to the Grândola Fault, and from the Tagus Abyssal Plain to the coastal outcrops of Sagres, Bordeira, Sines, Santiago do Cacém and Sesimbra (Fig. 5.1).

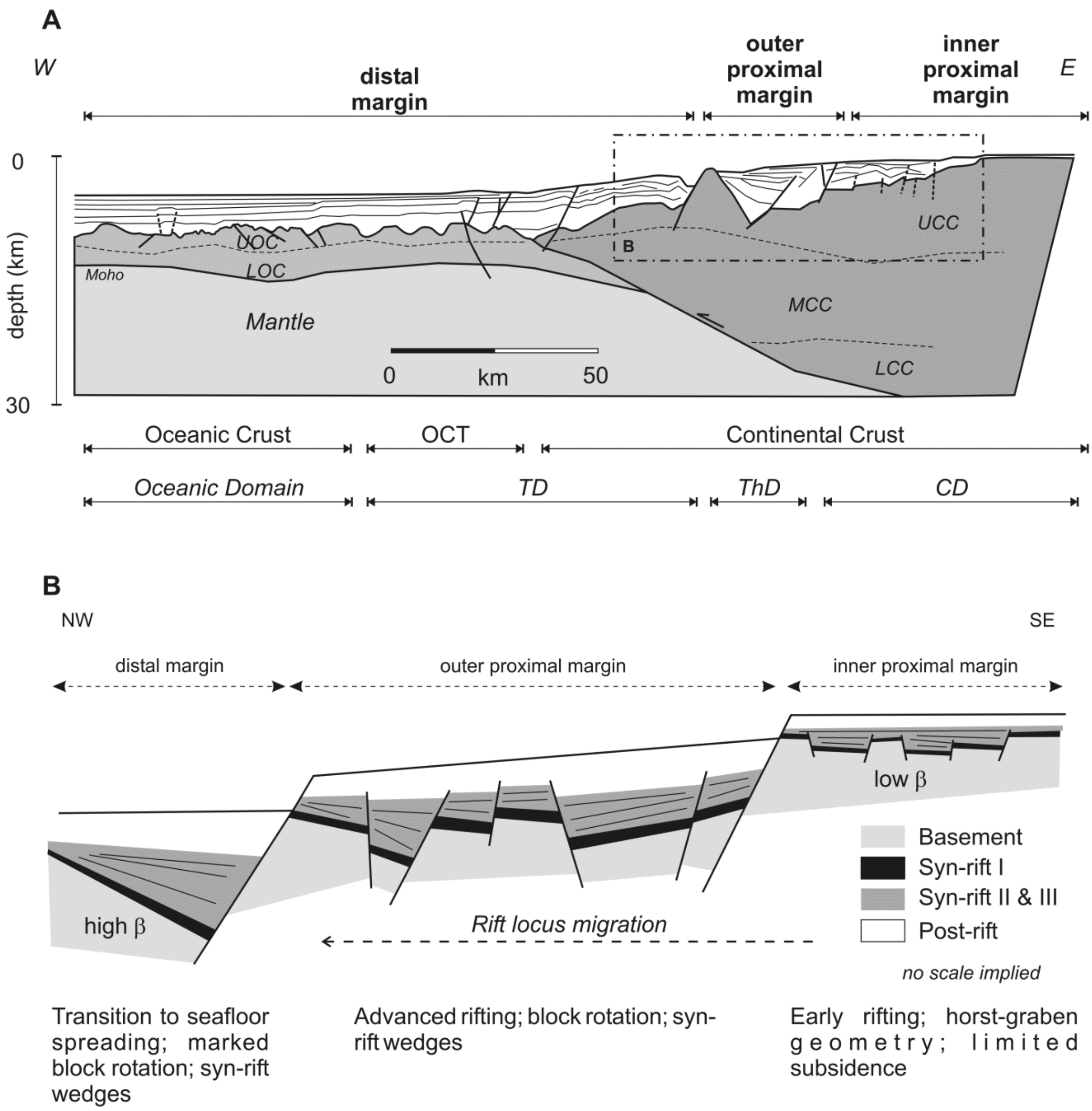

Figure 5.2 - Crustal segmentation on the rifted margin of SW Iberia. A - Segmentation and the deep crust geometry; modified from Afilhado et al. (2008). OCT, ocean-continent transition; TD, transitional domain; ThD, thinned domain; CD, continental domain; UOC, upper oceanic crust; LOC, lower oceanic crust; UCC, upper continental crust; MCC, middle continental crust; LCC, lower continental crust. B - Schematic representation, from the proximal to distal margins showing the distinct geometries of the rifted margin and relative rift-locus migration.

Its present-day morphology is marked by a wide continental slope, gently dipping to the west, on which the Príncipe de Avis and the Descobridores Seamounts are two prominent features (Fig. 5.1). The Pereira de Sousa Fault and the Marquês de Pombal High bound the transition to the deep-water domain of the Tagus Abyssal Plain.

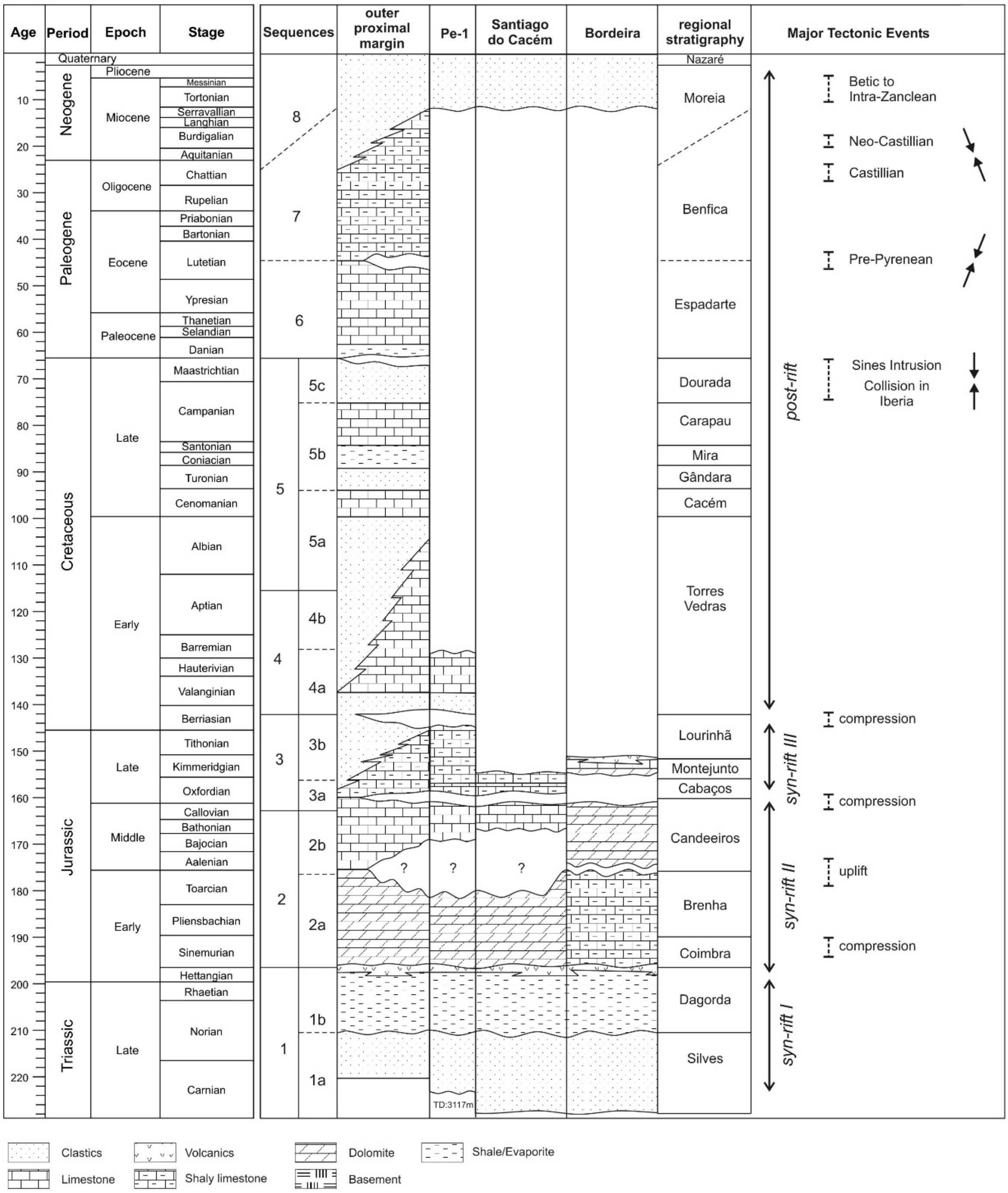

Figure 5.3 - Simplified lithostratigraphy, interpreted sequences and major tectonic events from the Alentejo Basin. Onshore lithostratigraphy based on GPEP (1986), Azerêdo et al. (2003), Rey et al. (2006) and Alves et al. (2009). Outer proximal margin lithologies based on Alves et al. (2009). Mesozoic compressive events from Terrinha et al. (2003). Cenozoic compressive events from Alves et al. (2003a).

The SW Iberian margin can be subdivided into distinct rift-related structural sectors: the inner proximal, outer proximal and distal margins (Manatschal and Bernoulli, 1998, 1999; Wilson et al., 2001; Alves et al., 2009; Pereira and Alves, 2010b, 2011) (Fig. 5.2) (see Chapter 4 for additional details). The distinct segmentation of the margin resulted from multi-phase extension and rift locus migration prior to continental breakup, which occurred in the Tagus Abyssal Plain region (Pereira and Alves, 2011).

The inner proximal margin is characterized by limited tectonic subsidence and syn-rift deposition, whereas the outer proximal margin is characterized by multiple rotational fault blocks and in growth strata revealing significant subsidence during the Mesozoic (Pereira and Alves, 2011). The distal margin, broadly extending west of the Pereira de Sousa Fault, comprises highly-rotated fault blocks likely rooted on deep crustal detachments similar to those described from the Galicia margin (Pérez-Gussinyé et al., 2001; Wilson et al., 2001). In this sector of the margin, syn-rift seismic packages reveal thick Late Triassic to earliest Cretaceous growth strata (Pereira and Alves, 2011).

The distal margin extends from a thinned continental crust domain to the oceanic crust across the OCT (Wilson et al., 2001; Tucholke et al., 2007; Tucholke and Sibuet, 2007). However, between the Tagus Abyssal Plain and the proximal margin of Southwest Iberia, the boundary and nature of the OCT are still under debate (Mauffret et al., 1989a; Pinheiro et al., 1992; Srivastava et al., 2000; Rovere et al., 2004; Tucholke and Sibuet, 2007; Afilhado et al., 2008). At the Gorringe Bank, the exhumed mantle ridge, composed mainly of highly-serpentinized peridotites enclosing gabbros and extrusive rocks, is interpreted to depict the OCT (e.g. Jiménez-Munt et al., 2010)(Fig. 5.1).

Southwest Iberia can also be subdivided into distinct crustal domains: the continental domain, the thinned continental crust, the highly-extended transitional domain and the oceanic domain, each with associated compressive features (Afilhado et al., 2008; Neves et al., 2009) (Fig. 5.2). The limited width of the thinned domain (roughly coinciding with the OCT) contrasts with the wider OCT boundary of the NW Iberian segments (Afilhado et al., 2008; Neves et al., 2009) (Fig. 5.2). East-dipping crustal reflections broadly positioned 150 km west of the São Vicente Canyon mark the westernmost position of the OCT, defining the onset of oceanic crust formation (Cunha et al., 2010a).

Breakup in Southwest Iberia is interpreted to have occurred by the Tithonian–Berriasian (M20–M17 magnetic anomalies) (Mauffret et al., 1989a; Hiscott et al., 1990; Srivastava et al., 2000), or in the Hauterivian (M10–M8 anomalies) (Pinheiro et al., 1992; Pinheiro et al., 1996; Tucholke et al., 2007; Tucholke and Sibuet, 2007).

5.3.2. Regional syn-rift tectonics

Continental rifting in West Iberia occurred from the Late Triassic (and earlier?) to the Aptian–early Albian (Boillot et al., 1979; Wilson, 1988; Tucholke and Sibuet, 2007). Throughout the North Atlantic, continental rifting led to the northward propagation of sea-floor spreading (e.g. Hiscott et al., 1990; Tucholke and Sibuet, 2007). In West Iberia, four major syn-rift phases are recognized: I) an initial phase, which occurred during the Late Triassic to the earliest Jurassic (Hettangian); II) a second extensional phase, which was initiated by the earliest Jurassic in association with northern Central Atlantic rifting; III) Late Jurassic to the Early Cretaceous extension reflecting a gradual transition to sea-floor spreading in SW Iberia–South Newfoundland, together with increased subsidence in the Lusitanian and Peniche Basins; and IV) a final rifting phase (Berriasian to Aptian or Albian), mainly expressed in central and NW Iberia margin and offshore Newfoundland (Alves et al., 2006; Tucholke and Sibuet, 2007; Alves et al., 2009). Syn-rift phases I–III are imaged across the margin, from its proximal to distal zones, by distinct structural styles, highlighting an increased tilt-block subsidence towards the West (Alves et al., 2009; Pereira and Alves, 2011). New studies involving the modelling of lithospheric break-up at the continent–ocean transition zone (Afilhado et al., 2008) and subsidence analyses (Cunha et al., 2009) also concluded that rifting on the SW Iberian margin comprised three major events of extension.

5.3.3. Post-rift tectonics

A second tectonic episode in SW Iberia is associated with continental drift and subsequent collision of the Iberian microplate with the European and African plates

(Boillot et al., 1979; Mougenot et al., 1979; Malod and Mauffret, 1990; Srivastava et al., 1990b).

A first major compressive event within this episode is dated as Late Cretaceous to middle Eocene, when Iberia was connected to North Africa and the active plate boundary was located at the Bay of Biscay (Malod and Mauffret, 1990; Srivastava et al., 1990b; Pinheiro et al., 1996). Crustal shortening resulted from north-south to NE–SW convergence that formed the Pyrenees (Mougenot et al., 1979; Ribeiro et al., 1990; Sainz and Faccenna, 2001; Cloetingh et al., 2002). During the latest Cretaceous, the inner proximal margin was also deformed by the intrusion of the large igneous bodies of Sines, Sintra and Monchique (e.g. Miranda et al., 2009).

Eocene compression resulting from the reactivation of NE-SW rift-related faults is recorded along the West Iberian margin, although its effects are most evident in the northern basins (Boillot et al., 1979; Mougenot et al., 1979). On the Galicia margin, mid- to Late Eocene compression resulted in large-scale buckling of the OCT and localized reverse faulting (Masson et al., 1994; Vázquez et al., 2008). In the Lusitanian and Peniche Basins, Cenozoic inversion is mainly recorded in regions of thin-skinned tectonics, where overburden units are detached over a shaley–evaporitic Hettangian sequence (Ribeiro et al., 1990; Alves et al., 2006).

During the Oligocene, Iberia (now part of the Eurasian plate) established its boundary at the Azores–Gibraltar Fault Zone, as a result of NNE–SSW convergence with North Africa (Ribeiro et al., 1990; Srivastava et al., 1990b; Pinheiro et al., 1996; Cloetingh et al., 2002). At the end of the Oligocene (Chattian), a new compressive event resulted in regional uplift (Mougenot et al., 1979; Pinheiro et al., 1996; Alves et al., 2003a).

Compression persisted on the West Iberian margin from the Miocene to the present day, in association with the collision of Iberia with North Africa (Ribeiro et al., 1990; Cloetingh et al., 2002). This resulted in the reactivation of faults and folds aligned NE–SW to WSW–ENE, often showing left-lateral movement (Ribeiro et al., 1990). Within this setting, crustal rupture beneath the Marquês de Pombal High has been interpreted as one of the possible epicentres for the 1755 "Lisbon earthquake", with estimated magnitude of 8.7 (Terrinha et al., 2003; Zitellini et al., 2004).

Table 5.1 - Principal megasequences from the Southwest Iberian margin. IPM – Inner Proximal Margin, OPM – Outer Proximal Margin and DM – Distal Margin.

Mega-sequence	Probable age of base	Internal character	Type of base	Related major events
8	Miocene (Chattian-Burdigalian)	*IPM/OPM*: sub-parallel to wavy, hummocky. *DM*: sub-parallel	Erosional; conformable	Iberia-N Africa collision
7	Eocene (Lutetian)	*IPM/OPM*: sub-parallel to hummocky, occasionally transparent. *DM*: sub-parallel, occasionally transparent	Erosional; conformable	Iberia-Eurasia collision at Pyrenees
6	Maastrichtian-Danian(?)	*IPM/OPM*: chaotic to sup-parallel reflections. *DM:* sub-parallel to chaotic reflections	Erosional, conformable	Sines intrusion
5	Mid Aptian	*IPM*: absent(?). *OPM*: sub-parallel to chaotic reflections. *DM*: sub-parallel reflections	Conformable to paraconformable	Tectonic quiescence(?)
4	Latest Tithonian-earliest Berriasian(?)	Downlaps towards the syn-rift. *IPM/OPM*: Sub-parallel to chaotic reflections. *DM*: chaotic to sub-parallel (often transparent) reflections	Erosional to conformable	Rifting to breakup at Lusitanian Basin and Jeanne d'Arc Basin
3	Early-Middle Oxfordian	Wedge reflectors thickening towards master faults; sub-parallel at inner proximal margin; chaotic reflections	Angular unconformity to conformable; erosional	Rifting to breakup at Tagus Abyssal Plain; rifting at Lusitanian and Peniche Basins
2	Hettangian/ Sinemurian	Sub-parallel to wedge reflectors; growth towards master faults	Angular unconformity to conformable	Rifting at SW Iberia; Rifting to breakup at Central Atlantic, Africa-Nova Scotia
1	Carnian(?)	Sub-parallel to divergent reflections, chaotic reflections	Angular unconformity; erosional	Early continental North Atlantic extension

5.4. Seismic stratigraphy

The analysis of the regional lithostratigraphy based on outcrop, dredge and borehole data, together with the interpretation of the seismic data on the SW Iberian margin, allows the definition of eight distinct megasequences bounded by major unconformities (sensu Hubbard, 1988) (Figs 5.3 and 5.4). Detailed information on each of the megasequences observed, and related tectonic events, is summarized in Table 5.1 and in chapter 4.

5.4.1. Syn-rift megasequences

Megasequence 1 (Norian?–Hettangian), synchronous with continental extension across the North Atlantic and western Tethys, is represented by continental red bed siliciclastic rocks and evaporites (Fig. 5.2) (Oliveira, 1984; Azerêdo et al., 2003). On seismic data, megasequence 1 overlies the acoustic basement, interpreted to comprise accreted Palaeozoic terranes (Fig. 5.4). Between Bordeira and Sagres, a major Late Triassic angular unconformity observed at outcrop marks the onset of continental extension. Seismic units chiefly comprise subparallel to chaotic reflections, or in some cases wedge reflections thickening towards normal.

Syn-rift megasequence 2 (Hettangian–Callovian) shows marked stratal growth on the outer proximal and distal margins (Fig. 5.4). The internal seismic character of growth strata is dominated by divergent reflections, sometimes chaotic, often recognized by presenting downlap onto megasequence 1. Megasequence 2 is bounded at the top by a regional Callovian-Oxfordian unconformity (e.g. Azerêdo et al., 2002a). The final syn-rift megasequence (megasequence 3, middle Oxfordian–Berriasian) is characterized by thick growth strata. It is best expressed on the outer proximal and distal margin and represents the transition to sea-floor spreading (Fig. 5.4). It is bounded at its top by a Late Jurassic (Tithonian) to early Cretaceous (Berriasian?) unconformity interpreted to reflect continental breakup occurring in the Tagus Abyssal Plain region.

5.4.2. Post-rift megasequences

Megasequence 4 (Berriasian–Aptian) is characterized at the base by parallel to chaotic reflections downlapping the latest Jurassic–earliest Cretaceous unconformity (see Table 1 for seismic facies and detailed description). This unit shows significant thickness variations from the proximal to the distal margin (Fig. 5.4).

In exploration well Pe-1, the lowermost sequence (sequence 4a, Berriasian–Barremian) is represented by shallow marine sandstones and limestones. Sequence 4b (Barremian–Aptian), absent or with limited expression on the proximal margin, is best observed on the distal margin. The top of megasequence 4 is characterized in some areas of the proximal margin by significant erosion (Fig. 5.4).

Megasequence 5 (Aptian to latest Cretaceous or earliest Palaeocene) comprises the first strata deposited after complete breakup of the Atlantic margins of Iberia and Newfoundland. This megasequence is absent in the shallower portion of the margin (as observed in Pe-1 and Go-1). It is characterized on the outer proximal margin by a thick prograding seismic unit with subparallel to chaotic reflections, interpreted to represent a deltaic wedge. This unit was dredge sampled and comprises Late Cretaceous deep marine limestones and sandy limestones (Matos, 1979) (Figs. 2.13, 3.3 and 5.4). The top of this prograding unit is intensely eroded, suggesting that it was deposited prior to regional uplift resulting from the intrusion of the Sines igneous massif in the Late Cretaceous. In some parts of the outer proximal margin erosion is estimated to exceed 500 m (Fig. 5.4). The distal margin reveals thick seismic sequences with subparallel reflections blanketing the deeper domain of the proximal margin of Southwest Iberia to the Tagus Abyssal Plain (Fig. 5.4).

Megasequence 6 (Palaeocene to mid-Eocene) reflects deposition between the hiatus generated by late Cretaceous uplift and prior to the first major compressive event affecting the margin by the middle Eocene. On the inner proximal margin, the lack of outcrop and dredge information prevents the identification of distinct depositional units. On the outer proximal margin, megasequence 6 shows moderate thickness (up to 500 ms TWT (two-way travel time)) and is characterized by downlapping subparallel to chaotic or transparent reflections (Fig. 5.4). The distal margin reveals thicker deposition (c. 200–900 ms TWT) blanketing the Cretaceous sequences. Megasequence 6 is mainly characterized by subparallel prograding reflections (Table 5.1).

On the proximal margin, the base of megasequence 7 (Late Eocene to Early Miocene) is characterized by significant erosion ranging from the Palaeocene–Eocene to the Cretaceous. On the distal margin, this boundary is characterized by the presence of internal reflections showing downlap onto late Eocene anticlines (Fig. 5.4). Internal reflections on the proximal margin are mainly chaotic to subparallel, whereas on the distal margin, subparallel reflections dominate.

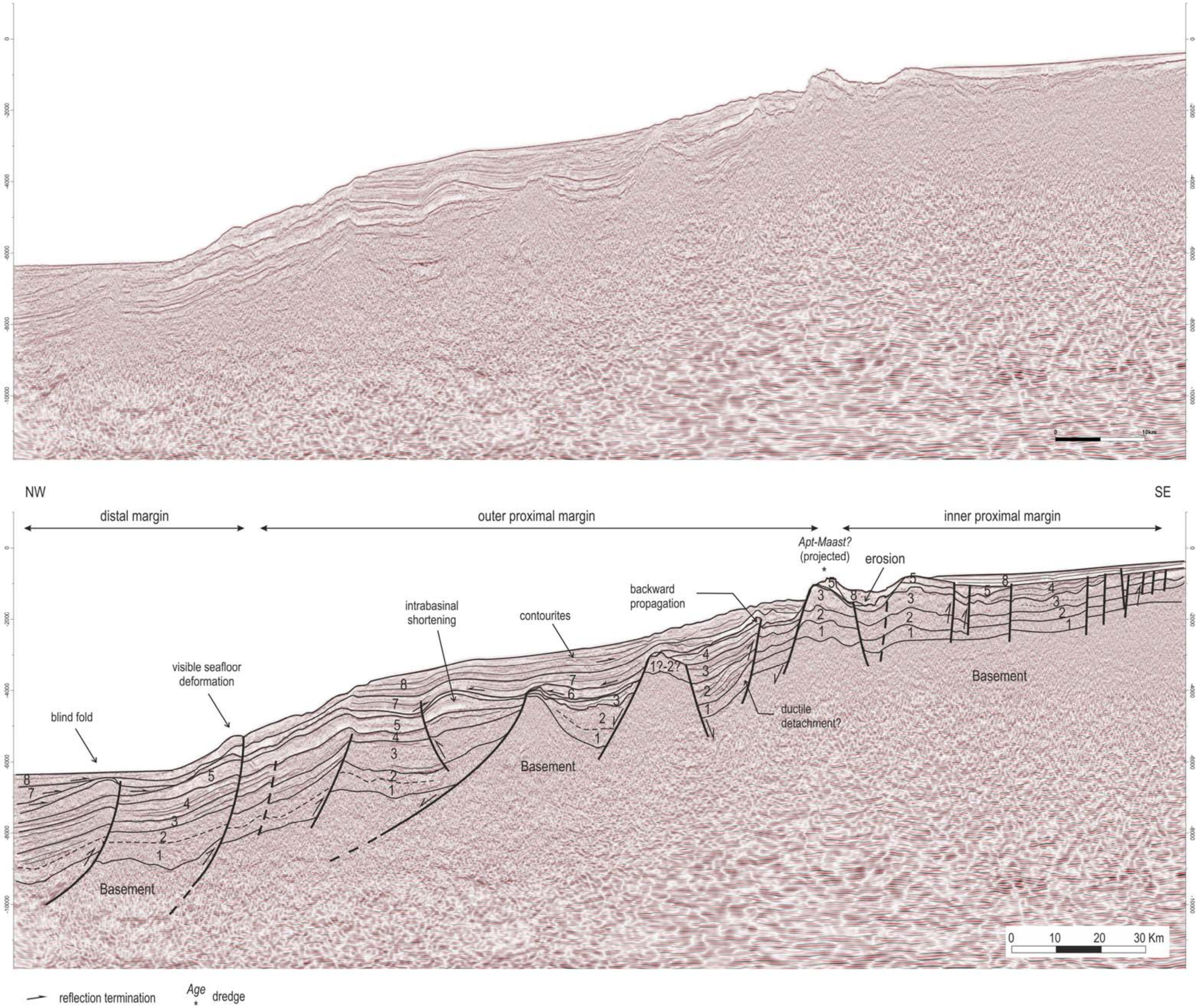

Figure 5.4 - Seismic line across the SW Iberian margin showing syn-rift segmentation and correlative compressive features. Note the effects of Paleogene to recent shortening represented by blind faulting, dissimilar folding and backthrusting across the margin.

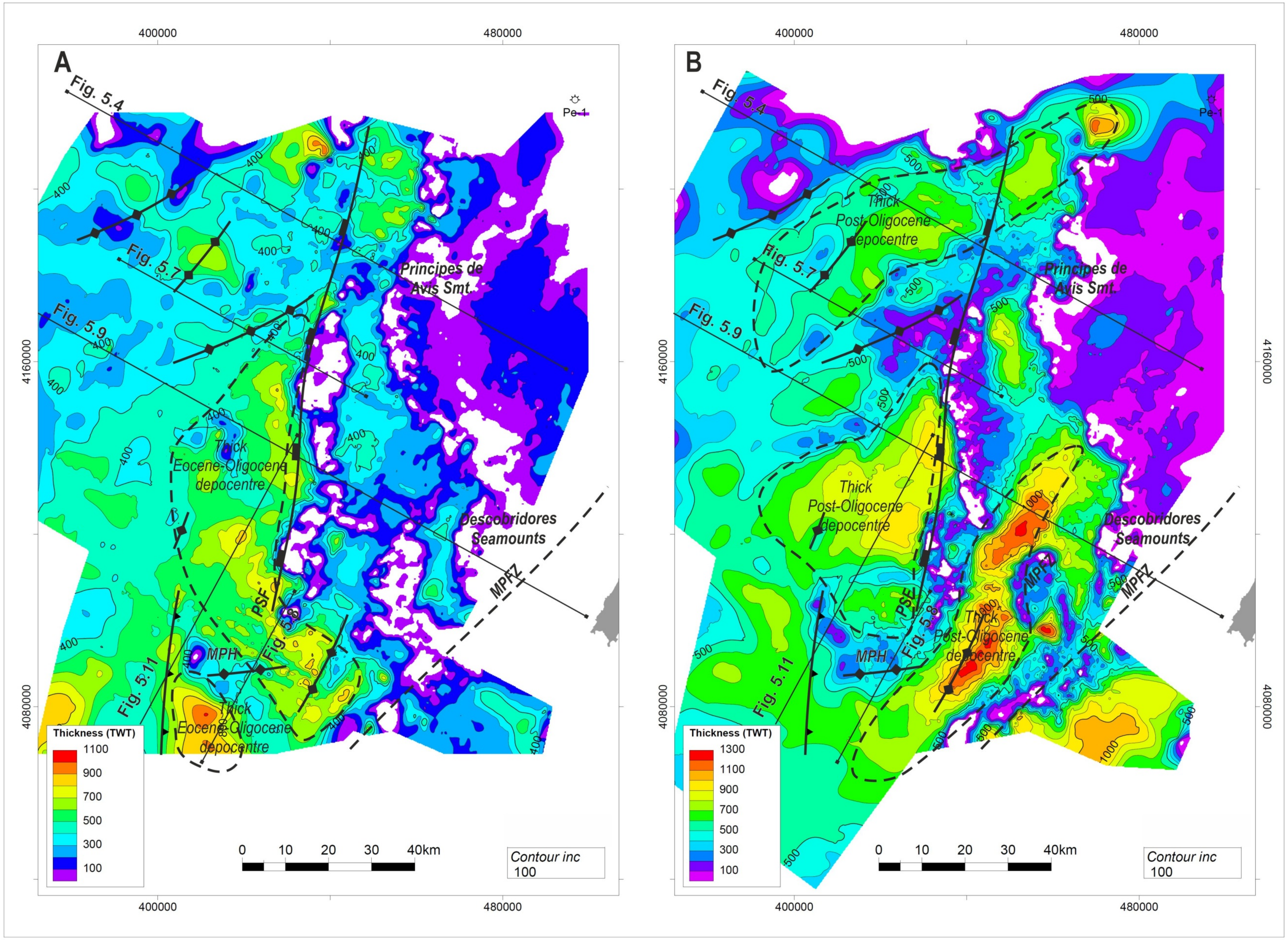

Figure 5.5 - Thickness TWT (ms) maps and principal depocentres of syn-tectonic Cenozoic megasequences. A - Megasequence 7 (Eocene–late Oligocene). B - Megasequence 8 (late Oligocene–present). Major faults and fold axial traces are projected.

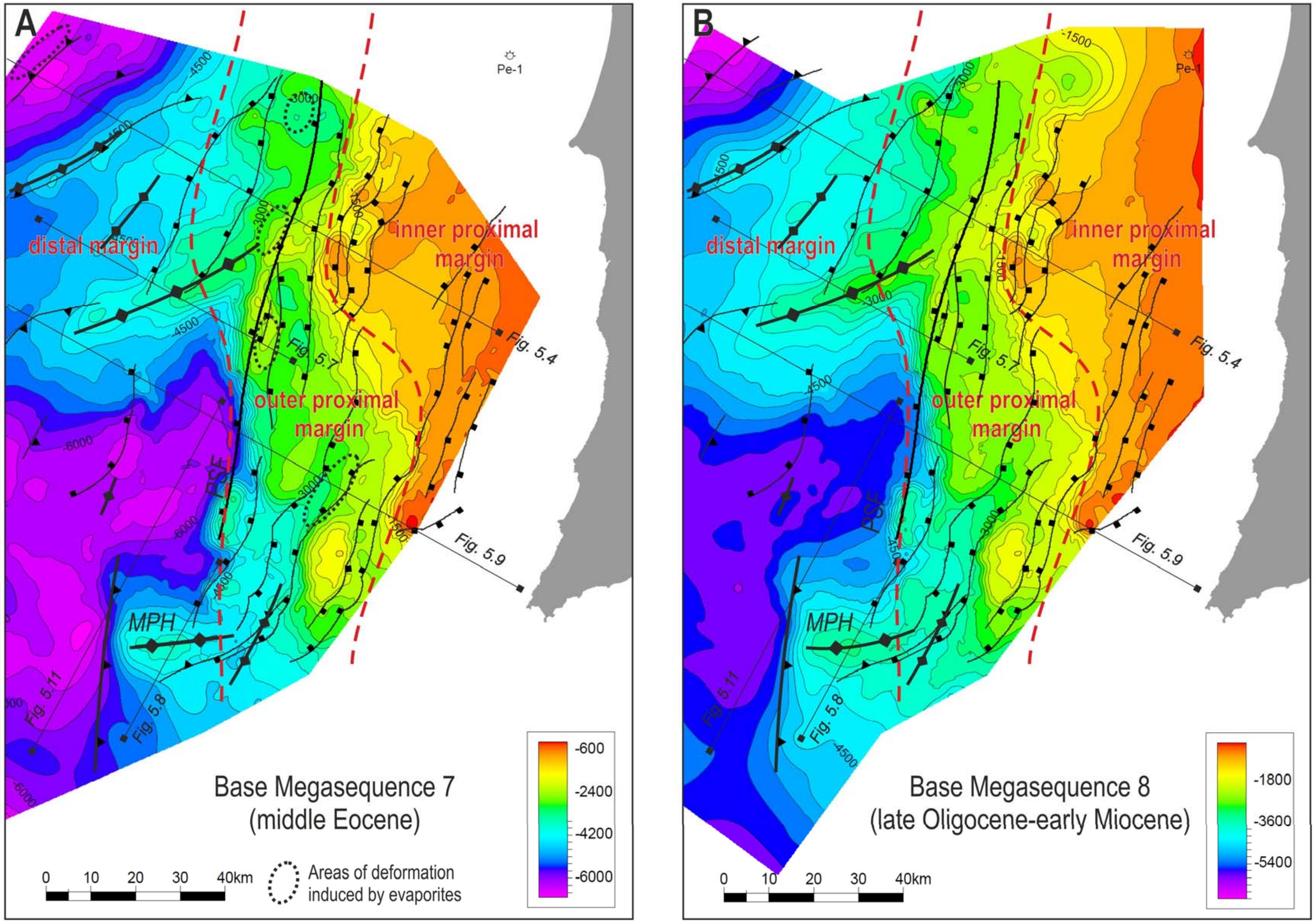

Figure 5.6 - Structural TWT maps of major Cenozoic unconformities at Alentejo Basin. A - Base mid-Eocene. B - Base Miocene. Major faults are projected. Dotted areas show the location of the principal domains of shortening in relation to inherited syn-rift faults likely associated with detachments rooted on evaporite units. Red dashed lines show the distinct structural sectors of the continental rifted margin.

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Thickness variations in this megasequence reveal thick depocentres on the distal margin (Fig. 5.5a). Dredge samples from the proximal margin collected shallow neritic limestones (Baldy, 1977; Matos, 1979; Oliveira, 1984) (Figs. 2.13 and 3.3).

The final depositional megasequence (megasequence 8, Miocene to recent) is characterized at the base by downlapping reflections on the distal margin and erosion on the proximal margin (Fig. 5.4).

The thickness of megasequence 8 can be up to 1.0 s TWT on the inner proximal margin. Deposits within this unit are mostly composed of Miocene to Holocene shallow marine siliciclastic deposits, as shown by well Pe-1 and dredge data. On the outer proximal margin, strata in Megasequence 8 show subparallel to hummocky reflections, with prevalence of plastered deep oceanic sediments (*s.l.,* contourites) and interbedded turbidites on structural highs. The thickest depocentres are located on the outer proximal and distal margin (up to 1.3 s TWT) (Fig. 5.5b).

5.5. Structural evolution of post-rift basins

5.5.1. Deformation on the inner proximal margin

Compression on the inner proximal margin is dominated by reverse faulting (rather than folding) in contrast to the broad compressive structures observed to the west (Fig. 5.4). Faults in this sector are broadly aligned NE–SW, subvertical or verging to the SE, suggesting that post-rift compression reactivated older syn-rift sub-basins (Fig. 5.6). Folding is characterized by minor anticlines near fault zones, which along with the underlying thick continental crust indicate strong resistance to compression. However, the Mesozoic is highly-deformed in the vicinity of the Sines igneous intrusion.

5.5.2. Compressional structures on the outer proximal margin

Compression on the outer proximal margin is characterized by reverse faulting and short-wavelength anticlines, mainly located on the periphery of syn-rift sub-basins (Figs. 5.4 and 5.7). Such distribution shows the variable response to compression in the different sectors of the margin.

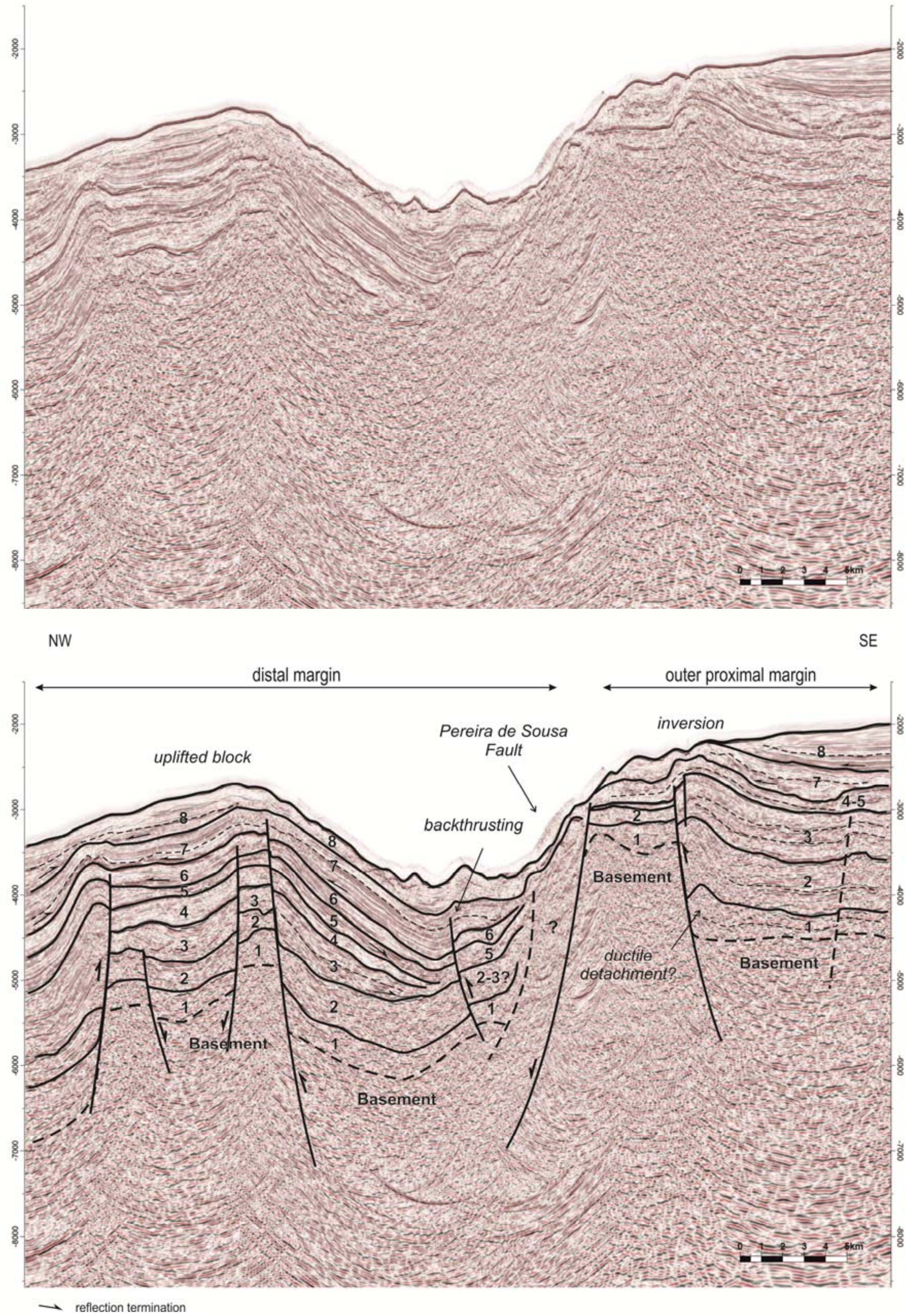

Figure 5.7 - Seismic line imaging distinct compressive features across the outer proximal to distal margin. Shortening in this area includes reverse faulting, dissimilar folding and backthrusting of syn- to post-rift megasequences, some likely associated with proximal margin detachments at ductile evaporite-shale units (Megasequence 1).

Reverse faults broadly strike NE, dipping to the NW (Fig. 5.6). Analysis of seismic data suggests that such faults link to deep detachments within the shaley–evaporitic unit of the Dagorda formation (Fig. 5.7). In parts of the outer proximal margin, compression and inversion suggest backward propagation *sensu* Hayward and Graham (1989) (Fig. 5.4). Occasionally, intrabasinal shortening can be observed (Fig. 5.4). In such cases, low-amplitude anticlines are bounded by inherited syn-rift faults. Crustal shortening on the outer proximal margin varies from around 5–10% to 15–20%.

5.5.3. Compression on the distal margin

The distal margin is characterized by highly-rotated fault blocks, overlain by superimposed thick syn-rift megasequences and post-rift draping deposits (Fig. 5.4). Compressive tectonic styles in this sector are diverse and their expression along the margin, varies considerably, with the majority of shortening accommodated close to the transition to the outer proximal margin along the Pereira de Sousa Fault (Figs. 5.7 and 5.8) and the Marquês de Pombal High (Figs. 5.6 and 5.10).

Two distinct families of faults show that rift-inherited reverse faults broadly strike NNE–SSW, whereas post-rift faults are aligned SW-NE and dip to the northwest. To the North, deformation resulting from compression is dominated by multiple piggy-back thrusts and anticlines broadly aligned SW–NE, verging to the SE, usually deforming the sea floor (Fig. 5.4). However, in some cases, such folding is not expressed at the sea floor, but is evident at depth as blind folds (Fig. 5.4). Crustal shortening in this area is estimated to approach 10%.

Along the Pereira de Sousa Fault, compression is expressed by uplift of the footwall and continued rotation and subsidence of the hanging wall, resulting in the formation of minor reverse faulting, small localized backthrusting anticlines and westward backward propagation (Fig. 5.7). Additionally, the segment west of the Pereira de Sousa Fault reveals a complex structure with multiple thrusts verging west and east over an uplifted block, with an estimated shortening of about 25% (Fig. 5.7). This value contrasts with other estimates along the margin and is discussed in the following section.

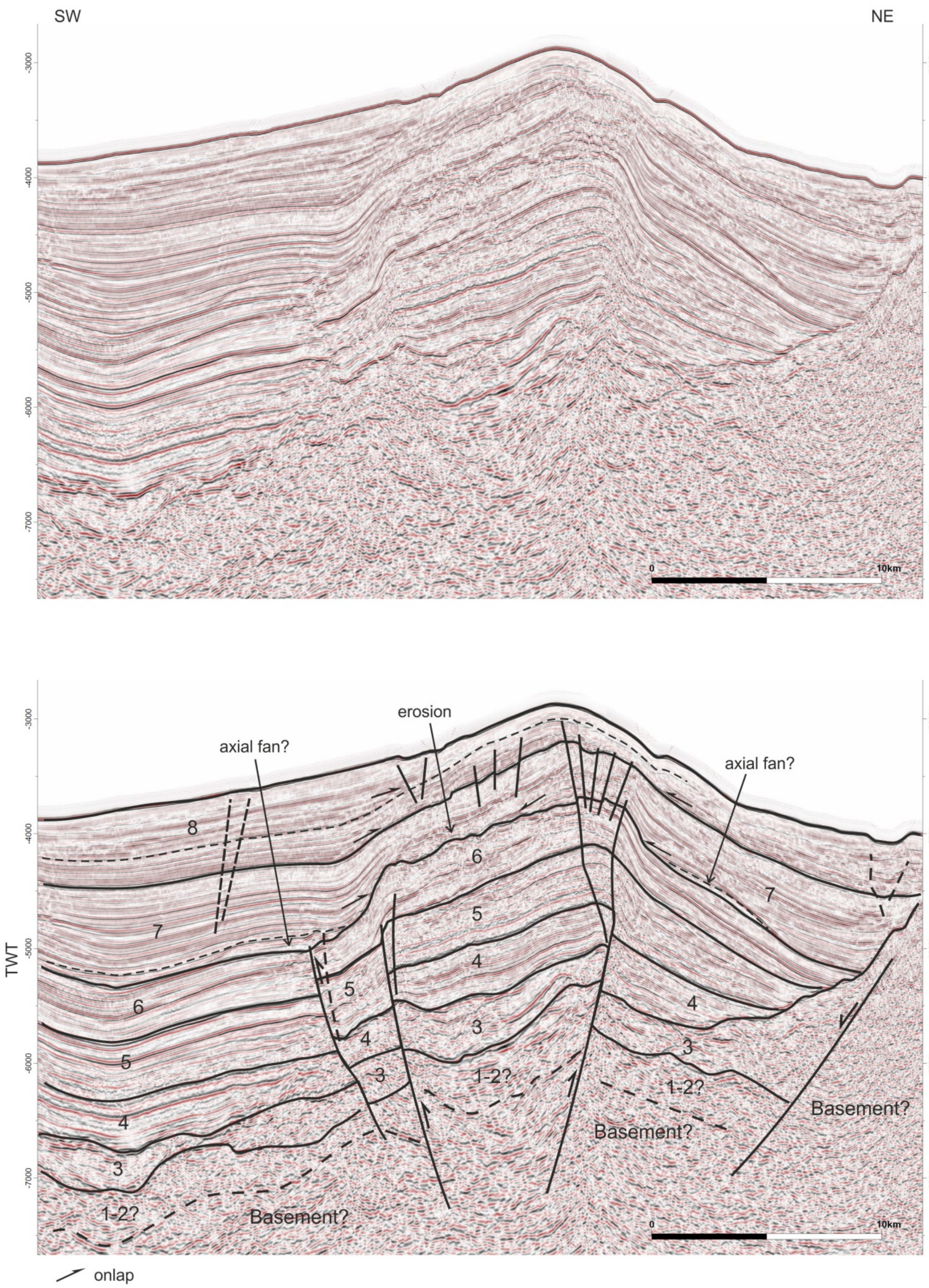

Figure 5.8 - Transition zone between continental and oceanic crust across the SW Iberian margin.

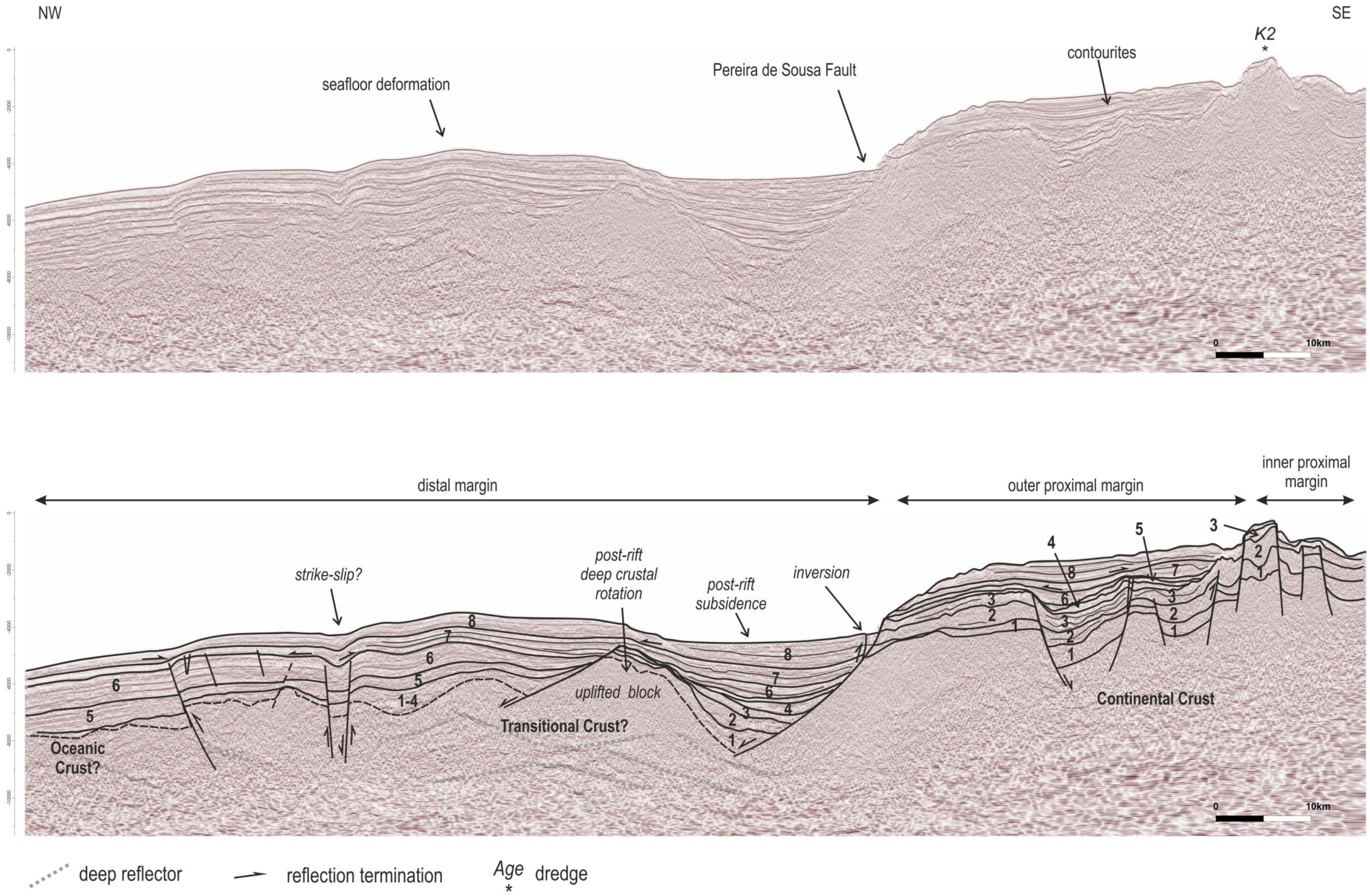

Figure 5.9 - Effects of compression across the Marquês de Pombal High. Onlapping reflections on top of an erosional surface mark the onset of an incipient mid-Eocene structure. Megasequence 7 reveals significant thickness variations at the hinge of the anticline.

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The Marquês de Pombal High (Fig. 5.9), is a prominent tectonic feature with impressive sea-floor deformation (Figs. 5.1, 5.9 and 5.10). Its geometry demonstrates that the evolution of this structure is complex and that it results from the multiple and long-lived compressive events affecting the Southwest Iberian margin. The analysis of the deep structure of the Marquês de Pombal High suggests this feature to comprise a highly-rotated syn-rift tilt block subsequently inverted during the convergence of a middle–upper continental crust indentor (sensu Neves et al., 2009) rooted on a lower continental crust detachment surface (Figs 5.3 and 5.10).

Moreover, seismic profiles imaging this structure reveal deep-rooted reverse faults similar to a "flower structure", suggesting transpression (Fig. 5.9).

Megasequence 7 (mid-Eocene–late Oligocene) and megasequence 8 (late Oligocene–present) are thinner at the hinge zone (Fig. 5.5). These sequences are folded following a WSW–ENE trend, with the short limb of the anticline suggesting northward vergence (Figs. 5.6 and 5.9). This kinematic indicator is in agreement with the Eocene–Miocene regional compression interpreted by Mougenot et al. (1979) and Ribeiro et al. (1990). Downlapping reflections marking the onset of compression at the hinge zone reveal these to have changed position with time (Fig. 5.8).

The analysis of the seismic data and the sea-floor expression of the Marquês de Pombal High reveal a north–south thrust fault verging to the west, the Marquês de Pombal Fault, which partly controls the present-day (post-Miocene?) evolution of the margin (Fig. 5.5).

This geometry suggests a change in the direction of compression to accommodate the recent convergence of the Iberian continental plate and the oceanic domain. Shortening at the Marquês de Pombal High (c. 7–10%), differs significantly from other areas in the distal margin. This indicates that compression on the SW Iberian margin was accommodated differently in response to distinct rheological behaviours of the continental crust and overlying syn- to post-rift deposits. Evidence of differential response to compression includes the occurrence of distinct vergence of anticlines, and the different compressive tectonic styles throughout the margin (Fig. 5.10). This character indicates that the deep crustal body forces governing the principal shortening directions on the Marquês de Pombal High record a change in direction from the mid-Eocene to the Miocene. Compression on the distal margin is commonly expressed on the sea floor, demonstrating that this same shortening process is occurring at present.

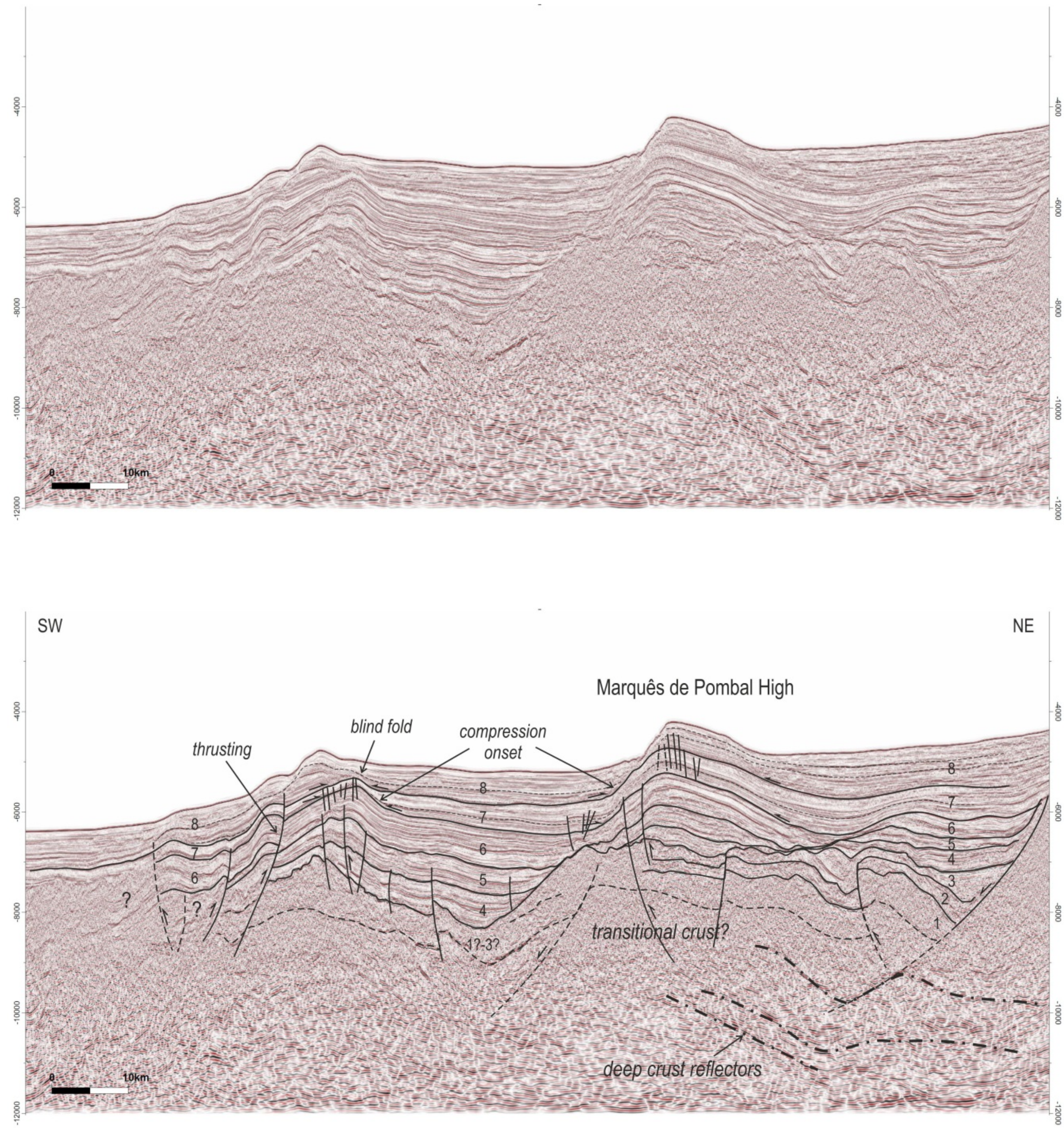

Figure 5.10 - Distinct styles of compression in the region of transitional continental crust. The distinct vergence of the two anticlines should be noted. The deep crustal reflections indicate the position of the thinned continental crust.

5.5.4. The influence of deep-rooted evaporites in post-rift crustal shortening

Seismic data reveal that although the thickness and distribution of the evaporitic succession is not very significant in the study area, it still controls the deformation styles of post-salt units. Inversion structures occur mainly in the outer proximal margin (and possibly in the distal margin), with the formation of narrow anticlines and thrusts being likely related to detachments within evaporitic sequence 1a (Figs. 5.4 and 5.7). Similar examples of thin-skinned tectonics have been described by Ribeiro et al. (1990) at the Sesimbra region.

Inversion structures are primarily located at the boundaries of syn-rift sub-basins. Figure 5.6a shows the approximate position of evaporite-related areas of inversion in the SW Iberia.

5.6. Discussion

5.6.1. Dating compressional events on the SW Iberian margin

The ages of compressive events in SW Iberia have been constrained on the proximal margin by outcrop data, seismic profiles tied to boreholes and low-resolution seismic data. However, on the highly-segmented domains of the outer proximal and distal margin, in the absence of well control or dredges, assigning a probable age to key unconformities and their coeval seismic packages is difficult.

The principal difficulty when correlating compressive events and defining the onset of compression in distinct areas of the margin concerns the continuity of major unconformities and their correlative surfaces. Folding, reverse faulting and uplift on the proximal margin are often accompanied by incision surfaces, but towards the distal margin erosional features are less frequent or below the resolution of seismic data. Estimations of the timing of compression are also hindered by the seismic expression of some contourites and/or distal turbidites (e.g. Faugères et al., 1999). The wavy seismic character of contourites may be incorrectly interpreted as the initiation of compression.

Thus, this work highlights that compressive phases rarely comprise a discrete event. Compression occurs during relatively prolonged periods of convergence and therefore a single basal unconformity defining the onset of deformation is difficult to pinpoint. Furthermore, a compressive phase may not simultaneously be recorded throughout the margin.

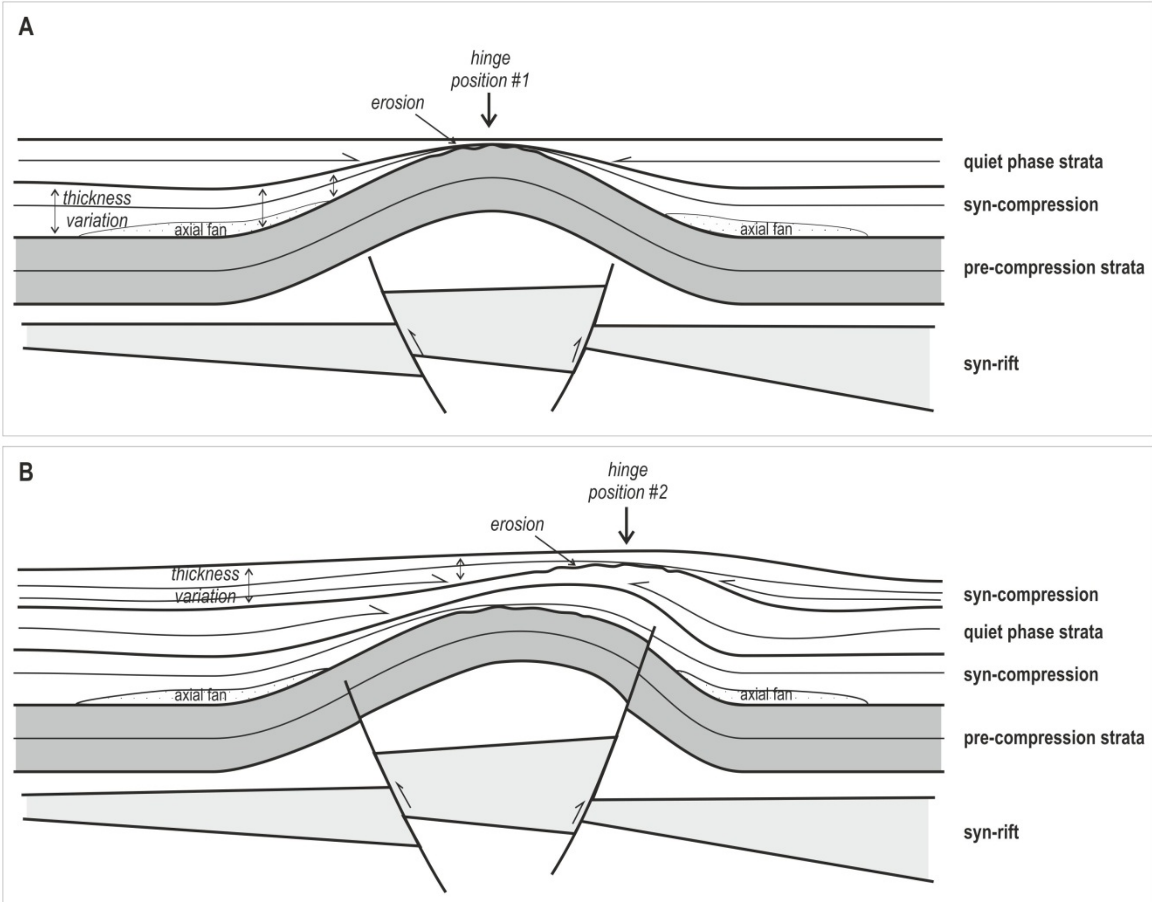

Figure 5.11 - Schematic representation of the criteria for the identification of syn-tectonic compression on the distal margin: (a) Initial formation of incipient anticlines; (b) continued compression with migration of anticline hinges.

The estimation of the onset of compression in the distinct domains of the margin was chiefly guided by the interpretation of several criteria, including: 1) the recognition of regional unconformities; 2) limited deposition in hinge zones; 3) onlapping reflections towards anticline limbs; 4) the deposition of axial fans on fold limbs; and 5) the erosional features crosscutting previous megasequences (Fig. 5.11). The combination of these criteria, together with regional data, allowed the recognition of two main compressive events in SW Iberia, herein interpreted to have been initiated by the middle Eocene (Lutetian?) and by the latest Oligocene (Chattian?) to early Miocene (Burdigalian?).

Detailed analysis of reflections between these major pulses of compression reveals that intermediate shortening events are also significant.

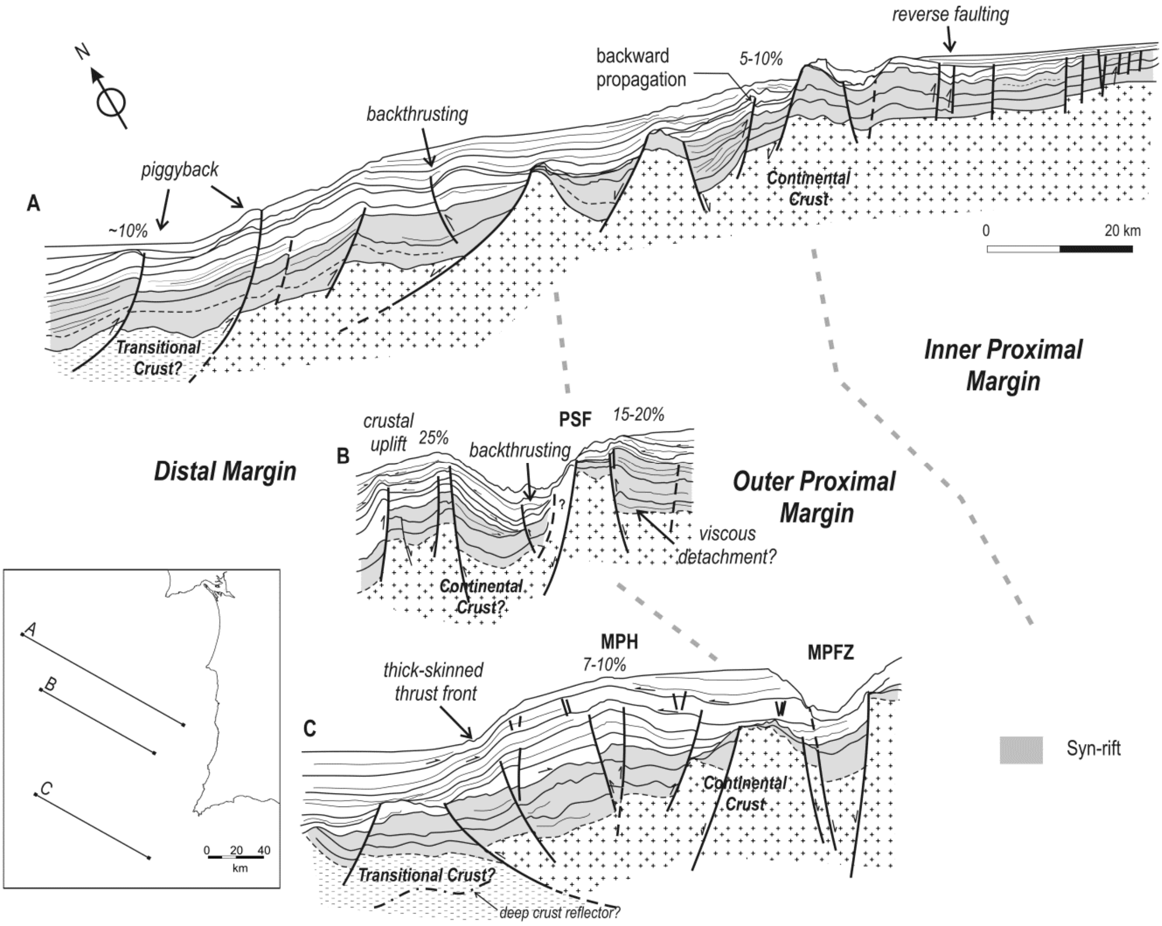

Figure 5.12 - Line drawings depicting the distinct compression structural styles observed on the SW Iberian margin. Percentage values indicate the estimated percentage of shortening. 4X vertical exaggeration.

The data reveal that the minor compressive events recognized between these major episodes are often followed by short-lived periods of quiescence. Such periods of diminished tectonic shortening are characterized by subparallel seismic reflections.

The Marquês de Pombal High clearly depicts this type of relationship (Figs. 5.9, 5.10 and 5.12). Overlying a subparallel to chaotic Early Cenozoic pre-compressive seismic package with relative constant thickness (megasequence 6), the Middle Eocene (Lutetian?) event is marked by the presence of onlapping reflections on immature anticlinal structures (Figs. 5.9, 5.10 and 5.11). Sediment thickness subsequent to this event is diminished in the hinge zone, indicating that syntectonic deposition is controlled by reverse faulting and folding initiated at depth (Fig. 5.5).

Moreover, axial fan deposits at the base of the evolving anticline are the result of hinge erosion or sediment bypass marking the onset of compression. Similar reflection geometries and thickness variations are observed in megasequence 8 above the

Oligocene–Miocene (Chattian?–Burdigalian?) event (Figs. 5.8, 5.10 and 5.11). These features, materializing syntectonic deposition during post-rift compression, are similar to those described from the NE Atlantic (Masson et al., 1994; Doré et al., 2008).

The analysis of isochron data for the post-rift units reveals preferential areas of deposition, which are accompanied by large areas of erosion on the inner proximal margin (Fig. 5.5). Sediment bypass from proximal to distal sectors occurred along distinct pathways, probably controlled by relay ramps and/or transfer faults, canyons and incision surfaces. Sediment was mainly deposited on the distal margin, controlled by growth anticlines and the inherited physiography of the palaeo-seafloor. More evidence of the heterogeneity and diachronous expression of compression is the presence of blind folds (Figs. 5.4 and 5.10). These occur only in parts of the distal margin (North of the Pereira de Sousa Fault and on the Marquês de Pombal High, for instance), and are related to the presence of thin continental crust at depth. This suggests that folding in some areas occurred prior to the latest compressive event or that present-day compression has not yet induced the fold to deform the sea floor. Observation of similar structures on the distal margin suggests that the latter hypothesis is the most likely (Figs. 5.9 and 5.11). In summary, post-Cretaceous to Miocene NW–SE shortening of the Southwest Iberian margin was chiefly controlled by long-lived (and multiphased) Pyrenean–Alpine compression. In contrast, the structure of the distal margin suggests recent convergence between the continental and ocean crustal domains.

5.6.2. Compression and the ocean-continent transition

Assuming an approximate average interval velocity for the crystalline continental crust of about 6.000 m/s presented by Afilhado et al. (2008), and by applying an approximate depth conversion for the interval comprising seafloor to top of acoustic basement, we estimate that continental crust on the inner proximal margin exceeds 20 km in thickness. On the outer proximal margin these values range from around 10 to 20 km (Fig. 5.13). On the distal margin, thickness of the highly-thinned continental crust underlying the syn-rift ranges from 5 to 10 km (Fig. 5.13). Such results are in agreement with those estimated by Afilhado et al. (2008).

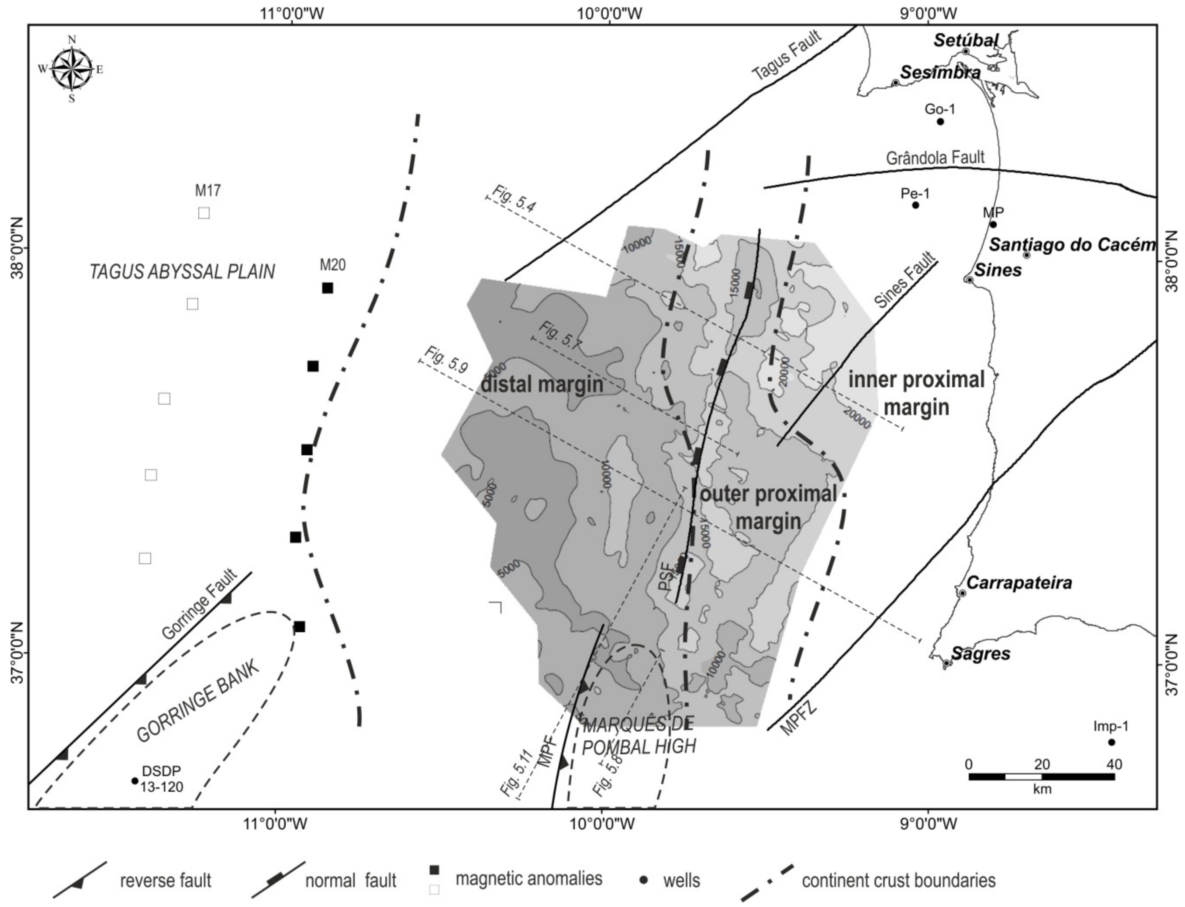

Figure 5.13 - Vertical thickness of the upper continental crust throughout the SW Iberian margin, estimated from deep crustal reflections.

Comparisons between the thickness and structural styles of continental crust demonstrate that the effects of compression are more prominent where the continental crust is markedly thin, for example on the distal margin close to the boundary with the Pereira de Sousa Fault and to the Marquês de Pombal High.

Considering these results and using the proposed boundaries for the COB (Mauffret et al., 1989a; Rovere et al., 2004; Afilhado et al., 2008) and the magnetic anomalies on the Tagus Abyssal Plain (Srivastava et al., 2000; Rovere et al., 2004), it is possible to map the estimated position of the different domains of continental crust and the transition to the oceanic crust (Fig. 5.14). The occurrence of deep crustal reflections on the distal margin suggests that this sector is the actual position of the crustal detachments, defining the transition from the continental to the oceanic domain (Figs. 5.7 and 5.10).

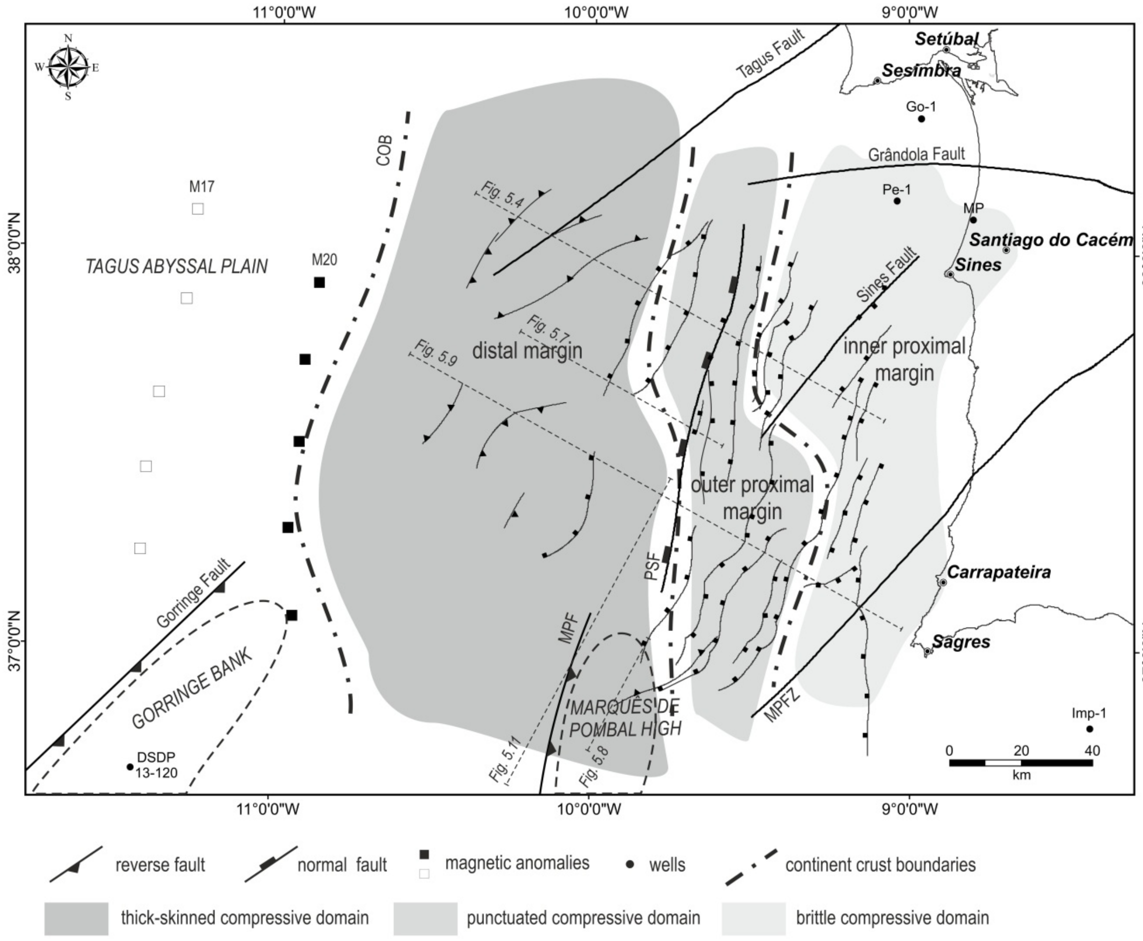

Figure 5.14 - Estimated position of the transitional crust and dominant compressive styles along the SW Iberian margin. COB position adapted from Mauffret et al. (1989a), Rovere et al. (2004) and Afilhado et al. (2008). Magnetic anomalies based on Rovere et al. (2004).

Comparing the compressional tectonic styles of the SW Iberian margin with the OCT at Galicia (Murillas et al., 1990; Malod et al., 1993; Masson et al., 1994; Ercilla et al., 2008; Vázquez et al., 2008), it is concluded that compression on Southwest Iberia is far more significant than previously estimated. At Galicia, compression is mainly expressed by broad anticlines related to large-amplitude folding at the OTC, and to minor reverse faulting. In Southwest Iberia, compressive features are dominated by thick-skinned deformation areas, piggy-back thrusting and sizeable sea-floor deformation, probably related to transpression

These data suggest that post-Cretaceous to Miocene multi-phase collision of Iberia with North Africa is significant and tectonic deformation is widespread on the distal margin. The architecture of the compressive sectors on the whole of the margin is the result of pre-existing basement lineaments associated with the convergence of the contrasting crustal segments of the thick continental crust and the extremely thinned transitional continental crust.

5.7. Conclusions

Multichannel seismic data imaging the continental crust to the ocean–continent transition at Southwset Iberia reveal the complete syn- to post-rift evolution and the effects of compression in the various sectors of the margin, which depend on: 1) the inherited fabric of the continental crust and overlying strata deposited prior to breakup; 2) the rheological behaviour of both continental crust and syn- to post-rift megasequences; and 3) the variable directions of shortening recorded during convergence between Iberia, North Africa and Eurasia.

The inner proximal margin reveals the rheological influence of a relatively thick continental crust (in excess of 20 km) where brittle deformation dominates in the form of limited reverse faulting and folding.

Compression on the outer proximal margin is characterized by localized shortening in shoulder areas to single sub-basins, including reverse faulting and folding, backward propagation and minor intrabasinal shortening. These structures are often related to detachments rooted on syn-rift shaley–evaporitic deposits. Continental crust in this sector ranges from 10 to 20 km thick.

The thinned continental crust of the distal margin (<10 km) is characterized by highly-rotated tilt blocks underneath thick syn-rift megasequences. Shortening in this sector is expressed by broad anticlines, reverse faulting and thrusting, piggy-back thrusting, backthrusting, backward propagation and some local transpression.

On the SW Iberian margin compression was initiated as early as the Late Cretaceous, but was most evident during the Pyrenean–Alpine phases (in the mid-Eocene and the late Oligocene–mid-Miocene). However, inversion styles are neither synchronous nor similar or discrete throughout the margin.

Intermediate episodes of shortening and tectonic quiescence are clearly expressed in distinct sectors of the margin. In parts of the study area, crustal shortening results from almost continuous convergence from the mid-Eocene to the present day.

Post-Miocene westward vergence at the Marquês de Pombal High marks the onset of the continent–ocean convergence, probably associated with the indentation by the thick continental crust.

The detailed characterization of the syn- to post-rift architecture of the SW Iberian margin allowed estimating the position of the ocean–continent transition along the distal margin, c. 80–100 km of the present-day shoreline.

Chapter 6

Tectono-stratigraphic signature of multiphased rifting on divergent margins (deep-offshore Southwest Iberia, North Atlantic)

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Figure 6.2 was modified after publication in order to correct Early Jurassic TR 3rd order sequences.

Figure 6.5 was modified after publication.

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6. Tectono-stratigraphic signature of multiphased rifting on divergent margins (deep-offshore Southwest Iberia, North Atlantic)

Abstract

Regional 2D multichannel seismic, borehole, dredge and outcrop data, together with burial models for strata in southwest Iberia, are used to investigate the tectono-stratigraphic signature of multiphased rifting on divergent margins. The burial model reveals that Mesozoic extension occurred during three main phases, each comprising distinct subsidence pulses separated by short-lived periods of crustal uplift. The importance of the three phases varies across discrete sectors of the margin, each one revealing similar depositional architectures and associated tectonic systems tracts: 1) the Rift Initiation pulse, characterised by incipient subsidence and overall aggradation/progradation over a basal unconformity, 2) the Rift Climax pulse, which marks maxima of tectonic subsidence and is characterised by retrogradation-progradation, and 3) the Late Rift pulse, recording the progradational infill of the basin and the effects of eustasy. The Rift Initiation systems tracts comprise Sinemurian and late Callovian-early Oxfordian strata. Marine units in the Pliensbachian and Late Oxfordian-Kimmeridgian represent the Rift Climax pulse, a period marked by the development of Maximum Flooding Surfaces. Late Rift deposits were identified in the Rhaetian-Hettangian, Toarcian-Bathonian and Kimmeridgian-Berriasian. The results of this chapter are important to the economic exploration of deep-offshore rift basins, as they reveal that sequence stratigraphy can be used to predict sedimentary facies distribution in more distal segments of such basins. Significantly, this work recognises that multiple tectonic-stratigraphic (rift) cycles can occur on deep-offshore rift basins, from the onset of rift-related extension until continental break-up, a character that contrast to what is known from deep-sea drilling data from the distal margin of Northwest Iberia.

6.1. Introduction

Depositional processes in rift basins have been comprehensively studied as many of the world's hydrocarbon-bearing provinces are located in regions that experienced significant crustal extension (e.g. Frostick and Steel, 1993). Deposition, in either marine or non-marine rift basins, results from a complex interplay of tectonic subsidence and uplift, eustasy, sediment supply and climate (Leeder and Gawthorpe, 1987; Frostick and Steel, 1993; Prosser, 1993; Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000). In addition, strata accumulated in rift basins can also record the complex evolution of continental margins, providing at the same time critical information on the crustal processes leading to continental break-up (Frostick and Steel, 1993; Nøttvedt et al., 1995; Ravnås and Steel, 1998; Gawthorpe and Leeder, 2000).

West Iberia is one of the most important regions from which some of the fundamental concepts on rifting mechanisms were derived. Many of these concepts are based on data from deep-sea drilling campaigns, industry wells, and outcropping Lusitanian Basin (Mauffret and Montardet, 1987; Leinfelder and Wilson, 1998; Manatschal and Bernoulli, 1998; Ravnås and Steel, 1998; Manatschal and Bernoulli, 1999; Wilson et al., 2001; Tucholke et al., 2007; Péron-Pinvidic et al., 2008; Péron-Pinvidic and Manatschal, 2009) (Fig. 6.1). In this context, the southwest Iberian margin remains a poorly investigated area despite the recent understanding of its structural architecture, the nature of the deep continental crust, and the effects of compression on its evolution (Afilhado et al., 2008; Alves et al., 2009; Neves et al., 2009; Cunha et al., 2010b; Pereira and Alves, 2011; Pereira et al., 2011) (Fig. 6.1). These latter findings, however, revealed significant uncertainties concerning the Mesozoic rift evolution of southwest Iberia. Some of these uncertainties include: 1) the age of Mesozoic extensional pulses and whether they were continuous or discrete, 2) the timing of continental breakup in southwest Iberia, 3) the precise age of the major rift related unconformities, 4) the relative distribution of depositional facies in syn- to post-rift units along and across the western Iberian margin, and 5) the subsidence histories of distinct sectors on the western Iberian margin.

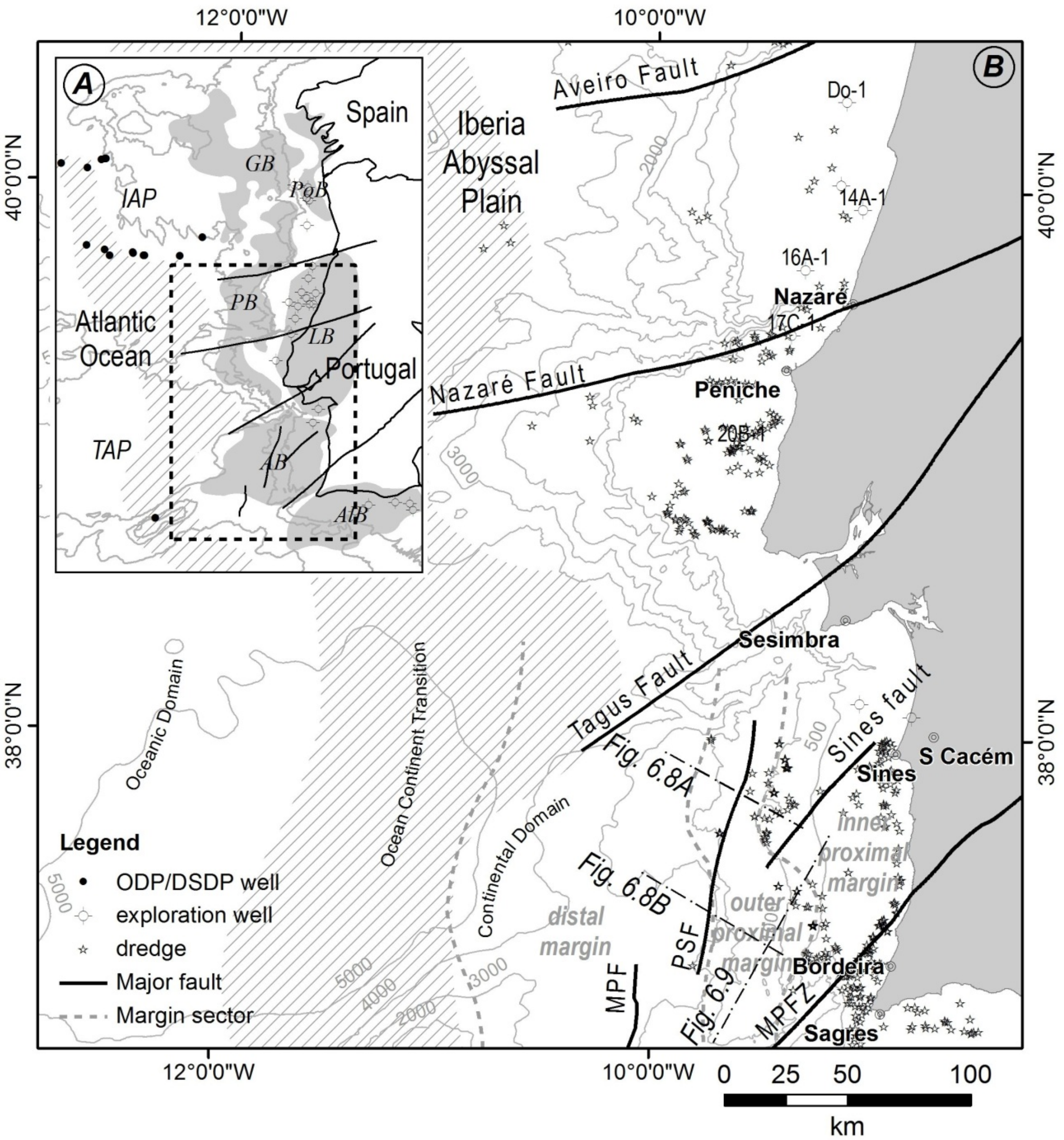

Figure 6.1 – A - Regional map with the location of the studied area and the main basins of the West Iberian margin and their relation with the main continental crust domains; GB – Galicia Basin, PoB – Porto Basin, PB – Peniche Basin, LB – Lusitanian Basin, AB – Alentejo Basin, AlB – Algarve Basin, IAP – Iberia Abyssal Plain, TAP – Tagus Abyssal Plain. B - Detailed map of the study area, showing the interpreted seismic lines, exploration wells and dredges; MP – Monte Paio well, MPFZ – Messejana-Plasencia Fault Zone. Diagonal pattern shows the approximate position of the Ocean Continent Transition zone (OCT), adapted from Rovere et al. (2004). Structural segments of the continental margin are taken from Pereira and Alves (2011).

This chapter presents an integrated sequence-stratigraphic analysis of multiphased rifting in the southwest Iberian margin. For the first time, the principal episodes of subsidence recorded this margin are assessed through the construction of a new burial history model, which is used in this chapter to explain the complex rift-related evolution of divergent margins. The interpreted data are used to construct a solid sequence-stratigraphy framework that allows the analysis of southwest Iberia in the context of continental rifting and lithospheric breakup between the North Atlantic, North Africa and West Tethys. Results are used to discuss and revise the criteria on which the currently used concepts on the stratigraphic signature of rift basins were erected.

This approach demonstrates that during successive episodes of extension, similar rift-related depositional tracts occur on the proximal margin of southwest Iberia, and that these depositional tracts can be used in regional correlations and sedimentary facies prediction throughout rifted continental margins and, more significantly, on the distal margin where scarce data are available. It is therefore postulated that during discrete rifting episodes, a complete stratigraphic cycle comprises three distinct phases of subsidence, which are materialised by different tectonic systems tracts (e.g. Prosser, 1993) bounded by coeval regional unconformities. This character contrasts to what is known from: 1) the distal margin of Northwest Iberia, where deep-sea drilling showed that only the final rift episode is recorded (Wilson et al., 2001); and 2) in the Peniche Basin, where the seismic packages deposited prior to the last rifting phase (usually referred as pre-rift units) often show a simple sub-parallel geometry (Alves et al., 2006).

6.2. Data and methods

This work used ~5.500 km of migrated multichannel 2D seismic data that cover ~23.000 km^2 of the southwest Iberian margin (Fig. 6.1). In order to investigate the tectono-sedimentary evolution of the multiple rift episodes that precede seafloor spreading in the study area, this work integrates data from well Pescada-1 (Pe-1), on the proximal margin, and six additional industry wells from offshore Lusitanian Basin (Fig. 6.1). Relevant information includes lithological data from non-exclusive completion reports and wireline profiles throughout the Mesozoic syn-rift successions. Burial history modelling was accomplished using freeware Petromod 1D license.

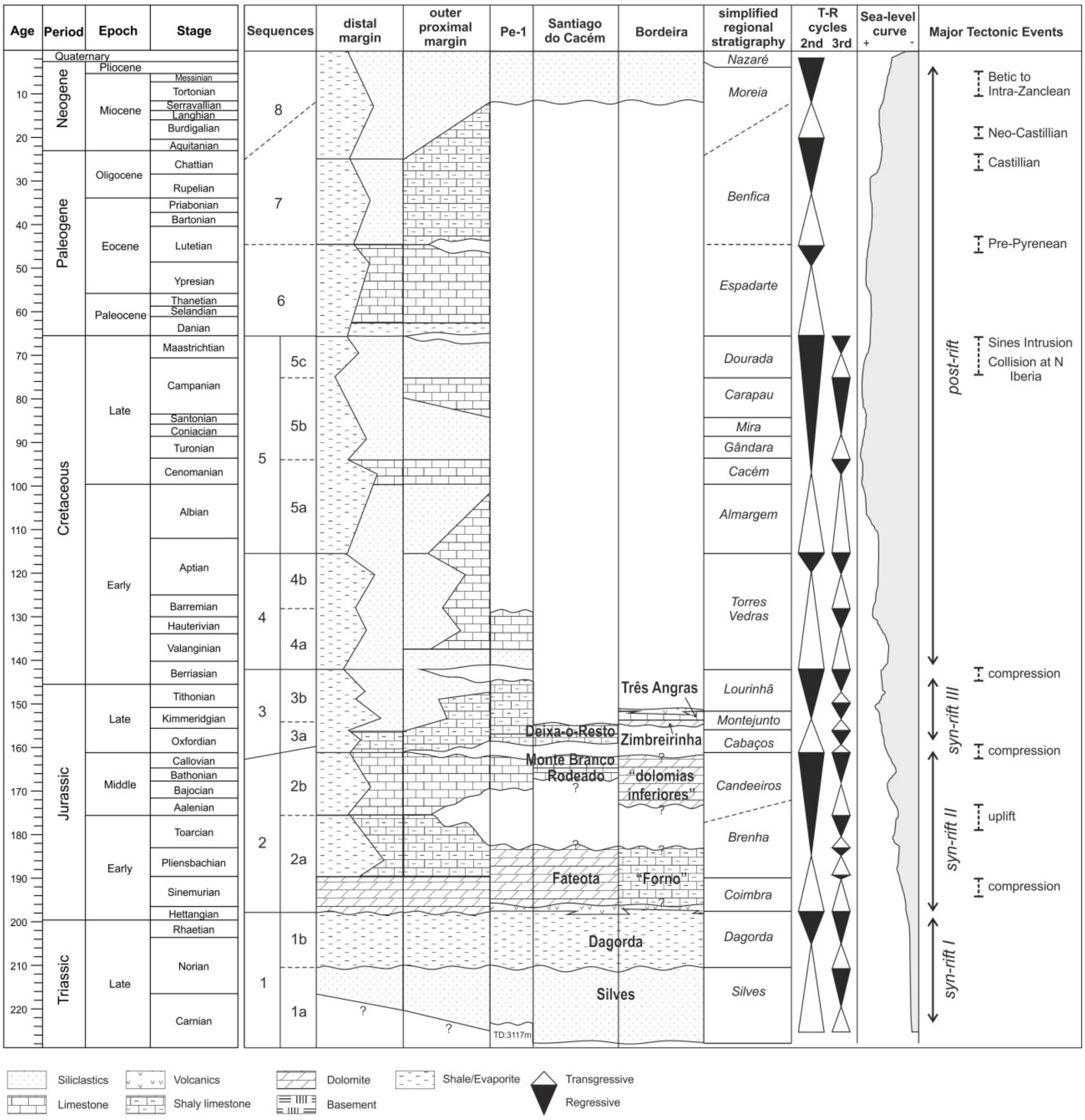

Figure 6.2 - Simplified lithostratigraphy of the southwest Iberian margin, showing the main stratigraphic sequences and major Transgressive-Regressive (T-R) events recorded in the study area and West Iberia. Regional informal lithostratigraphy based on the works of Witt (1977), Manuppella (1983), Ramalho and Ribeiro (1985), Ribeiro et al. (1987), GPEP (1986), Montenat et al. (1988) Wilson (1988), Inverno et al. (1993), Azerêdo et al. (2003), and Rey et al. (2006). T-R events adapted from Duarte (2007) and Reis and Pimentel (2010). Chronostratigraphy and Mesozoic-Cenozoic sea level curve extracted from TSCreator 4.2.5, based on Hardenbol et al. (1998).

Away from well control, information from dredge samples was used to calibrate the interpreted seismic data set (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Oliveira, 1984) (Fig. 6.1).

The zonation of the continental margin into proximal and distal sectors (e.g. Manatschal and Bernoulli, 1998, 1999; Alves et al., 2009; Pereira and Alves, 2011) can be tied with the broader continental crust domains defined for the southwest Iberian margin, namely the Ocean Continent Transition zone and the Continental Domain (Pinheiro et al., 1992; Rovere et al., 2004; Tucholke and Sibuet, 2007) (Fig. 6.1). Thus, the distal margin comprises the thinned crustal segment west of the continental slope fault system toward the estimated position of the Ocean Continent Transition zone, whereas the proximal margin (with its outer and inner sections) extends eastward to the outcropping Paleozoic basement (Pereira and Alves, 2011) (Fig. 6.1).

On seismic data, the interpretation of unconformity bounded sequences uses the concepts of Hubbard et al. (1985b) and Prosser (1993). The criteria of Driscoll et al. (1995) are used to identify the breakup unconformity and in the absence of well data on the distal margin, to estimate the age of continental breakup, i.e., the final separation of the continental crust and the rise of the asthenosphere along with the inception of seafloor spreading (e.g. Tucholke et al., 2007). These same criteria are subsequently used to tie the interpreted seismic megasequences with the main lithostratigraphic units recognised in West Iberia (Witt, 1977; Manuppella, 1983; Oliveira, 1984; Ramalho and Ribeiro, 1985; GPEP, 1986; Ribeiro et al., 1987; Wilson, 1988; Inverno et al., 1993; Azerêdo et al., 2003; Rey et al., 2006) (Fig. 6.2).

In order to construct a regional allostratigraphic framework, this work follows the criteria in Emery and Myers (1996), Catuneanu (2006) and Catuneanu et al. (2009). Additionally, this work applies the concepts of sequence stratigraphy in extensional settings to interpret the sequences deposited during rifting and to sub-divide them in distinct tectonic systems tracts (Prosser, 1993; Steel, 1993; Gawthorpe et al., 1994; Nøttvedt et al., 1995; Ravnås and Steel, 1998; Martins-Neto and Catuneanu, 2010). These same authors, however, use different nomenclature for similar tectono-stratigraphic stages and depositional units during rift-basin development. Prosser

(1993), who originally analysed the spatial and temporal distribution of deposits in active fault-bounded basins, described four distinct tectonic systems tracts: the Rift Initiation, the Rift Climax, the Immediate Post-Rift and the Late Post-Rift systems tracts. In contrast, Nøttvedt et al. (1995) considered only a Rift Initiation phase, a Rift Climax phase and a Late Rift phase to describe the events within a single rift cycle, each including distinct tectonic pulses. The terms Early Stage, Climax Stage and Late Stage are also often used (e.g. Ravnås and Steel, 1998), but, as pointed by Martins-Neto and Catuneanu (2010), "some of these concepts are yet to be fully devised".

This work shows that each rift phase includes three major pulses of subsidence resulting in correlative depositional sequences (tectonic systems tracts), i.e., the Rift Initiation, the Rift Climax and the Late Rift phases (Fig. 6.3). Therefore, as with to eustasy controlled depositional systems, each of the tectonic systems tracts is used to "emphasise facies relationships and strata architecture within a chronological framework" (Catuneanu et al., 2009) and to predict depositional sequences in settings controlled by extensional tectonic subsidence.

6.3. Geological setting

6.3.1. Mesozoic continental rifting in West Iberia

Iberia-Newfoundland are key examples of magma-poor passive margins (e.g. Manatschal, 2004). Similarly to other North Atlantic margins, southwest Iberia experienced continental extension since the Late Triassic (Hiscott et al., 1990; Wilson et al., 2001; Tucholke et al., 2007; Péron-Pinvidic and Manatschal, 2009). The onset of seafloor spreading has been interpreted as the latest Jurassic-earliest Cretaceous in southwest Iberia and in the Tagus Abyssal Plain (magnetic anomalies M20-M11) and migrated northward toward the Galicia margin, where continental breakup was completed by the Aptian-Albian (Mauffret et al., 1989b; Hiscott et al., 1990; Srivastava et al., 2000; Tucholke et al., 2007; Bronner et al., 2011). As a result, the main areas of subsidence on the west Iberian margin shifted both northward and westward as the rift locus migrated to its final position during the advanced rifting stage (Manatschal and Bernoulli, 1998, 1999; Alves et al., 2009; Pereira and Alves, 2011). This migration was responsible for the formation of discrete crustal segments along West Iberia, each with different subsidence histories, i.e., the inner proximal margin, the outer proximal margin and the distal margin (Manatschal and Bernoulli, 1998, 1999; Alves et al., 2009; Pereira and Alves, 2010a, 2011). Crustal segmentation resulted in the formation of several sub-basins broadly aligned with NNE-SSW to N-S master faults (Mougenot et al., 1979; Alves et al., 2009; Pereira and Alves, 2011) (Figs. 2.11 and 4.7).

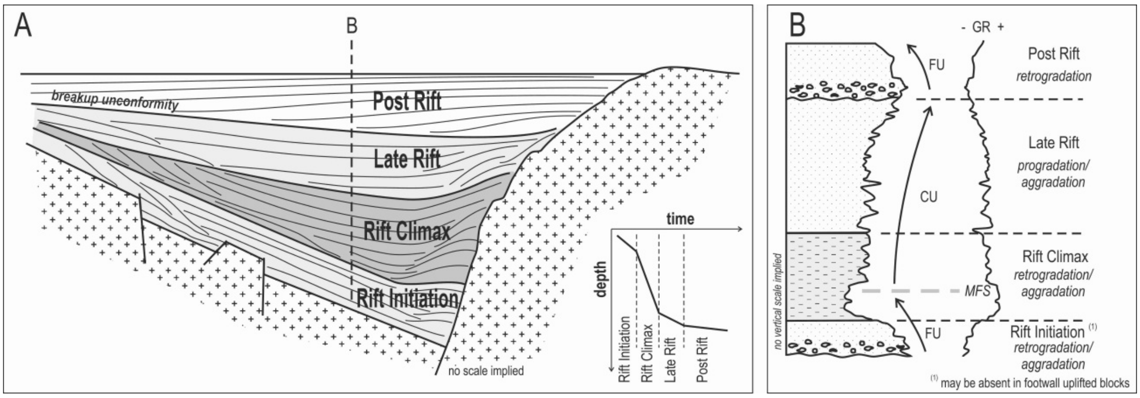

Figure 6.3 - Schematic tectonic systems tracts (A) on a transverse seismic section and (B) on outcrop, borehole and wireline data. Based on Prosser (1993), Gawthorpe et al. (1994) and Ravnås and Steel (1998). Rift subsidence curve adapted from Gupta et al. (1998).

The southwest Iberian margin experienced three major rift phases (Pereira and Alves, 2010a, 2011). The first episode of rifting (Syn-Rift I) occurred from the Late Triassic (Carnian?) to the earliest Jurassic (Hettangian), during widespread extension in northern Africa, western Tethys and North Atlantic. Syn-Rift II occurred from the Sinemurian to the Callovian, a period of time broadly synchronous to extension and continental breakup between Morocco-Nova Scotia at around 190 – 175 Ma (Withjack et al., 1998; Schettino and Turco, 2009; Labails et al., 2010). The last and final phase of continental extension (Syn-Rift III), occurring prior to the onset of seafloor spreading, span the Oxfordian (and possibly from the late Callovian) to the earliest Cretaceous (Berriasian) (Mauffret et al., 1989b; Hiscott et al., 1990; Pereira and Alves, 2011).

6.3.2. Seismic-stratigraphic units in offshore basins

Continental extension throughout the southwest Iberian margin resulted in the formation of four major regional unconformities, which bound three principal syn-rift Megasequences (1, 2 and 3) (Fig. 6.2).

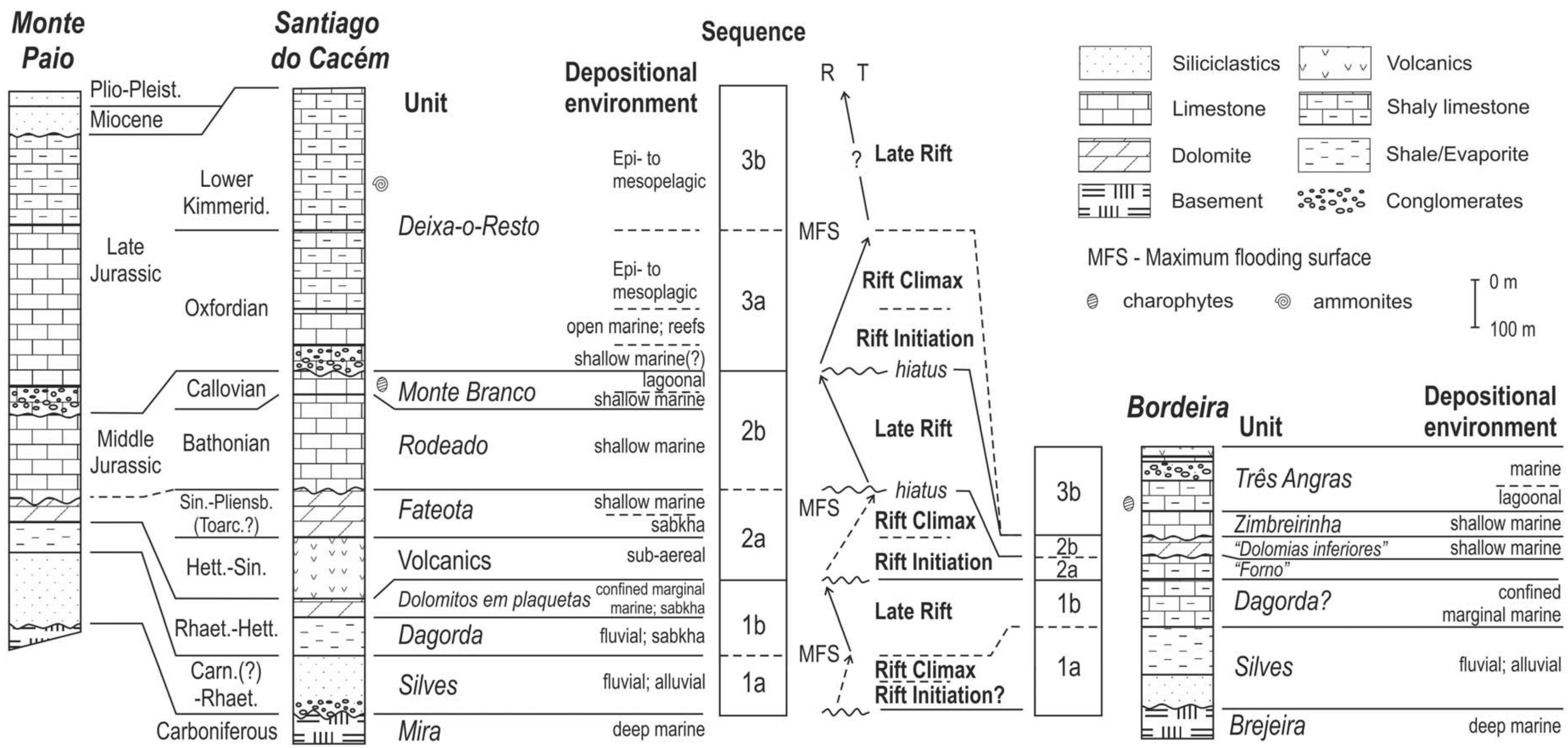

Figure 6.4 - Schematic lithostratigraphy, depositional environments and T-R trends from outcrop locations at Santiago do Cacém, Bordeira and in well Monte Paio. Based on Manuppella (1983), Ramalho and Ribeiro (1985), Ribeiro et al. (1987), Inverno et al. (1993) *and Alves et al. (2009).*

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Many of these unconformities are broadly synchronous across the Central and North Atlantic (Mauffret et al., 1989b; Hiscott et al., 1990; Pereira and Alves, 2011) (Figs. 2.11 and 4.7).

A basal angular unconformity separates the tightly folded Late Paleozoic (Devonian to Carboniferous) metasediments from Late Triassic (Carnian to Norian/Hettangian?) continental red beds (Silves formation), comprising the base of Megasequence 1 (sequence 1a) (Oliveira, 1984; Ramalho and Ribeiro, 1985; Inverno et al., 1993) (Figs. 6.2, 6.4 and 6.5). Overlying this unit, the shaley-evaporitic sequence of the Dagorda formation (sequence 1b) marks the progressive infilling of the margin in continental to restricted marine conditions (e.g. Azerêdo et al., 2003) (Fig. 6.5C).

Above the Dagorda evaporites, Megasequence 2 is bounded at its base by the Hettangian-Sinemurian disconformity (Inverno et al., 1993). Overlying this surface, extrusive toleitic volcanics and dykes of the Central Atlantic Magmatic Province (CAMP) (Martins et al., 2008) mark the onset of a new phase of extension (Syn-Rift phase II). The Sinemurian-Pliensbachian interval at Santiago do Cacém correlates with the dolomitic succession of the Fateota formation, whereas marly limestones outcrop at Bordeira (Ribeiro et al., 1987; Inverno et al., 1993) (Fig. 6.2). These deposits are lateral equivalent to Pliensbachian marine black shales and limestones in the Lusitanian Basin, which denote a period of increased subsidence in West Iberia (Stapel et al., 1996; Cunha et al., 2009) (Figs. 6.2 and 6.4).

From the late Pliensbachian-Toarcian to the Aalenian (and in some cases into the Bathonian), a major depositional hiatus is unevenly recorded in Southwest Iberia (Fig. 6.2). Deposition resumed in the Bathonian at Santiago do Cacém and Bordeira in the form of shallow marine limestones (Rodeado and Monte Branco formations) and dolomites (“dolomias inferiores”) (Oliveira, 1984; Ramalho and Ribeiro, 1985; Ribeiro et al., 1987; Inverno et al., 1993) (Figs. 6.2, 6.4, and 6.5D).

As a result of a forced regression, Megasequence 2 is bounded at its top by a late Callovian-middle Oxfordian angular unconformity (Azerêdo et al., 2002a). Overlaying this unconformity, the Late Jurassic is characterised at Santiago do Cacém by Oxfordian conglomerates and black pebbles of the Deixa-o-Resto and Três Angras formations, both synchronous to the Cabaços formation in the Lusitanian Basin, and by shallow marine limestones (Inverno et al., 1993; Azerêdo et al., 2003) (Figs. 6.4, 6.5E and 6.5F). The top of Megasequence 2 comprises a Tithonian-Berriasian disconformity and associated erosional surface, expressed on seismic, borehole and outcrop data (e.g. Rey et al., 2006; Pereira and Alves, 2011).

From the earliest Cretaceous (Berriasian) onwards, southwest Iberia evolved as a passive margin, with siliciclastic and prograding carbonate strata dominating the Mesozoic post-rift deposition (Alves et al., 2009; Pereira and Alves, 2011). In well Pe-1, Early Cretaceous post-rift units comprise shallow marine, high-energy siliciclastics, whereas on the inner proximal margin, dredge data collected shallow marine carbonates (Figs. 2.13 and 6.6). In addition, submarine dredges collected Late Cretaceous deep marine carbonates in the southern part of the study area (Matos, 1979; Mougenot et al., 1979) (Figs. 2.13 and 3.3).

From the end of the Cretaceous to the present-day, southwest Iberia was affected by prolonged post-rift compression, with the major pulses of shortening occurring during the Eocene, late Oligocene and early Miocene (Boillot et al., 1979; Mougenot et al., 1979; Pinheiro et al., 1996; Alves et al., 2003a; Péron-Pinvidic et al., 2008; Pereira and Alves, 2010a, 2011) (see chapter 5 for additional details).

6.4. Sequence stratigraphy analysis of the Southwest Iberian Margin

Isochron maps for Late Triassic to Late Jurassic-earliest Cretaceous strata show the location of the main syn-rift depocenters on the southwest Iberian margin (Fig. 6.7). The maps reveal that subsidence during this time interval was significant on the outer proximal and distal margins, where individual sub-basins were generated. Syn-rift strata in such sub-basins can be as thick as 2,4 s TWT (up to 6 km) (Fig. 6.7A).

Distinct phases of rifting and their correlative Megasequences, interpreted as second-order tectono-stratigraphic cycles (e.g. Catuneanu, 2006), are integrated within the major first order cycle of continental rifting (~80 Myr).

Subordinate third-order cycles (approximately with 6 to 20 Myr intervals) correlate with intermediate pulses of extension and quiescence, often with lithostratigraphic affinities (Fig. 6.2).

In Figures 6.2, 6.4, and 6.6 and in Table 6.1, a description of the principal stratigraphic sequences in the study area is presented, aiming to construct a tectono-stratigraphic framework for the southwest Iberian margin, in which three major rift-related megasequences occur.

6.4.1. Syn-rift megasequences

6.4.1.1. Megasequence 1 (Carnian?-Hettangian)

Megasequence 1 marks the onset of continental rifting in west Iberia, synchronous with the western Tethys Sea. Thickness variations reveal that the main depocenters in southwest Iberia were located on the proximal margin at this time (Fig. 6.7B). Megasequence 1 exceeds 200 m in thickness at Santiago do Cacém (Fig. 6.4), whereas in Pe-1 it is thicker than 380 m (Fig. 6.6). Offshore southwest Iberia, TWT thickness maps indicate that Megasequence 1 can reach up to 1 s (~2200 m) (Fig. 6.7B). Thickness variations in Megasequence 1 are associated with the generation of NE-SW depocenters bounded by syn-rift master faults (Fig. 6.7B). This shows that the deposition of Megasequence 1 was controlled by an initial, but significant, phase of crustal subsidence.

The occurrence of growth strata within sequence 1a is limited, suggesting minor subsidence (Fig. 6.8). At Bordeira, Santiago do Cacém and in wells Pe-1 and Monte Paio, this same unit comprises retrograding continental red beds of the Silves formation (Figs. 6.4, 6.5B and 6.6). Additionally, well Pe-1 shows a fining-upwards trend on gamma-ray curves. This character suggests an overall retrogradational trend as a result of the sedimentary infill of the margin during Syn-Rift phase I.

Sequence 1b (Dagorda Fm.) includes shales, interbedded halite, gypsum, anhydrite, dolomite and limestones, suggesting the progressive infill of the margin under an increasingly strong marine influence (Figs. 6.4, 6.5C and 6.6). In this uppermost sequence no clear depositional trends are observed (Figs. 6.6 and 6.8).

6.4.1.2. Megasequence 2 (Hettangian/Sinemurian-Callovian)

Megasequence 2 is characterised by thick growth strata aligned along NNE-SSW to NE-SW depocenters. This character reveals that distinct sub-basins were created during Syn-Rift phase II (Figs. 6.7C and 6.8).

Its lower boundary, marked at outcrop by an unconformity and CAMP related volcanics, is shown on seismic by prograding reflections on both hanging wall and footwall blocks (Fig. 6.8 and Table 6.1). Wireline data from Pe-1 reveal alternating retrograding-progradational cycles. Within the Megasequence, Sinemurian-Pliensbachian dolomites of the Fateota fm. precede a major Toarcian-Aalenian in age. This hiatus subdivides the Megasequence into two third-order sequences (sequences 2a and 2b).

Dolomitic and limestone strata in sequence 2a were deposited in the latest Hettangian-Sinemurian at the start of Syn-Rift II (Figs. 6.4 and 6.5D). These deposits reveal a predominant retrograding trend and a progressive establishment of marine conditions toward the top of the sequence. In well Pe-1, the gamma-ray shows sequence 2a to comprise more than 60 m of dolomitic deposits (Fig. 6.6). This latter character was likely generated by a relative rise in base level at the start of Syn-Rift II.

Above the Toarcian-Aalenian hiatus occur shallow sediments in sequence 2b, which is partly equivalent to the low energy limestones of the Rodeado and Monte Branco formations (Fig. 6.6). In well Pe-1, sequence 2b is recognised by presenting a sharp break on gamma-ray and density logs (Fig. 6.6), whereas on seismic data this event is expressed as a correlative paraconformable boundary (Figs. 6.8 and 6.9). On the outer proximal and distal margin, sub-parallel and divergent reflectors suggest the deposition of submarine fans and turbidites on subsiding tilt-blocks, with sediment being mainly sourced from uplifted and eroded hinterland areas, on the East (Fig. 6.8).

Table 6.1 - Summary of the interpreted third order sequences throughout the Southwest Iberian margin, their seismic stratigraphic features, correlated Informal lithostratigraphy and interpreted lithology of the distal margin.

Sequence (3rd order)	**Probable age of base**	**Seismic stratigraphy**	**Lithostratigraphy**		**Lithology of the proximal margin**	**Lithology of the distal margin**	**Overall depositional trend**
			Regional	**SW Iberia**			
5c	Mid Campanian	Downlap, internal reflections varying from chaotic to sub-parallel and an overall prograding trend	Dourada	(Not defined)	Absent to deep marine limestones; deltaic siliciclastics?	Deep marine limestones and siliciclastics	Progradation
5b	Turonian	Downlap, internal reflections varying from chaotic to sub-parallel and an overall prograding trend	Gândara, Mira, Carapau	(Not defined)	Absent to deep marine limestones; deltaic siliciclastics?	Deep marine limestones and siliciclastics	Progradation
5a	Mid to late Aptian	Downlap, internal reflections varying from chaotic to sub-parallel and an overall prograding trend	Almargem, Cacém	(Not defined)	Absent to deep marine limestones; deltaic siliciclastics?	Deep marine limestones and siliciclastics	Progradation
4b	Barremian	Sub-parallel to chaotic reflections, often downlapping the previous units	Torres Vedras, Cascais	(Not defined)	Absent to shallow marine carbonates and siliciclastics	Shallow to deep marine carbonates and siliciclastics	Progradation
4a	Berriasian	Sub-parallel to chaotic reflections, often downlapping the previous units	Torres Vedras, Cascais	(Not defined)	shallow marine siliciclastic, limestones and dolomites	Shallow to deep marine carbonates and siliciclastics	Progradation
3b	Kimmeridgian	Divergent to sub-parallel reflectors	Lourinhã	Deixa-o-Resto; Zimbreirinha, Três angras	shallow to deep marine carbonates	Deep marine carbonates and siliciclastics	Progradation
3a	Late Callovian	Divergent to sub-parallel reflectors	Cabaços-Montejunto	Deixa-o-Resto	Limestones, axial fan conglomerates; open marine reefs to deep marine marly limestones	Deep marine carbonates and siliciclastics	Aggradation; retrogradation
2b	Aalenian	Downlap, sub-parallel to divergent reflections	Candeeiros	Rodeado-Monte Branco; "dolomias inferiores"	Marine carbonates, dolomites	Deep marine carbonates and siliciclastics (?)	Progradation
2a	Sinemurian	Downlapping reflections and high amplitude sub-parallel to slightly divergent reflections	Coimbra-Brenha	Fateota	Sabkha and shallow marine dolomites	Dolomites and shallow marine limestones; turbiditic limestones?	Aggradation; retrogradation
1b	Norian	Chaotic, sub-parallel and transparent reflectors	Dagorda	Dagorda	Continental shales, evaporites and limestones	Siliciclastics, carbonates and evaporites	Progradation(?)
1a	Carnian	Growth strata and downlap towards the acoustic basement; sub-parallel to chaotic internal reflections	Silves	Silves	Continental red siliciclastics	Continental red siliciclastics	Retrogradation

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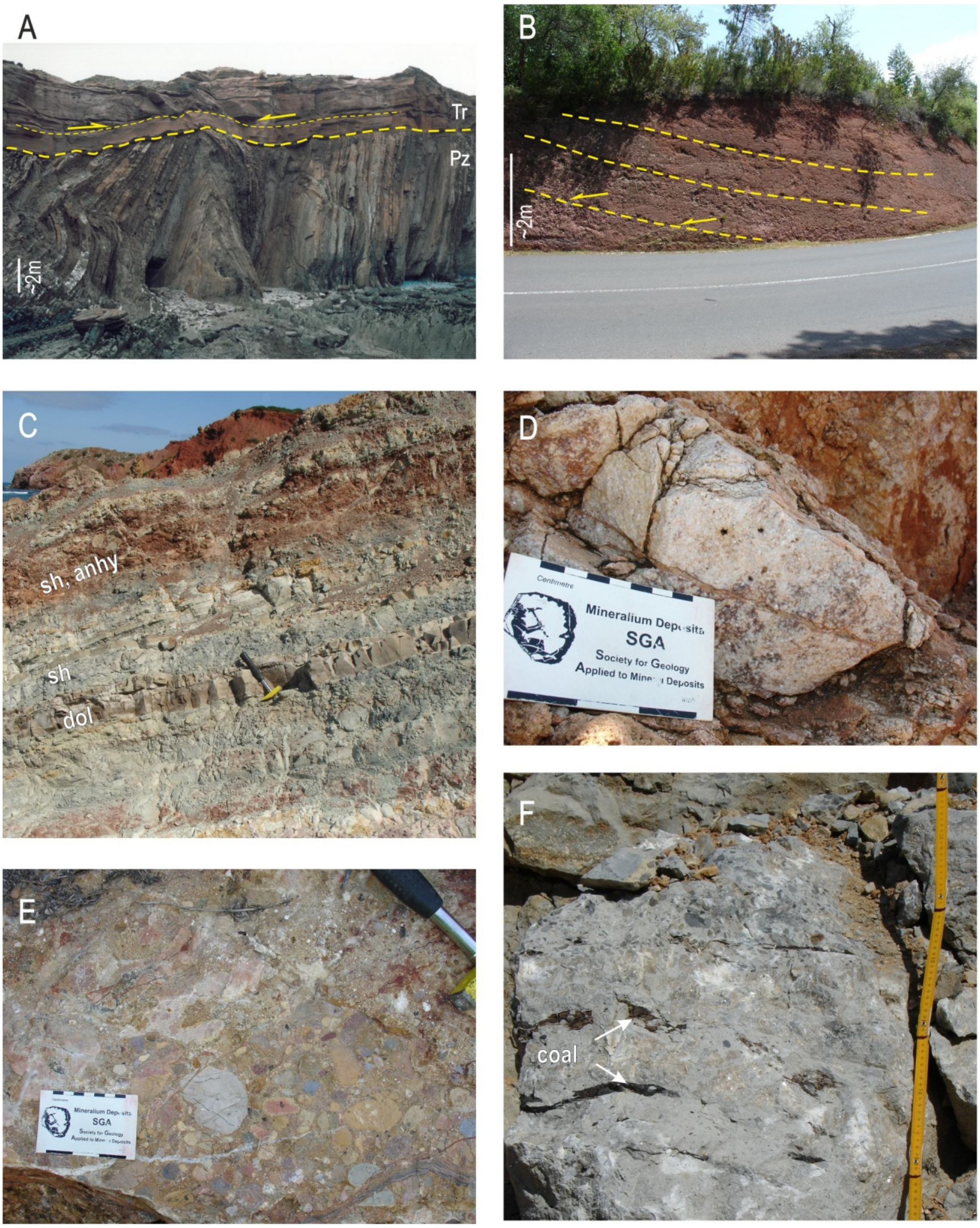

Figure 6.5 - (A) Angular unconformity between the Late Triassic Silves formation and crosscutting the Paleozoic basement units, south of Bordeira (Telheiro beach). (B) Stratification within the Late Triassic (Silves Fm., southeast of Santiago do Cacém). (C) Dagorda formation south of Bordeira (Amado beach). (D) Detail of the Mid-Late Jurassic dolomites of the "dolomias inferiores" south of Bordeira (Porto do Forno). Note the secondary porosity resulting from the dolomitization. (E) Basal conglomerates of the Oxfordian of the Deixa-o-Resto fm. (locality of Deixa-o-Resto, northeast of Sines). (F) Basal conglomerates and coal debris of the Oxfordian of the Deixa-o-Resto fm. (Deixa-o-Resto, northeast of Sines).

Wright and Wilson (1984) inferred a similar process for the Peniche area (Lusitanian Basin), where prograding submarine fan carbonates and siliciclastics are accompanied by distal organic-rich facies. In well Pe-1, shallow-marine limestones of Bathonian-Callovian age show limited progradation and aggradation (Fig. 6.6).

A predominant shallowing-upward trend reveals minor progradation, a character interpreted as the result of progressive infill of the margin within a context of continued base level fall (Fig. 6.2). This latter trend denotes a close interplay between subsidence and eustasy during the final pulses of rift phase II. Outcrop data from Santiago do Cacém, Bordeira and lithological information from the Monte Paio well show prograding carbonate successions (Rodeado, Monte Branco and “dolomias inferiores” formations), with increasing influence of continental conditions toward the top (Fig. 6.4). Sequence 2b is crosscut at its top by a widespread Late Callovian to Middle Oxfordian angular unconformity (Figs. 6.4, 6.6 and 6.8).

On the proximal margin, seismic data reveal a prograding/aggrading rimmed carbonate platform of probable middle Jurassic age (Fig. 6.9). This suggests that carbonate deposition throughout the south-western Iberian margin was widespread at this time, similarly to what has been described in the Lusitanian Basin (Azerêdo et al., 2002a). Considering the hiatus recorded in Nova-Scotia and on its conjugate margin of North Africa (Welsink et al., 1989), the Toarcian-Aalenian hiatus in southwest Iberia and western Algarve can be correlated with the unconformity marking the transition to post-rift in the northern Central Atlantic. This unconformity is less evident or absent in the Lusitanian Basin, but can correlate with the boundary between the Brenha and Candeeiros formations (Fig. 6.2).

6.4.1.3. Megasequence 3 (Callovian-Berriasian)

The Callovian-Oxfordian regional angular unconformity defines the base of Megasequence 3 (Figs. 6.2 and 6.4). At Pe-1, Megasequence 3 is characterised by an overall progradational (coarsening-upward) trend at its base, followed by a retrogradational trend toward a subsidence maxima recorded near the top of sequence 3a (Fig. 6.6 and Table 6.1).

On the distal margin, growth strata indicate that important subsidence continued at this time into the Advanced Rifting and Transition to Seafloor Spreading stages (Fig. 6.8). On seismic data, Megasequence 3 is best observed on the outer proximal and distal margins, with growth strata thickening onto NNE-SSW to N-S listric faults, which mainly dip to the west (Figs. 6.7d and 6.8).

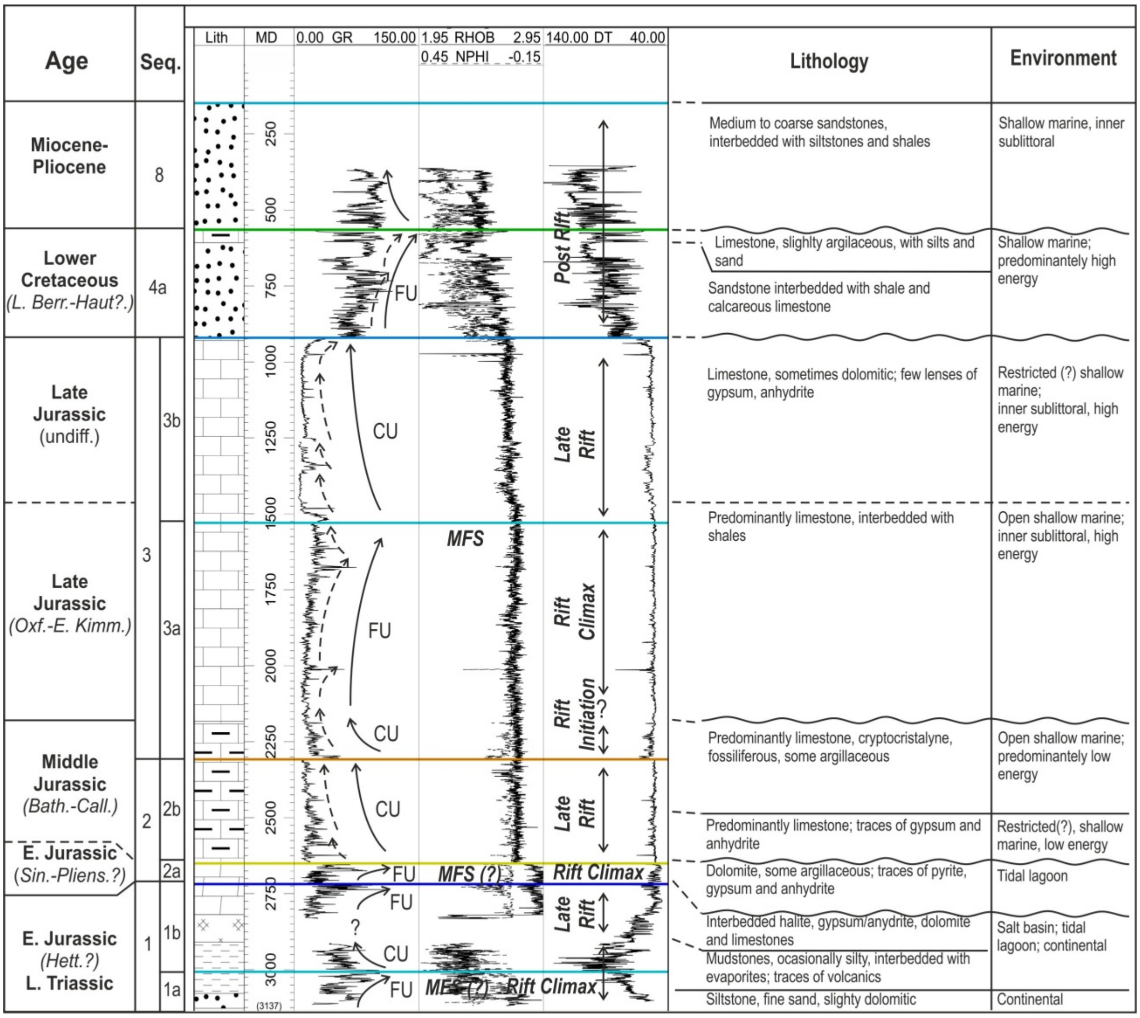

Figure 6.6 - Interpreted wireline data and depositional trends from well Pe-1. Lithologies and depositional environments are based on the well completion report.

Where faults dip to the east, upper Jurassic strata appear planar (Fig. 6.8).

At Santiago do Cacém, a significant influx of carbonate breccias and conglomerates (Deixa-o-Resto formation) marks the onset of a new subsidence episode in southwest Iberia during the late Callovian-early Oxfordian (Fig. 6.4).

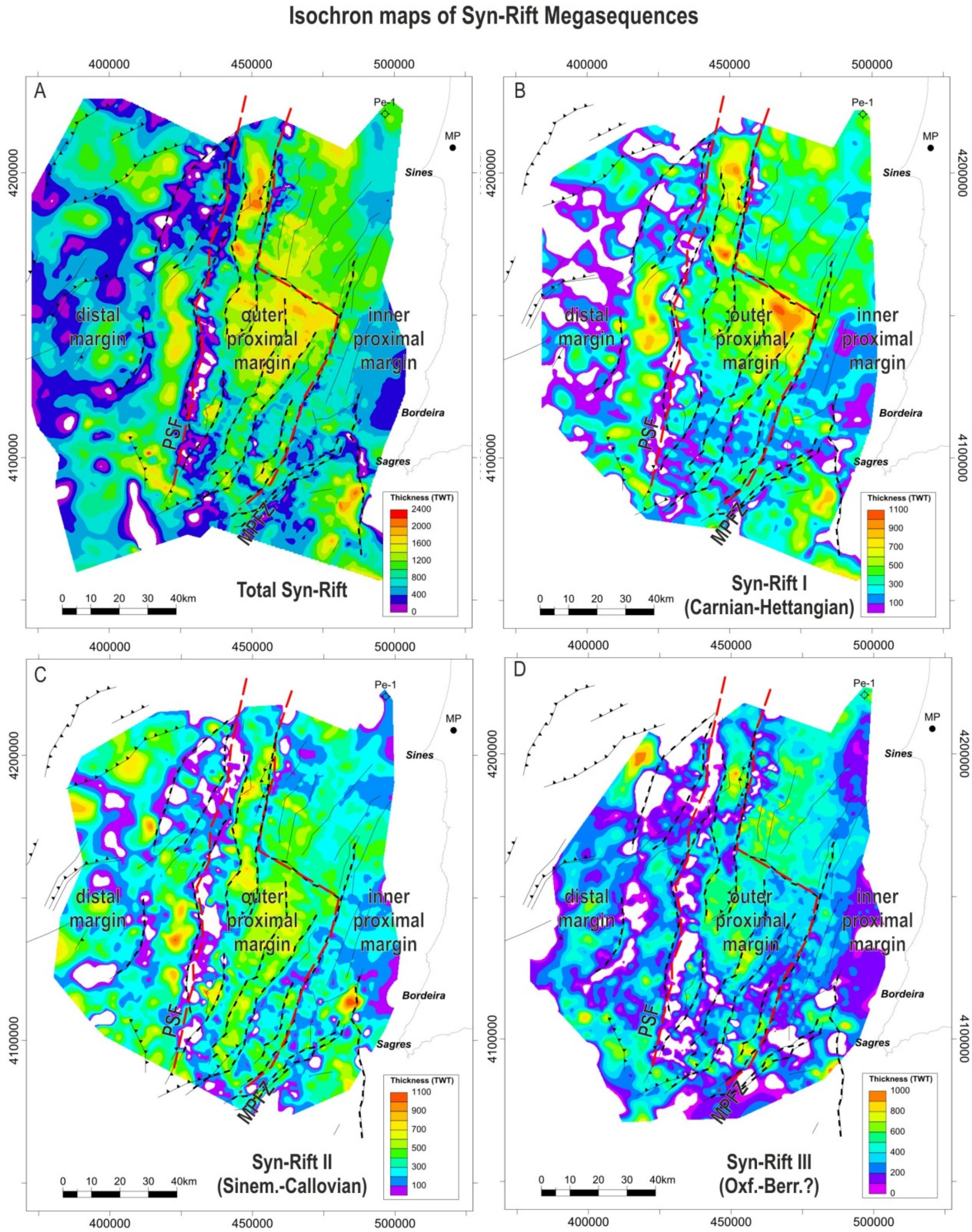

Figure 6.7 - Maps showing the structural control and major rift depocenters throughout the southwest Iberian margin. A - Total syn-rift thickness isochron map (TWT) of the southwest Iberian margin. B - Isochron map (TWT) of top of Syn-Rift phase I. C - Isochron map (TWT) of top of Syn-Rift phase II. D - Isochron map (TWT) of the Syn-Rift phase III.

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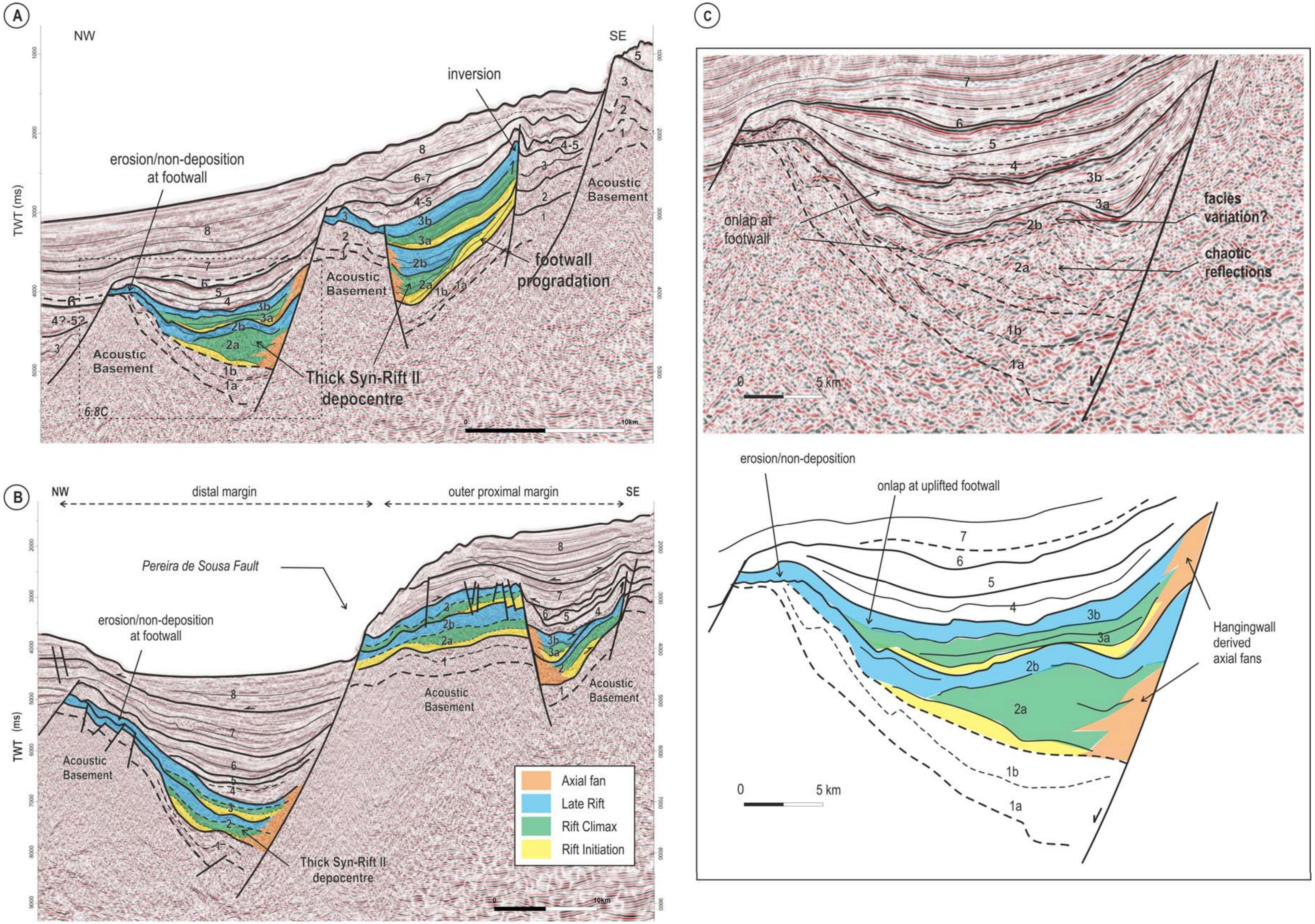

Figure 6.8 - Interpreted migrated multichannel 2D seismic section across the (A) outer proximal and (B) distal margin, evidencing the tectonic systems tracts described in this work and thick syn-Rift II depocentres. Note the early Jurassic rift initiation footwall progradation and the limited deposition over uplifted footwalls. Inset (C), shows a detail in the seismic stratigraphic interpretation of 6.8A and the interpreted tectonic systems tracts.

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On the road from Grândola to Sines, the Oxfordian-Kimmeridgian breccia-conglomerates are polymictic (Fig. 6.5E), whereas at Deixa-o-Resto, 5 km northwest of Santiago do Cacém, equivalent strata include black pebbles in a gray limestone matrix with fragments of coal (Fig. 6.5F). Toward the top of this unit, early Kimmeridgian marine limestones with ammonites mark the increased marine influence of the proximal margin (Fig. 6.4).

At Bordeira, the deposits of sequence 3a are probably absent, likely due to local uplift. Even so, black-pebble intervals are described in early Kimmeridgian strata of the Três Angras formation, which likely represents the continuation of the Rift Climax phase in syn-rift III (Fig. 6.4). In addition, dredge samples from the outer proximal margin collected shallow marine limestones, some impregnated with hydrocarbons (Matos, 1979; Mougenot et al., 1979). The prograding character of sequence 3a is interpreted to record the renewed deepening of the margin during the Oxfordian-Kimmeridgian, after a brief period of tectonic quiescence. This event was accompanied by uplift on basin-bounding footwalls blocks. At well Pe-1, wireline data shows an overall aggrading/prograding trend with minor prograding cycles over the late Callovian-early Oxfordian unconformity (Fig. 6.6). Seismic data from the outer proximal margin reveals limited sub-parallel reflectors with minor thickening toward master faults, suggesting decreased subsidence and the progressive infill of the margin (Fig. 6.8 and 6.9). The unconformity bounding the top of Megasequence 3 is therefore interpreted to represent the end of continental rift subsidence and is likely synchronous with the first magnetic anomalies recorded on the Tagus Abyssal Plain (M20-M17) (Srivastava et al., 2000).

6.4.2. Mesozoic post-rift megasequences

Megasequence 4 (Berriasian to mid Aptian) comprises retrograding shallow-marine siliciclastics overlain by limestones (Fig. 6.6). On seismic data Megasequence 4 shows marked retrogradation, with main depocentres located on the inner proximal and distal margins (Fig. 6.10). This suggests sediment bypass from hinterland sources, accompanied by widespread uplift of the inner proximal margin.

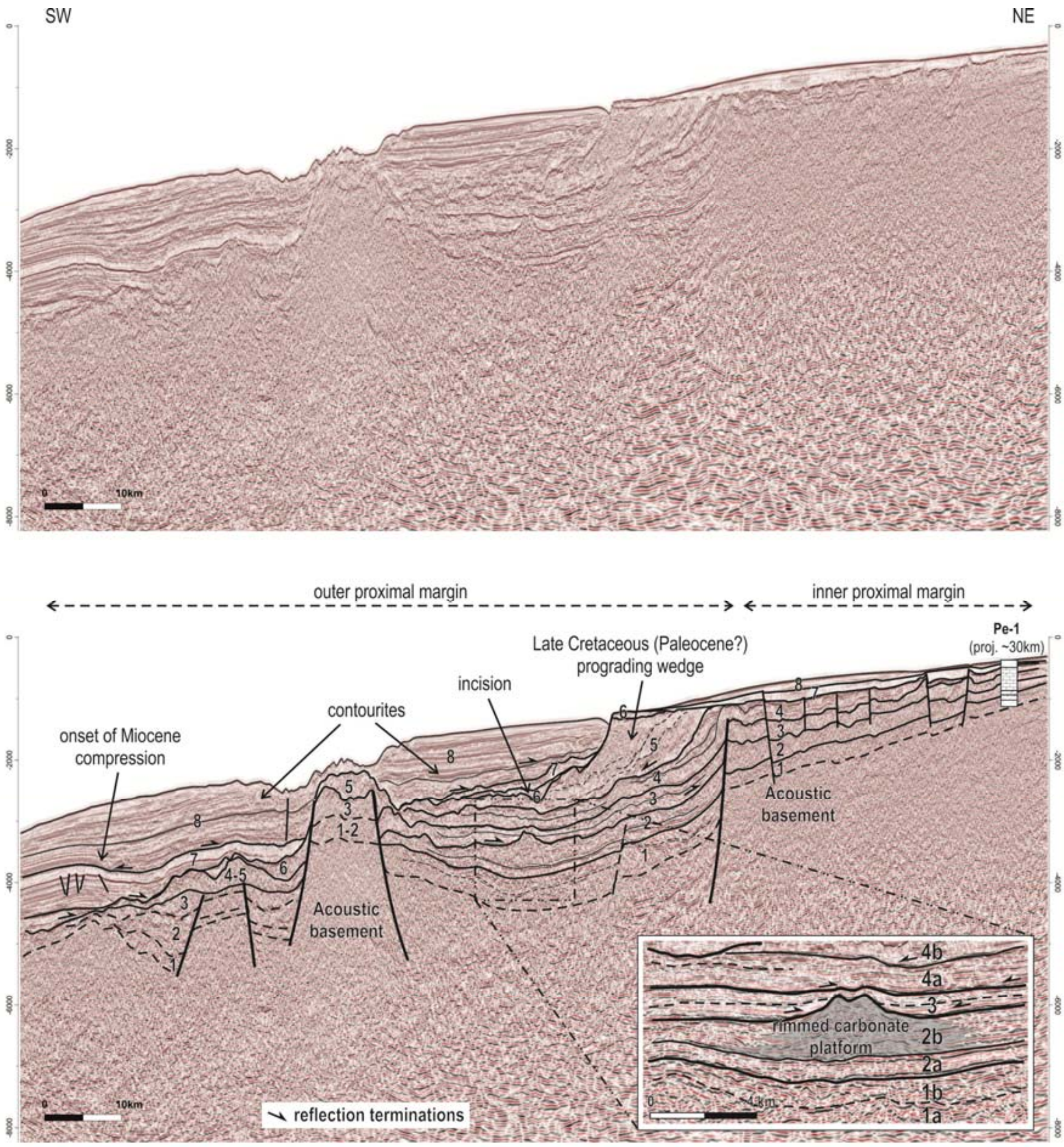

Figure 6.9 - Interpreted multichannel 2D seismic section across the proximal margin, showing a probable mid Jurassic prograding rimmed carbonate platform. Deposition of the Late Cretaceous (Paleocene?) prograding wedge is controlled by a palaeo-shelf break, subsequently eroded during the Paleocene-Eocene (see Figure 10 for location and thickness map). Exploration well Pe-1 projected on the inner proximal margin. Also note the deposition of post-Miocene contourites draping the margin.

Megasequence 5 (Mid Aptian to Maastrichtian-Paleocene) is often absent on borehole data and outcrops (Figs. 6.4, 6.6 and 6.10). However, on the outer proximal margin a prograding wedge up to 2500 m thick was deposited on a paleo-platform break (Fig. 6.10). Seismic reflections are mostly chaotic within the Megasequence, becoming increasingly sub-parallel toward the outer proximal margin (Fig. 6.9). This character suggests Megasequence 5 to comprise a deltaic wedge or prograding slope depositsBurial history in the proximal margin

6.4.3. Objectives and boundary conditions

In order to demonstrate the existence of multiple events of continental extension in the southwest Iberia, strata in well Pe-1 (located on the inner proximal margin) were modelled for its burial history (Fig. 6.11). Burial history models on the distal margin are not included in the present chapter (but are discussed in chapter 8.1 and in the Annexes), although the superimposed growth strata (Megasequences 1, 2 and 3) points to prolonged tectonic subsidence of this domain of the southwest Iberian margin (Fig. 6.8). Subsidence analyses using similar data (Stapel et al., 1996; Alves et al., 2009; Cunha et al., 2009) did not account for, or underestimated, the principal events of uplift and erosion documented in this chapter. Such simplification of the burial history has a significant impact on model results as they conceal the effective subsidence rates subsequent to uplift periods. The burial history model includes a suite of input parameters and boundary conditions, presented in Table 6.2.

Thickness values for major lithological units were obtained from the completion well report and re-interpreted in this work (Fig. 6.6).

The age of erosive (and uplift) events were estimated on the basis of regional context of the Lusitanian and the Alentejo Basins (see additional references in chapters 2 and 4). The lateral and temporal extent of such hiatus (in the absence of accurate data for some of the units) was estimated from seismic data on the inner proximal margin, in the proximity of well Pe-1. In the present model, erosion is applied to the main hiatuses recorded on borehole data, i.e., the Toarcian-Aalenian, Tithonian-Berriasian and the Albian-Miocene intervals (Table 6.2).

Aiming to constrain the model, paleowater depth (PWD) values were based on data from Stapel et al. (1996) for the Lusitanian Basin, which according to these authors do not exceed 200 m. In parallel, Hiscott et al. (1990) used 300 m as maximum PWD. Also, considering the predominant carbonate lithologies in well Pe-1, and data from the Lusitanian Basin, a maximum of paleowater depth of 100 m was used in the burial model for Late Jurassic strata.

Table 6.2 - Input parameters for the burial history modelling of borehole Pe-1.

	top (m)	base (m)	thickness (m)	eroded (m)	deposition from (M.a)	deposition to (M.a)	erosion from (M.a)	erosion to (M.a)
Mio-Plio	149	567	418		23	0		
K2-C2	567	567	0	300	120	23	70	23
K1 ls	567	607	40		130	120		
K1 ss	607	921	314		144	130		
J3 (Tith.)	921	2.182	1.261	50	159	144	148	144
J2 (Bat.-Cal.l)	2.182	2.652	470		169	159		
J1 (Hett.-Toar.)	2.652	2.652	0	200	190	169	180	169
Coimbra	2.652	2.719	67		200	190		
Dagorda dol	2.719	2.820	101		202	200		
Dagorda salt	2.820	2.910	90		205	202		
Dagorda sh	2.910	3.080	170		210	205		
Silves	3.080	3.117	37		220	210		

6.4.4. Analysis of results

As in the analysis of Cunha et al. (2009), a first pulse of extension on the inner proximal margin is characterised by significant subsidence from the Late Triassic to the earliest Jurassic (Megasequence 1). In Pe-1, this interval is over 400 m thick, but is significantly thicker on the outer proximal and distal margin (in excess of 1000 m in some areas), as estimated from seismic data (Figs. 6.8 and 6.9). The model also reveals that during the Sinemurian to Pliensbachian (sequence 2a), prior to Toarcian-Aalenian uplift, the inner proximal margin of southwest Iberia recorded subsidence usually in excess of 200 m (Fig. 6.7C). Considering this value as a conservative estimate, the model suggests that subsidence could have been even more pronounced prior to the Toarcian-Aalenian regional uplift (Fig. 6.11).

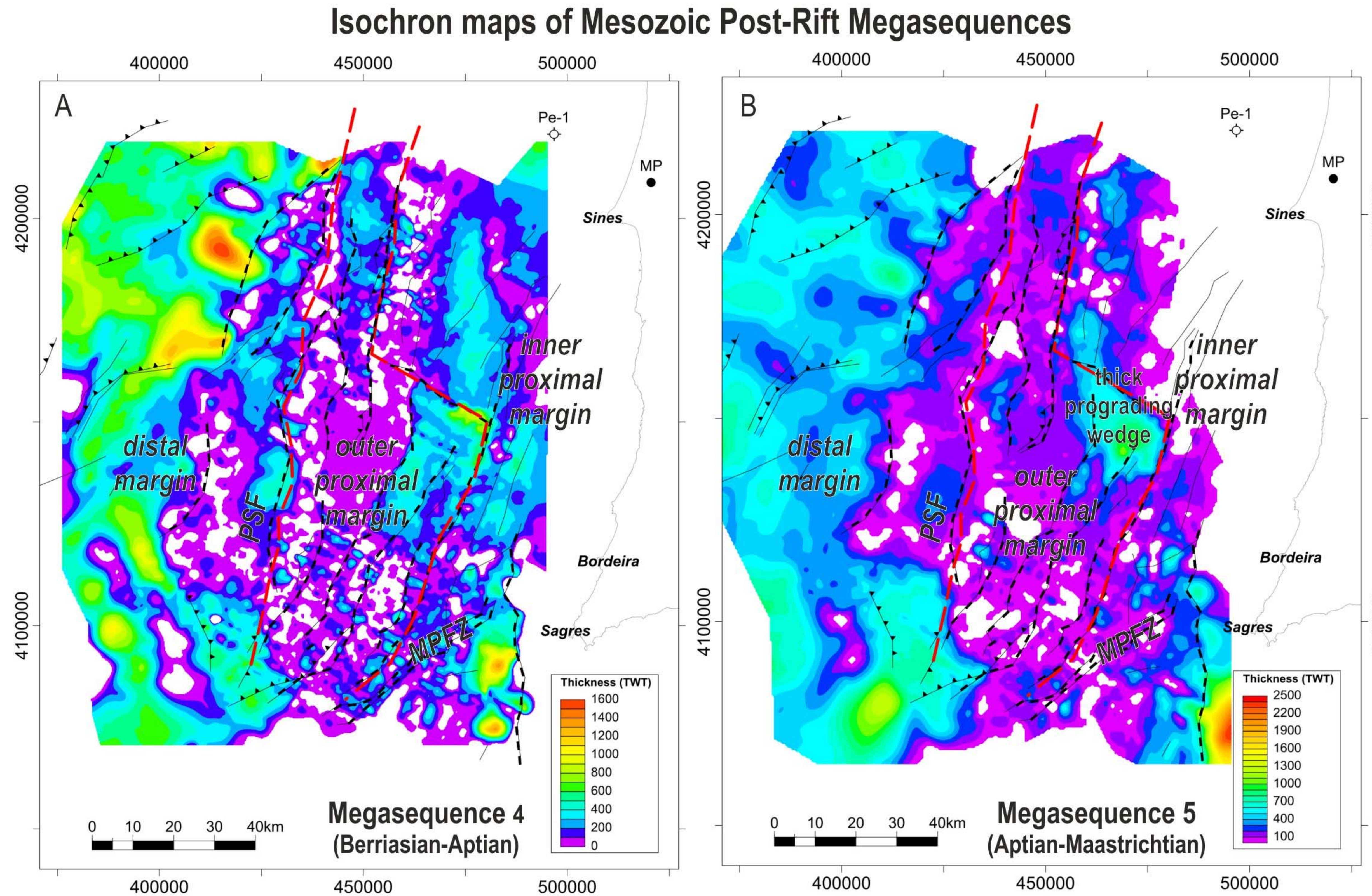

Figure 6.10 - Isochron (TWT) maps of the principal Mesozoic post-rift depocenters, largely controlled by inherited the syn-rift physiography. A - Megasequence 4 (Berriasian-Aptian) shows that favoured depocenters are located on the inner proximal and distal margin. B - Megasequence 5 (Aptian-Maastrichtian?), shows favoured deposition on the distal margin and a prograding wedge on the outer proximal margin.

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This interpretation assumes that during this same period, uplifting and erosion of the inner proximal margin were balanced by continued/increased deposition in more distal areas.

A third and final phase of significant subsidence was initiated during the Bathonian-Callovian and persisted until the Kimmeridgian, followed by a decrease in subsidence by the end of the Jurassic, when a new minor period of uplift is recorded. During the Early Cretaceous (Berriasian-Hauterivian) subsidence was relatively moderate on the inner proximal margin, and even more during the Late Cretaceous. From the latest Cretaceous onwards, continued Cenozoic compression and tilting uplifted the inner and outer proximal margins, hindering both deposition at the present-day continental slope region and eroding pre-Miocene deposits.

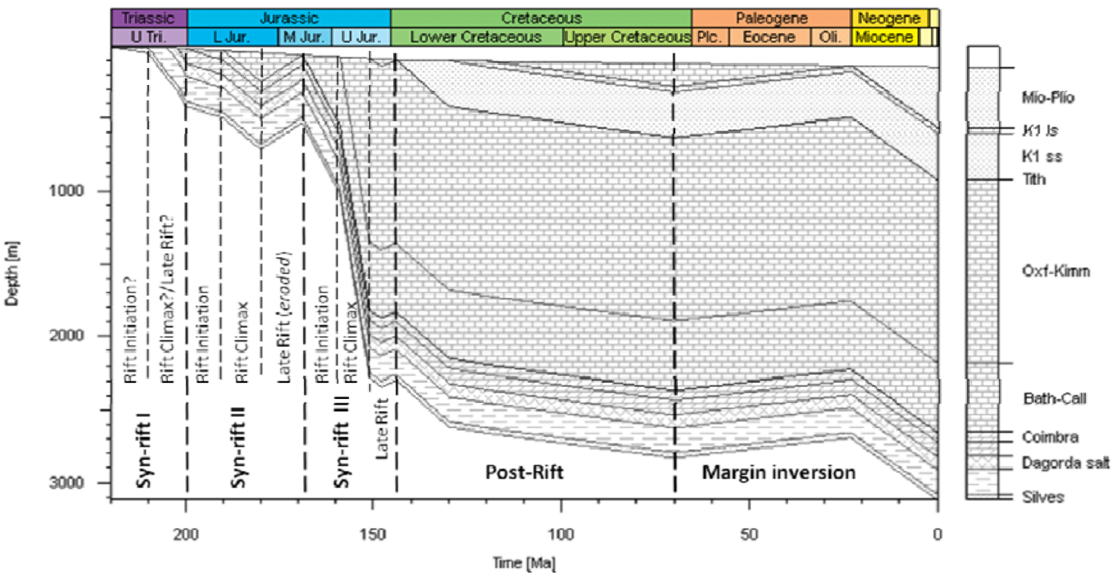

Figure 6.11 - Burial history model of Pe-1 evidencing the distinct pulses within each rift phase (I, II and III). Subsequent to the final rift phase (Late Jurassic – earliest Cretaceous), the margin reveals limited subsidence and from the Late Cretaceous onwards, uplifting is estimated. Modelling made with Petromod freeware license.

Although far from conclusively explaining all the uncertainties regarding the differential subsidence throughout southwest Iberia, this model reveals that multiphased subsidence was significant, not only on the inner proximal margin, but westward on the margin where thick syn-rift strata are observed (Fig. 6.7 and 6.8). Such an observation suggests coeval timings for the multiple subsidence events on the inner and outer proximal margins, prior to the onset of seafloor spreading.

Similar results can be found in Newfoundland and North Sea, where multiphased subsidence predominated in the Late Jurassic-Early Cretaceous. In the Jeanne d'Arc Basin, burial history modelling shows continued Triassic-earliest Cretaceous subsidence across the margin, interrupted by short-lived periods of uplift (Hiscott et al., 1990; Baur et al., 2010). In the Inner Moray Firth Basin (North Sea) Early and Late Jurassic subsidence pulses are documented, although dissimilar from other domains in the eastern and northern North Sea, which are dominated by Paleocene extension (e.g. Kubala et al., 2003).

6.5. Discussion

6.5.1. Multiphased tectonic systems tracts offshore Southwest Iberia

Continental extension in southwest Iberia occurred as three major phases of tectonic subsidence. Each of these phases is recognised on seismic, outcrop and borehole data in which three correlative second-order megasequences represent the multiphased syn-rift recorded on the margin.

In order to better investigate depositional trends on borehole data, six additional wells from offshore Lusitanian Basin were re-interpreted (Fig. 6.12). By applying the criteria of sequence stratigraphy to deposition in extensional tectonic settings, distinct systems tracts can be identified in within each phase of rifting, i.e., the Rift Initiation, the Rift Climax and Late Rift.

6.5.1.1. Rift Initiation Systems Tract

The Rift Initiation systems tract marks the first increment of subsidence that occurred in response to the onset of extension (Fig. 6.11). It is often accompanied by a basal unconformity, overlain by coarse-grained deposits representing a regression maximum (Figs. 6.4 and 6.6).

Seismic data shows that rift initiation sequence tracts are often characterised by an overall wedge-shaped geometry, showing limited vertical expression due to reduced tectonic-related subsidence (Fig. 6.8). Internal reflections are sub-parallel to divergent, often downlapping a basal unconformity (Fig. 6.9). Prosser (1993) indicated hummocky channelised longitudinal systems to predominate in this systems tract. However, internal reflections may vary, depending on the nature of the sediments accumulated within each sub-basin, as well as to their position at the hanging wall or the uplifted footwall (Figs. 6.8 and 6.9).

Data from studied outcrops and from well-logs documenting Early to Late Jurassic strata west of the Lusitanian Basin, reveal that the rift initiation systems tract is characterised by alternate aggradational to retrogradational pattern (Figs. 6.4, 6.6 and 6.12). In well Pe-1, Rift Initiation deposits from sequence 2a show a retrogradational trend within a predominantly dolomitic succession, whereas the sequence is mostly aggradational/progradational in the Lusitanian Basin (Fig. 6.12).

Also in well Pe-1, sequence 3a is initially marked by progradation, followed by retrogradation toward the rift climax phase. Similar depositional trends are observed in wells 17C-1, 16A-1, 14A-1, 13C-1 and Do-1 (Fig. 6.12). At Santiago do Cacém, sequence 3a is marked by the presence of conglomerates at its base, often rich in organic matter (Deixa-o-Resto formation) (Figs. 6.4, 6.5, and 6.5F). These conglomerates mark the transition toward the Rift Climax deposits, overlain by progressive dominance of marine influenced sediments, and define a predominant retrogradational trend for the sequence. At Bordeira, the base of this sequence includes black pebbles, which also mark a retrogradational sequence.

A similar response on wireline data to that in this chapter can be found in pre-Tithonian and mid-Aptian successions of the Jeanne d'Arc and Porcupine basins rift initiation phases (e.g. Sinclair, 1995), and in the Late Jurassic of the North Sea (e.g. Ravnås and Steel, 1998; Ravnås et al., 2000; McLeod et al., 2002). Here, retrogradational/aggradational trends define the rift initiation sequence. Subsidence during this pulse is relatively moderate, as observed on the burial history model for well Pe-1 (Fig. 6.11).

6.5.1.2. Rift Climax Systems Tract

The Rift Climax systems tract marks the period of maximum subsidence and fault growth in a rift basin (Prosser, 1993; Ravnås and Steel, 1998). In such conditions, sediment supply is usually outpaced by subsidence. On seismic data, rift climax strata are characterised by presenting wedge-shape geometry, with divergent reflectors denoting an increase in thickness toward basin-bounding faults. Retrograding deposits commonly downlap the underlying Rift Initiation systems tract, although on uplifted footwall areas these might be directly overlaying previous depositional units, as in the case of the Rift Climax sequence 3b, unconformably deposited onto Late Rift sequence 2b (Fig. 6.8 and 6.9).During the Rift Climax phase Pliensbachian marls at Bordeira and the organic-rich limestones of the Oxfordian-Kimmeridgian around Santiago do Cacém accommodated in individual sub-basins. At Santiago do Cacém and Bordeira, and in the Monte Paio well, the Pliensbachian Rift climax is partly absent due to Toarcian-Aalenian erosion (Fig. 6.4), but in the Peniche area marine black shales and marls represent a synchronous maximum in subsidence. Both events show a Maximum Flooding Surface preceding a transition to the progressive infill of individual depocentres.

On wireline data, maximum flooding surfaces are characterised by peaks of the gamma-ray profile showing a retrogradational trend at first, changing to a prograding trend after the maximum flooding surface (Fig. 6.6 and 6.12). Gamma-ray curves often show a sharp contact at the base followed by an aggradational trend (box-shaped), as that observed at the top of sequence 2b (Fig. 6.6 and 6.12). Seismic data also images this change from retrogradational to progradational (Fig. 6.8). The burial model for well Pe-1 reveals a significant increase in subsidence during the Sinemurian-Pliensbachian and Callovian(?) to early Kimmeridgian stages (Fig. 6.11). In a regional context, it is considered that the Toarcian-Aalenian event, although dissimilarly expressed along the west Iberian margin, reflects the coeval transition of active to passive rifting at the Morocco-Nova Scotia conjugate margins.

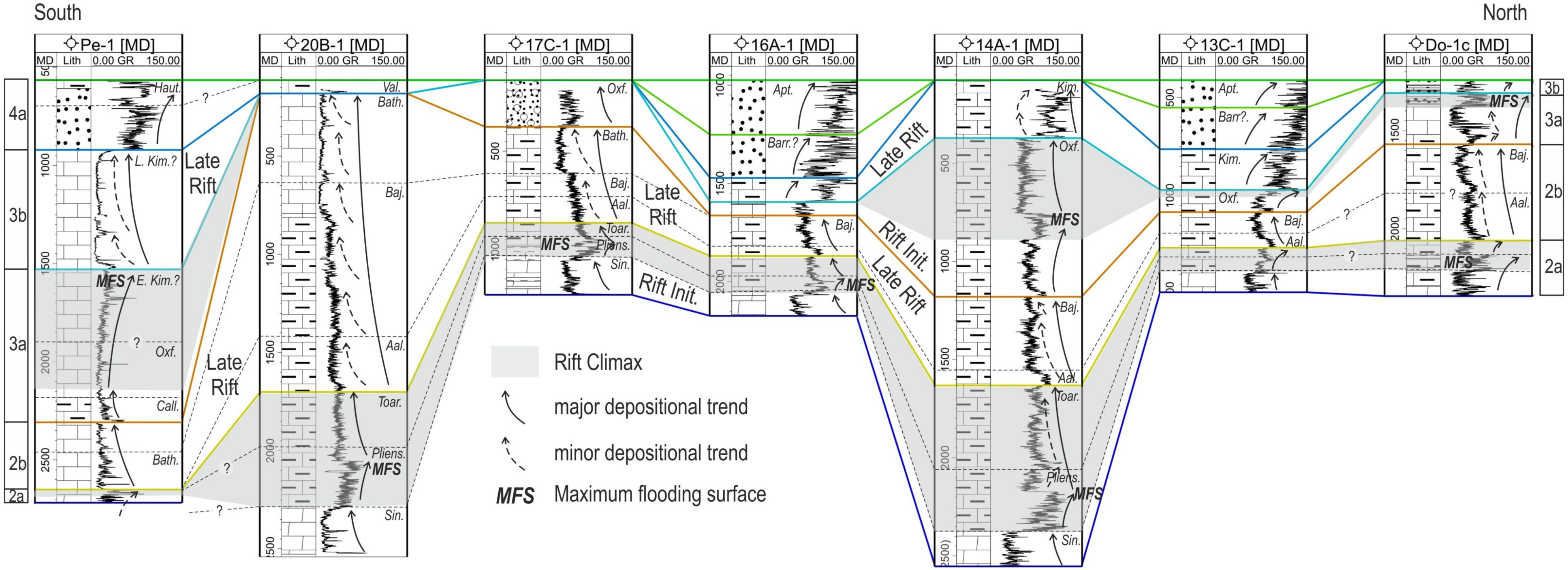

Figure 6.12 - Cross section correlating well Pe-1 with selected exploration boreholes of the proximal margin of West Iberia. The correlation panel highlights the major Pliensbachian and Oxfordian-Kimmeridgian Rift Climax phases and the similar depositional trends within each pulse of the discrete rift phases. Note the marked cyclicity of the Late Rift systems tract within sequence 2b at boreholes 20B-1 and Do-1, probably revealing the eustatic catch-up of a carbonate ramp during a phase of limited fault-related subsidence. Datum of section at the top of sequence 4a (mid to late Aptian).

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6.5.1.3. Late Rift Systems Tract

The Late Rift systems tract marks the progressive cessation of fault-controlled subsidence. This systems tract is predominantly characterised by sub-parallel continuous to gently divergent internal reflections (Fig. 6.8 and 6.9). As tectonic subsidence is gradually diminished, eustatic controls on deposition are likely to become more important at this stage when compared with the previous phases (Fig. 6.12).

The lowermost boundary of Late Rift systems tracts is often characterised by downlapping strata at the centre of individual basins and by onlapping sequences at their margins (Figures 6.8 and 6.9). Its upper boundary is marked by an unconformity, which in the case of cessation of rifting and the formation of oceanic crust is interpreted to represent the breakup unconformity (Fig. 6.8 and 6.9).

At outcrop and on wireline data, the Late Rift systems tract shows upward-coarsening strata predominantly showing progradation (Fig. 6.4 and 6.6).

On the outer proximal margin of southwest Iberia, sequence 2b reveals the progressive infill of the margin by a carbonate ramp, locally changing to a rimmed carbonate platform (Fig. 6.9). This suggests that the outer proximal margin of southwest Iberia was subsiding at a relatively moderate rate at this stage, with associated carbonate units likely catching-up with base-level rise (Fig. 6.11). Whether this mechanism is purely controlled by tectonic subsidence or eustatic variations is yet to be understood.

Wireline data reveal an overall retrograding pattern in what are essentially shallow marine limestones (Fig. 6.12). However, wells located west of the Lusitanian Basin show a distinct character when compared to Pe-1. Boreholes 17C-1 and 14A-1, show the Oxfordian-Kimmeridgian interval (sequence 3a) as markedly prograding, likely denoting distinct depositional pulses, whereas at wells 13C-1 and Do-1 this same interval is retrogradational.

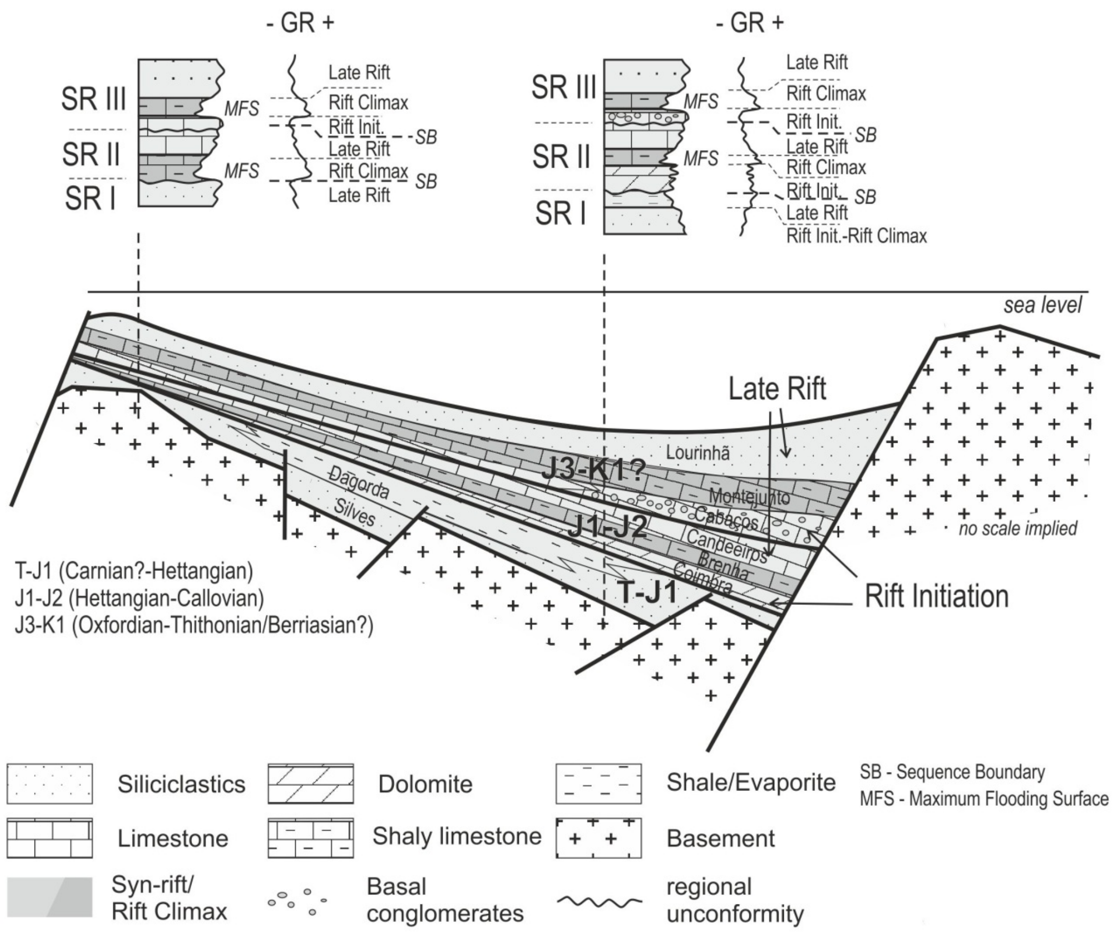

Figure 6.13 - Schematic multiphased syn-rift deposition on a tilted block at southwest Iberia. At the uplifted footwall a hiatus occurs, which is synchronous with deposition of the Rift Initiation (or Rift Climax) depositional sequences on the subsiding hanging wall.

6.5.2. Syn-rift tectono-stratigraphy across the Southwest Iberian Margin

The integration of depositional, seismic and wireline data shows that tilted-blocks formed during continental rifting accommodate discrete Megasequences, which are coeval with distinct tectonic phases (Fig. 6.13).

On the southwest Iberian margin, three major phases of extension resulted in the accumulation of second-order sequences (Megasequences in this thesis) and their subordinate third-order sequences. Each of the latter sequences is closely related to distinct tectono-stratigraphic cycles generated during multiphased continental extension and relate with the tectonic systems tracts identified in this work.

The three Rift Climax events recognised in the study area are considered to be synchronous throughout the Central and North Atlantic, namely at Nova Scotia-Morocco, Iberia-Newfoundland and in the North Sea. These rift climax units broadly coincide with the Silves (T-J1), Coimbra-Brenha (J1-J2) and the Cabaços-Montejunto (J3) lithostratigraphic units (Fig. 6.13). In addition, this model highlights the significant effect of footwall uplift in rift-shoulder areas, which greatly hindered, or completely eroded, Rift Climax deposits on the inner proximal margin (Fig. 6.13).

Figure 6.14 shows a schematic model to explain the distinct depositional architecture across a tilt-block (locations A, B and C) and its relationship with the multiple subsidence pulses recorded on a divergent margin as southwest Iberia. Twelve depositional layers are depicted to elucidate the contrasting sedimentation at the subsiding hanging wall when compared with the uplifted footwall (rift shoulder).

In this model, Rift Initiation systems tracts (layers 1-2, 5 and 10) are deposited during the infill of the newly generated accommodation space. This space is immediately filled by prograding deposits on the uplifted footwall and by coarse debris (e.g., alluvial or submarine fans, respectively in non-marine or marine settings) near basin-bordering faults (Fig. 6.8). Rift Climax systems tracts (layers 3, 6 and 11) show sharp variations in depositional facies, including the presence of prograding deposits on the footwall and retrograding deep marine (or non-marine) organic-rich facies at the basin depocentre(s), where the formation of a MFS is recorded. Subsequently, the Late Rift systems tract (layers 4, 7–9 and 12) reveal the progressive decrease of tectonic subsidence and the gradual infilling (progradation) of the previously generated accommodation space, often recording eustatic variations at a regional scale.

The model also highlights the distinct nature, extension and magnitude of major unconformities (*s.l.*) bounding distinct syn-rift Megasequences. On the uplifted footwall, angular unconformities (location A) are often present. Toward the basin depocentre(s) (locations B and C), the continued interplay between subsidence and deposition is often marked by disconformities or paraconformities.

When depositional trends for the interpreted second and third-order sequences in the study area are compared with the global sea level curve, a general fit of the major second-order rift-related T-R events (Megasequences) is far from satisfactory (Fig. 6.2).

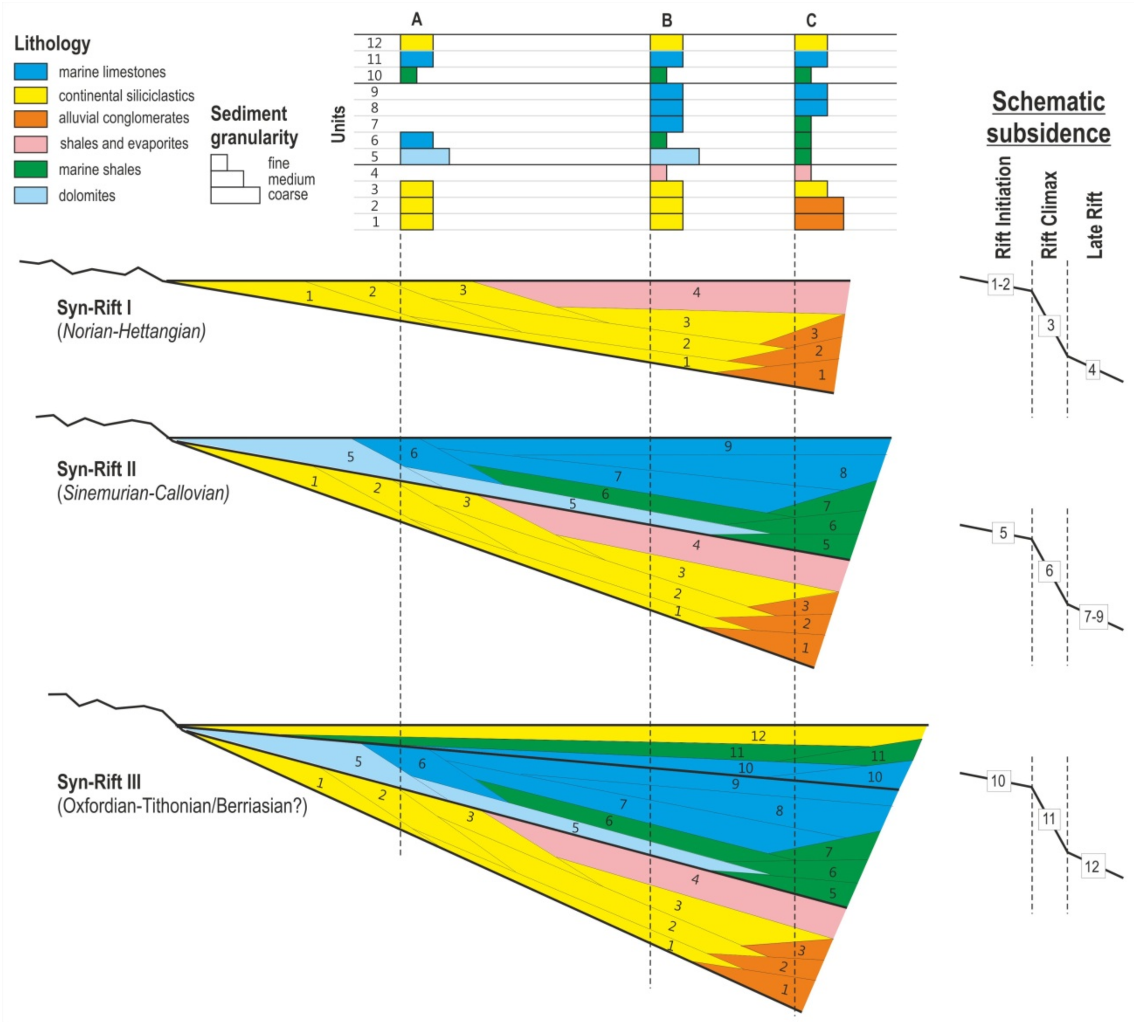

Figure 6.14 - Schematic evolution of the proximal southwest Iberian margin during the multiphased rifting showing associated depositional sequences. Pseudo-wells are located at (A) the basin uplifted footwall, (B) the basin center, and (C) the hanging wall. Subsidence curves depict the evolution of the sub-basin through the discrete Syn-Rift phases and their tectonic pulses.

Although the Pliensbachian and Bathonian base-level rise events are present, these seem to differ in magnitude with the observed data. The Toarcian-Aalenian global eustatic trend, however, correlates satisfactorily with the erosion and depositional hiatus observed on the inner proximal margin. However, it does not fully explain the reasons why a 20 Myr hiatus occurs in southwest Iberia. We postulate that important sea level variations took place during this Late Rift interval, but that they were greatly amplified by synchronous regional rift shoulder uplift during the upper part of Syn-Rift II. This event was, in turn, synchronous to the onset of the transition to seafloor spreading phase on the northern Africa-Nova Scotia conjugate margins.

In the case of the Callovian-Oxfordian forced regressive event, it is markedly opposite to the global transgressive trend, revealing a significant tectonic control on subsidence offshore southwest Iberia (Fig. 6.2).

These examples reinforce the idea that during the Late Triassic to the Late Jurassic rifting, the global eustatic curve has limited applicability in southwest Iberia. Tectonic subsidence was already the dominant factor controlling deposition since the early stages of continental rifting. The effects of sea level variations are mainly recorded during the Late Rift phases when tectonic subsidence was relatively moderate (Fig. 6.12).

Despite the multiple sequence stratigraphy concepts published to explained deposition in both marine and non-marine rift settings, or in proximal and distal domains of the margin, the data interpreted in this work prove that multiphased rifting results in the vertical stacking of discrete tectonic systems tracts, each with its depositional architectures. Therefore, during each rift pulse (the Rift Initiation, the Rift Climax and the Late Rift) such events favour the accumulation of correlative depositional tectonic systems tracts throughout continental margins. Results can therefore be used to compare adjacent sectors of rifted continental margins such as West Iberia, Newfoundland or the North Sea (Leinfelder and Wilson, 1989; Chang et al., 1992; Gawthorpe et al., 1994; Sinclair, 1995; Ravnås and Steel, 1997; Ravnås and Steel, 1998; McLeod et al., 2002; Alves et al., 2003c).

6.6. Conclusions

Multichannel seismic, borehole and outcrop data were used to document the stratigraphic response to multiphased rifting in southwest Iberia.

The three rift phases (I, II and III), segmenting the margin in discrete structural sectors, resulted in the deposition of distinct rift related Megasequences with similar depositional trends, grouped in this chapter as meaningful tectonic system tracts (e.g. Prosser, 1993).

Each of the rift phases includes discrete pulses of subsidence resulting in the deposition of Rift Initiation, Rift Climax and Late Rift systems tracts. Such systems tracts are used to build a tectono-stratigraphic framework, which explains the evolution of present-day deep-offshore basins in southwest Iberia, and also in rifted margins such as Newfoundland, the North Sea and the South Atlantic.

Rift initiation systems tracts are identified in the, Carnian-Norian, the Hettangian-Sinemurian and the Late Callovian-Oxfordian. The onset of subsidence within a rift pulse is characterised by overall aggradation/retrogradation overlying a basal regional unconformity.

Rift Climax phases are recorded during the Pliensbachian and late Oxfordian-Kimmeridgian in southwest Iberia. They are characterised by alternate retrograding/prograding trends, from which the transition to progradation coincides with a maximum flooding surface.

The Late Rift is commonly characterised by aggradation and/or progradation denoting the progressive infill of the margin, during which eustatic variations are often recorded. Late Rift pulses are recognised during the Rhaetian-Hettangian, the Toarcian-Callovian and the Kimmeridgian-Berriasian.

The modelling of the burial history of an exploration well intersecting the inner proximal margin reveals that the principal event of subsidence occurred during the late Callovian to the Kimmeridgian. The model also shows that subsidence during syn-rift phases I and II is significant, suggesting a Sinemurian-Callovian period of crustal extension on the outer proximal and distal margin.

Chapter 7

Crustal deformation and submarine canyon incision in a Meso-Cenozoic first-order transfer zone (SW Iberia, North Atlantic Ocean)

This chapter was submitted during editing of the thesis manuscript and subsequently published as "Pereira, R. and Alves, T. M. (2013). Crustal deformation and submarine canyon incision in a Meso-Cenozoic first-order transfer zone (SW Iberia, North Atlantic Ocean). Tectonophysics, 601, 148-162. DOI: 10.1016/j.tecto.2013.05.007".

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7. Crustal deformation and submarine canyon incision in a Meso-Cenozoic first-order transfer zone (SW Iberia, North Atlantic Ocean)

Abstract

The offshore prolongation of the Messejana-Plasencia Fault Zone (MPFZ), a first-order transfer zone, is investigated in order to explain the role of oblique extension on the Southwest Iberian margin, as it records firstly the effects of extension between Iberia, Newfoundland, and West Tethys prior to plate convergence with North Africa. In such a setting, the MPFZ is shown offshore as a deformed 5-10 km wide region, oblique to the continental margin that controlled local deposition since the onset of early Mesozoic rifting as part of a wider transcurrent domain, the São Vicente sub-basin. The accumulation of growth strata suggests the development of a Mesozoic rift-related dextral pull-apart basin within a releasing bend. A Late Cretaceous to Cenozoic shift in MPFZ kinematics towards a left-lateral transpressive component is proposed, in order to accommodate post-breakup counter-clockwise rotation and eastward migration of Iberia towards its present position. This work demonstrates that: 1) the true temporal and spatial scales in which first-order transfer zones accommodate crustal movements during continental rifting and subsequent basin inversion; 2) the recognition of an extensive region of strain accommodation, in what is one of the principal tectonic segments of the Iberian Plate has profound implications to future palaeogeographic reconstructions; 3) that the São Vicente Canyon, the physiographic expression of the MPFZ, incised the margin as early as the latest Cretaceous-Paleocene, a period of time synchronous with the onset of tectonic uplift in Southwest Iberia. In such a setting, structures as the MPFZ form important paths for sediment by-pass and canyon incision on newly-established divergent margins. The acknowledgement of the MPFZ as a complex releasing-restraining bend also has major implications on the seismogenic and tsunamigenic risk analyses in Southwest Iberia, with the structure being capable of generating large-magnitude earthquakes, and potentially tsunamis, as those of the 1755 Great Lisbon Earthquake.

7.1. Introduction

Transfer zones of continental margins comprise the preferred locus for the accommodation of crustal strain in both divergent and convergent settings (Morley et al., 1990; Mohriak and Rosendahl, 2003; Storti et al., 2003; Cunningham and Mann, 2007). Transfer zones are thus dominated by lateral movement over a narrow region of significant strike-slip tectonics, often forming coeval releasing and restraining bends that control adjacent depositional systems (Storti et al., 2003; Cunningham and Mann, 2007).

Southwest Iberia, located in the southernmost domain of the North Atlantic Ocean, is bounded to the south by the Newfoundland-Gibraltar Transform Zone (Fig. 7.1). Its Mesozoic evolution is dominated by the combined effects of normal and oblique rifting, followed by continental break-up in the vicinity of an oceanic triple-junction separating the Eurasian, North African and North American tectonic plates (e.g. Arthaud and Matte, 1975; Zitellini et al., 2009; Jiménez-Munt et al., 2010; Sallarès et al., 2011) (Fig. 7.2). In such a setting, the onshore and offshore segment of the Messejana-Plasencia Fault Zone, (MPFZ) comprises a major strike-slip lineament accommodating deformation in Iberia since the Paleozoic (Arthaud and Matte, 1975; Schermerhorn et al., 1978; Mauffret et al., 1989b; Ribeiro et al., 1990; Terrinha et al., 2009). Examples of neighbouring first-order strike-slip lineaments similar to the MPFZ include the Minas Fault Zone in Nova-Scotia (Canada) and the South Atlas Fault Zone in Morocco, both comprising large-scale basin bounding lineaments in the Central Atlantic (Laville and Petit, 1984; Welsink et al., 1989; Olsen and Schlische, 1990; Piqué and Laville, 1996) (Fig. 7.2).

Despite the importance of transcurrent fault zones to the evolution of continental margins, there are still scarce data on these large-scale geological features, and on the ways they accommodate both intra-plate deformation and the relative movement of tectonic plates (e.g. Lister et al., 1986; Etheridge et al., 1989). Open questions on first-order transfer zones include: a) what is their impact on stress readjustments during major changes in plate kinematics; b) what are the effects of variations in the relative rates of oceanic expansion on the geometry of transfer zones; and c) how important are these major strike-slip lineaments in controlling submarine canyon incision and sediment by-pass on continental margins.

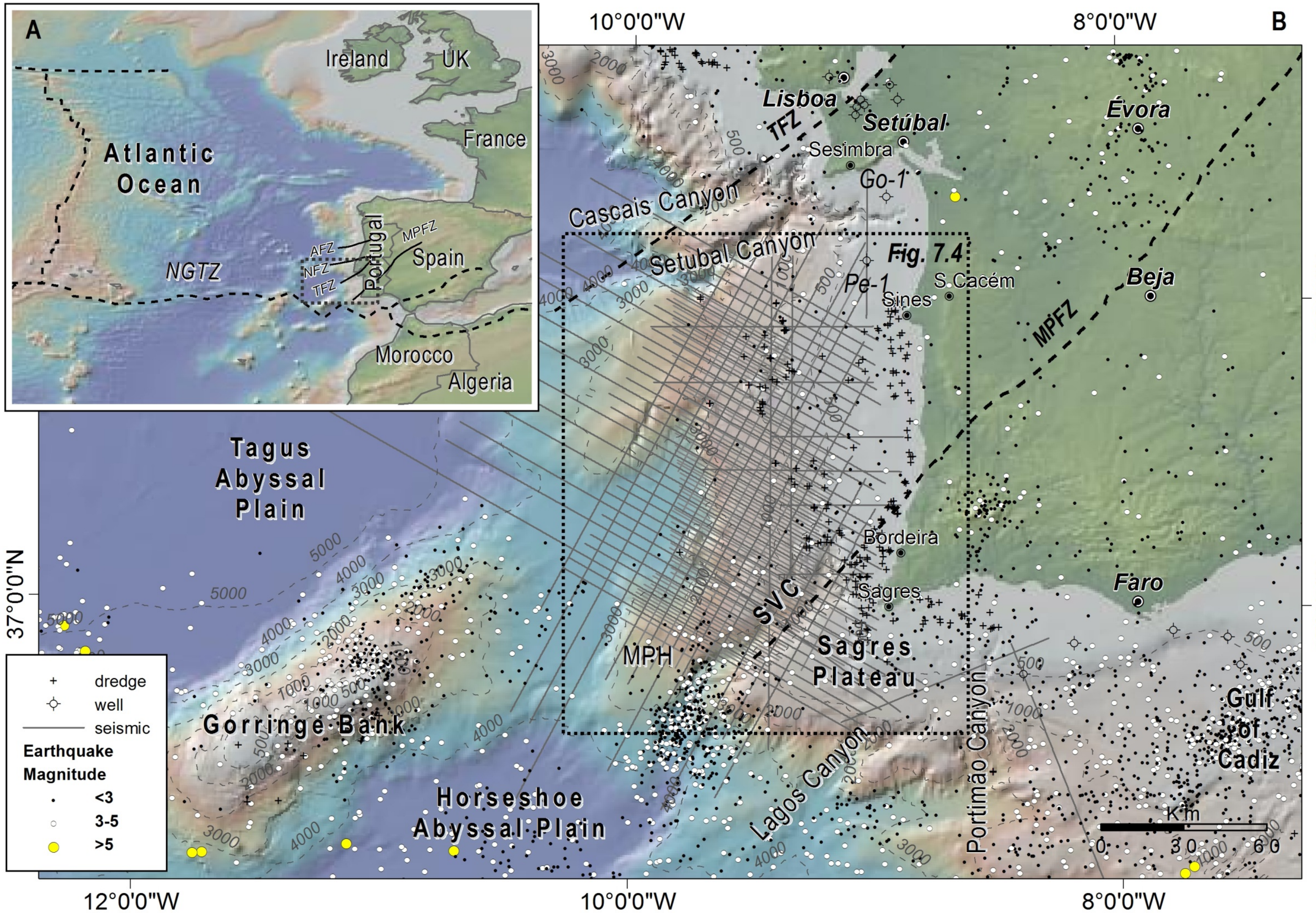

Figure 7.1 - Location of the study area, showing: A) The relative position of Iberia and its tectonic plate boundaries in relation to the Central and North Atlantic and the Newfoundland-Gibraltar Transform Zone (NGTZ); B) The location of the Messejana-Plasencia Fault Zone (MPFZ) across the Southwest Iberian margin and its prolongation towards onshore. The location and magnitude of earthquake historical data was obtained from the Instituto Geográfico Nacional de España (IGN-CNIG, http://www.ign.es). Note the cluster of earthquake epicentres at the southwest termination of the São Vicente Canyon, at the Gorringe Bank and in the Western Gulf of Cadiz. MPH – Marquês de Pombal High; SVC – São Vicente Canyon; TFZ – Tagus Fault Zone. Regional bathymetry in meters (regional map extracted from GeoMapApp 3.1.2)

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Using a dense grid of high-quality 2D multichannel seismic profiles, dredge and outcrop data from Southwest Iberia, this work investigates the evolution of a first-order transfer zone, the MPFZ, on a divergent continental margin (Fig. 7.1). The present chapter demonstrates that: 1) an early transtensional regime controlled the syn-rift history of the MPFZ, with the combined effects of extension and local uplift forming related pull-part basins and large hinge zones on the Southwest Iberian margin; 2) a prolonged period of submarine canyon incision within the MPFZ shaped the margin since, at least, the latest Cretaceous-Early Cenozoic; and 3) the reassessment of MPFZ's evolution has implications to future elastic palaeogeographic reconstructions of the North Atlantic Ocean.

At present, the southwest end of the MPFZ coincides with an important cluster of earthquake epicentres on the margin (Fig. 7.1b). Focal mechanisms along this distal segment of the MPFZ reveal a predominant transpressive regime (Gràcia et al., 2003a; Geissler et al., 2010), that differs from: 1) the setting interpreted in this paper for the Mesozoic evolution of the MPFZ; 2) the present-day geometry of the MPFZ, a major negative flower structure representing the offshore prolongation of the relatively narrow Messejana-Plasencia Fault.

7.2. Data and Methods

In this study was used an extensive dataset comprising ~8.500 km of 2D multichannel seismic lines from Southwest Iberia (Fig. 7.1). The dataset includes exclusive and non-exclusive migrated post-stack seismic surveys that image over 23.000 km^2 of the region between the Setúbal Canyon, near Lisbon, and the Sagres Plateau to the South (Fig. 7.1). The interpreted seismic data were tied to stratigraphic information from well Pe-1, located in the north-eastern part of the study area (Fig. 7.1). Elsewhere, away from well control, the interpreted seismic units were tied to dredge data collected on the proximal margin (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Coppier and Mougenot, 1982) (Fig. 3.3).

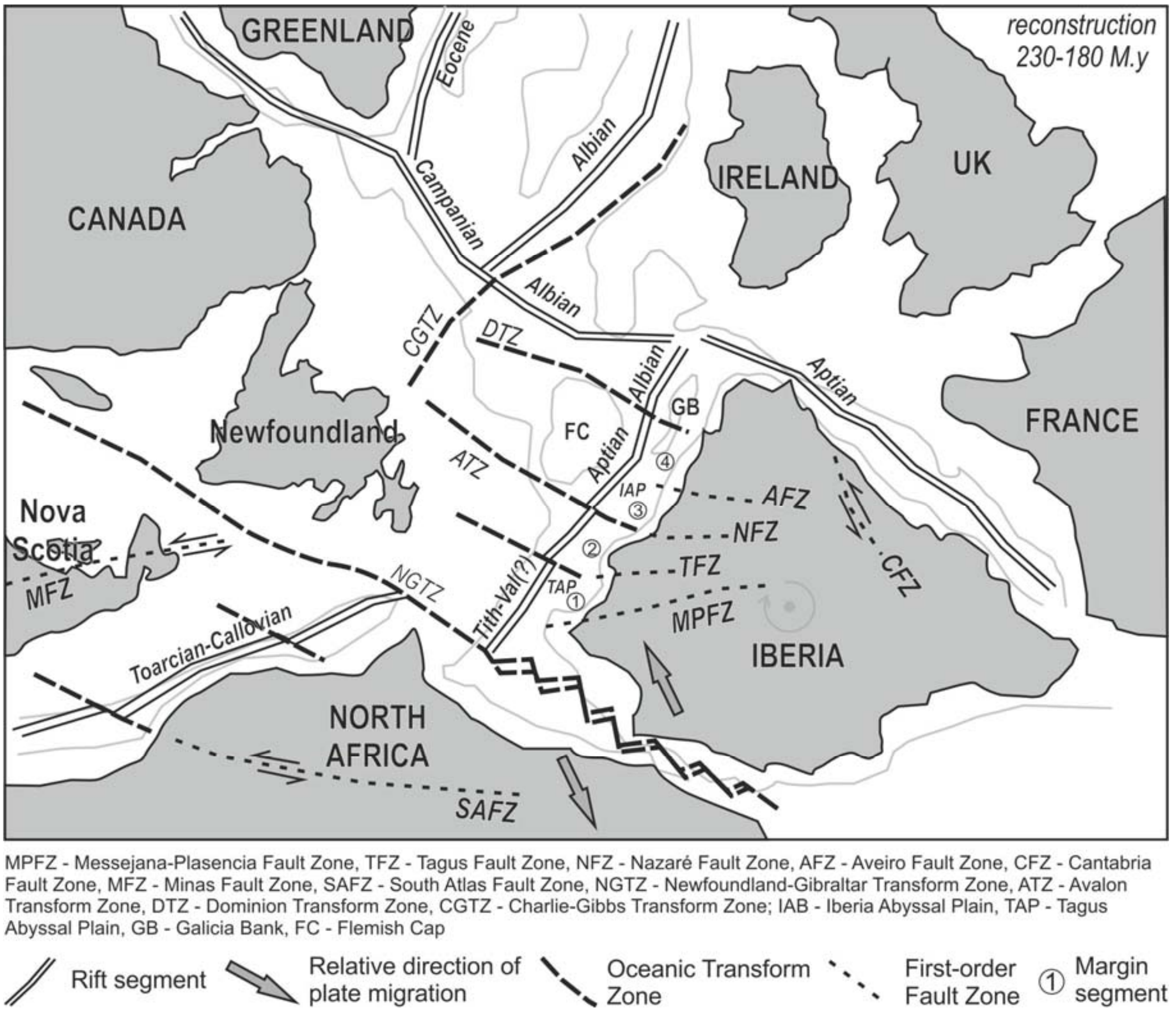

Figure 7.2 - Palaeogeographic reconstruction of the Central and North Atlantic Oceans during continental rifting, showing the main oceanic transform segments and transfer zones across Iberia, Morocco and Nova Scotia (Canada). Modified from Srivastava and Verhoeff (1992). Ages of lithospheric breakup from Hiscott et al. (1990). Segments 1 to 4 from Alves et al. (2009).

In this analysis, the concepts of Manatschal and Bernoulli (1998, 1999), Alves et al. (2009) and Pereira and Alves (2011) were applied to investigate the architecture of the Southwest Iberian margin, allowing its subdivision in specific sectors; the inner proximal, the outer proximal and the distal margins, each one presenting distinct syn-rift subsidence histories (Pereira and Alves, 2012) (see chapter 4 and 6 for additional details). The interpretation of main seismic units followed the criteria of Mitchum et al. (1977a) and Prosser (1993), and led to the definition of eight distinct syn-rift and post-rift megasequences (e.g. Hubbard et al., 1985b; Hubbard, 1988). These were tied to well and outcrop stratigraphic data (Witt, 1977; Oliveira, 1984; Wilson, 1988; Inverno et al., 1993; Azerêdo et al., 2003; Rey et al., 2006) (Fig. 7.3).

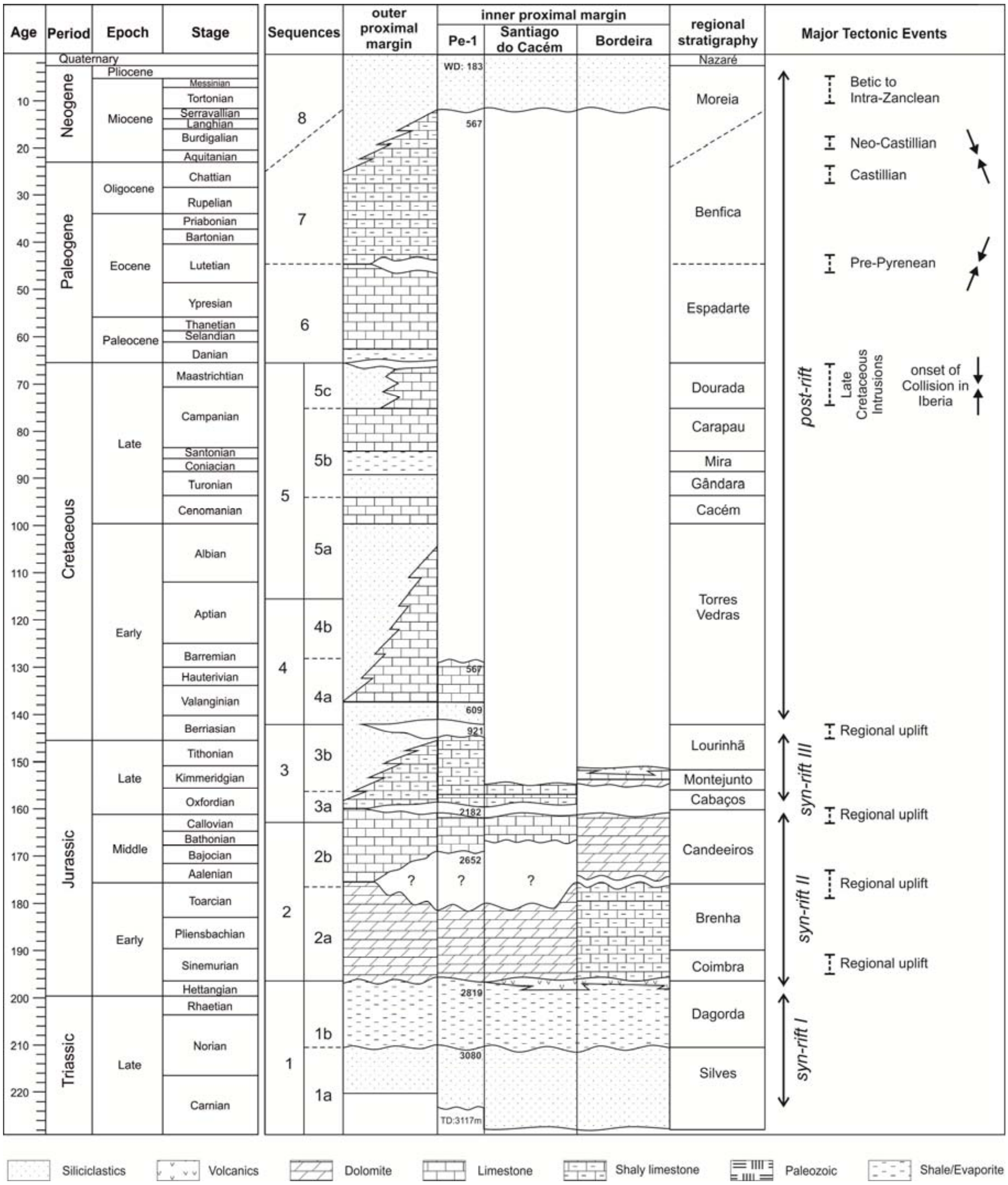

Figure 7.3 - Simplified lithostratigraphy and seismic-stratigraphy of the Southwest Iberian margin relative to main tectonic events. Stratigraphic tops in well Pe-1 are based on non-exclusive well reports. Onshore lithostratigraphy is based on GPEP (1986), Azerêdo et al. (2003), Rey et al. (2006) and Alves et al. (2003a). Outer proximal margin lithologies based on Alves et al. (2009). Cenozoic compressive events from Alves et al. (2003a).

The interpreted megasequences show lithostratigraphic affinity along the western Iberia margin and can also be correlated with the continental margins off Newfoundland, Nova Scotia and Morocco (Hiscott et al., 1990; Pereira and Alves, 2011, 2012) (see chapter 2 and 4).

7.3. Geological setting

7.3.1. Tectono-stratigraphic evolution

Southwest Iberia was located between the Central-North Atlantic and the West Tethys provinces during the Mesozoic, a region of uttermost importance to understand the evolution of magma-poor rifted continental margins located in the vicinities of oceanic triple junctions (Fig. 7.2). The study area evolved as an hyper-extended continental rift margin from the Late Triassic to the latest Jurassic-Early Cretaceous, when continental breakup resulted in the generation of oceanic crust in the Tagus Abyssal Plain (Mauffret et al., 1989b; Hiscott et al., 1990; Manatschal and Bernoulli, 1998; Tucholke et al., 2007). Together with continental rifting in what was to be the southern part of the North Atlantic Ocean by the Aptian, Iberia also records Late Triassic to Late Jurassic NW-SE oblique rifting at the western termination of the Tethys Ocean (Mauffret et al., 1989b; Jiménez-Munt et al., 2010; Sallarès et al., 2011) (Fig. 7.2).

Late Triassic to Early Cretaceous rifting was largely controlled by NE-SW basement structures formed during the Variscan Orogeny (Arthaud and Matte, 1975; Ribeiro et al., 1979). These major Paleozoic fault zones evolved as tectonic boundaries to distinct N-S rift segments and future abyssal plains (Alves et al., 2009) (Fig. 7.2). Onshore, a strong influence of oblique rifting and strike-slip movement in smaller-scale transfer zones separating individual sectors of the Lusitanian Basin is documented (Wilson, 1988; Leinfelder and Wilson, 1989).

Multiphased rifting (Syn-Rift phases I, II and III, Fig. 7.3) and associated rift-locus migration, both westwards and northwards (Fig. 7.2), led to the deposition of three discrete syn-rift megasequences in Southwest Iberia (Afilhado et al., 2008; Alves et al., 2009; Pereira and Alves, 2011, 2012).

Although poorly expressed onshore, Early to Late Cretaceous units (Megasequences 4 and 5) drilled in well Pe-1 and collected in multiple dredge locations, comprise alternate siliciclastic and carbonate units (Matos, 1979; Oliveira, 1984; Inverno et al., 1993; Pereira et al., 2011; Pereira and Alves, 2012) (Figs. 2.13 and 7.3).

From the Late Cretaceous onwards (Megasequences 6, 7 and 8), the Southwest Iberian margin experienced a prolonged phase of tectonic inversion that resulted from oblique convergence between the Iberian microplate, the African and Eurasian plates (Neves et al., 2009; Terrinha et al., 2009; Zitellini et al., 2009; Cunha et al., 2010b; Pereira et al., 2011) (Fig. 7.3). During this period, significant sediment by-pass towards the distal margin limited deposition on the inner proximal margin (Pereira et al., 2011). Borehole and dredge data record the accumulation of mixed carbonate and siliciclastic units on the proximal margin (Baldy, 1977; Matos, 1979; Mougenot et al., 1979) (Figs. 2.13, 3.3 and 7.3).

7.3.2. The Messejana-Plasencia Fault Zone in the context of Meso-Cenozoic evolution of Southwest Iberia

The modern Messejana-Plasencia Fault Zone, the onshore expression of a wider area of deformation extending over 500 km in length along Portugal and Spain, comprises a noteworthy left-lateral NE-SW strike-slip lineament (Arthaud and Matte, 1975; Schermerhorn et al., 1978; Ribeiro et al., 1990) (Fig. 7.1).

Its origin can be traced to inherited Late Paleozoic left-lateral sutures striking NNE to ENE (Schermerhorn et al., 1978; Ribeiro et al., 1990). During Triassic to Early Jurassic continental rifting, the MPFZ was reactivated as a transtensive strike-slip, allowing the intrusion of Central Atlantic Magmatic Province (CAMP) dolerites, important features to palaeogeographic reconstructions in the North Atlantic (Schermerhorn et al., 1978; Schott et al., 1981; Cebriá et al., 2003; Palencia-Ortas et al., 2006; Martins et al., 2008; Silva et al., 2008). The latter reconstructions indicate that during the Triassic-Jurassic interval, the Iberian microplate was migrating westwards in relation with the North African plate, recording clockwise rotation (Srivastava et al., 1990a; Srivastava et al., 1990b; Palencia-Ortas et al., 2006; Osete et al., 2011).

From the Late Cretaceous onwards, driven by the opening of the Gulf of Biscay and the collision with North Africa, Iberia was migrating eastwards with an associated counter-clockwise rotation (Srivastava et al., 1990a; Srivastava et al., 1990b; Palencia-Ortas et al., 2006; Osete et al., 2011).

After continental break-up, interpreted to have occurred in the latest Jurassic (Mauffret et al., 1989b) or Early Cretaceous (Tucholke et al., 2007), three main erosional events related to major tectonic phases affected Southwest Iberia in the early-mid Oligocene, the Miocene and the Pliocene-Quaternary (e.g. Alves et al., 2003a; Viszcaino et al., 2005). Thus, the Cenozoic Messejana-Plasencia Fault Zone was formed in alternating compressional and extensional regimes, which generated releasing and restraining bends onshore, some recording up to 30 km of horizontal displacement (Arthaud and Matte, 1975; De Vicente et al., 2011).

The offshore prolongation of the MPFZ also had an important control on the incision of the São Vicente Canyon, a 100-km long submarine canyon extending from near the coastline to the Horseshoe Abyssal Plain (Mauffret et al., 1989b) (Fig. 7.1). Miocene-Quaternary deposition within the São Vicente Canyon is characterized by heterogeneous sedimentary units largely deposited in response to erosion and enhanced tectonic activity at the offshore prolongation of the MPFZ (Roque, 2007). Outside the São Vicente Canyon, hemipelagic sediments (turbidites and contourites) were accumulated from the Late Miocene onwards (Alves et al., 2000; Viszcaino et al., 2005; Roque, 2007). Locally, thick Mesozoic sequences as old as the Late Triassic are observed underneath the São Vicente Canyon (Alves et al., 2003a; Terrinha et al., 2009). In such a context, the offshore prolongation of the MPFZ has been interpreted either as a NW-verging reverse fault (Terrinha et al., 2009) or a NW-dipping normal fault (Pereira and Alves, 2011; Pereira et al., 2011).

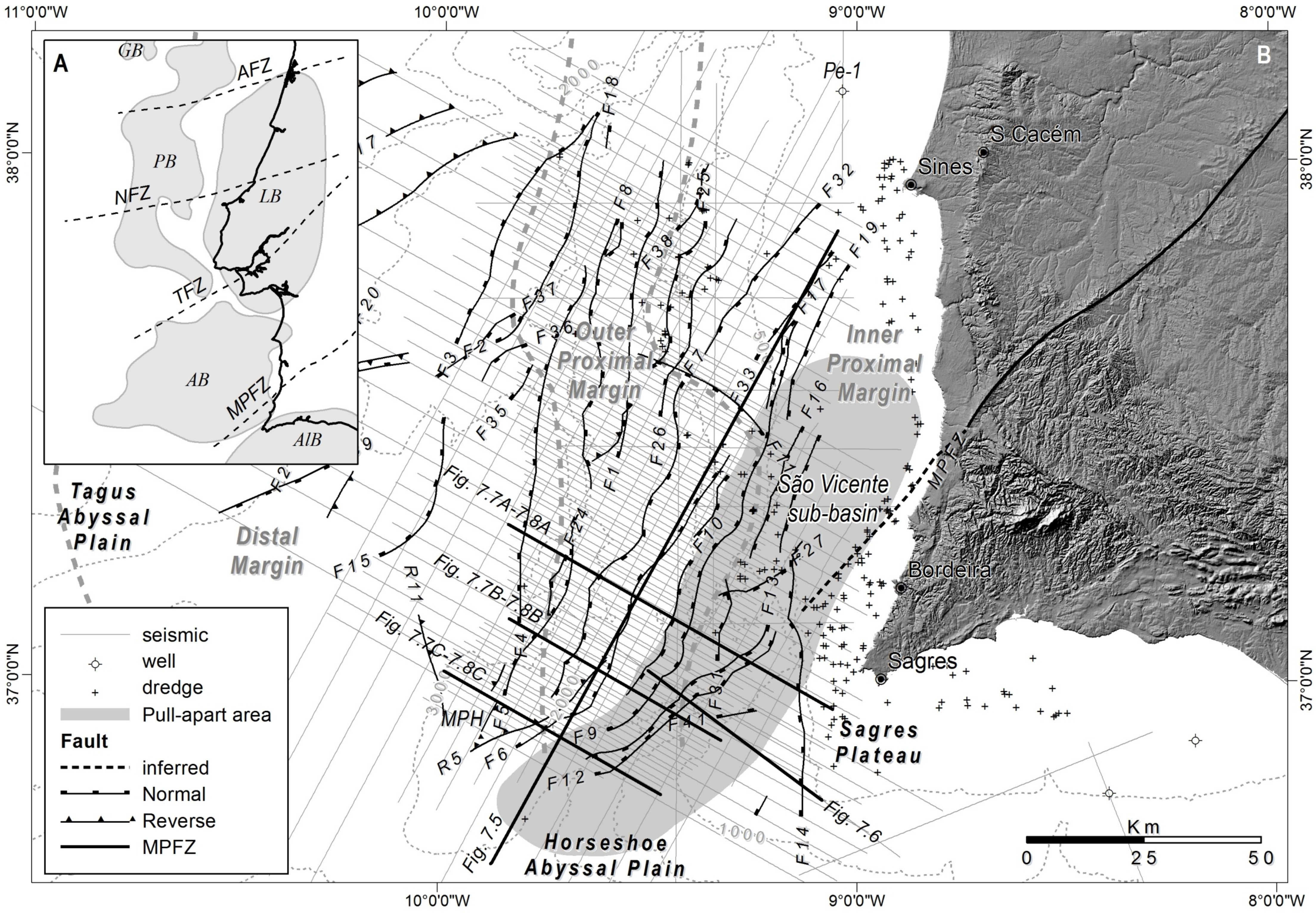

Figure 7.4 - Map of the study area showing: A) Main Mesozoic rift basins in South and West Iberia and corresponding basin-bounding transfer zones; and B) Faults interpreted on seismic data, location of multichannel seismic data presented in this work, exploration wells and dredge location used to calibrate the interpretation in this work (Baldy, 1977; Matos, 1979; Mougenot et al., 1979; Coppier and Mougenot, 1982). Bathymetric data is represented in meters, based on GEBCO (http://www.gebco.net/).

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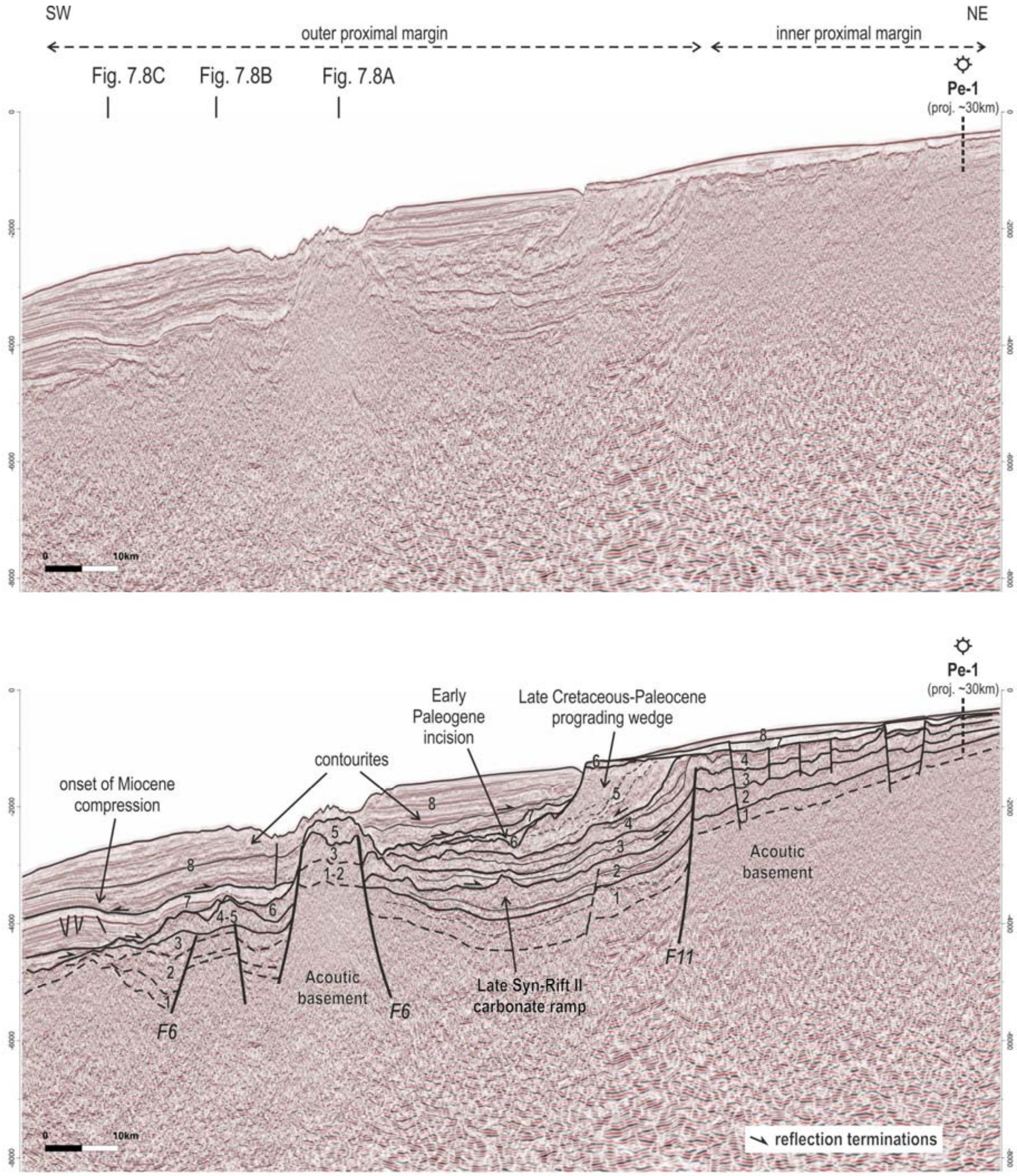

Figure 7.5 - Regional multichannel seismic line along the proximal Southwest Iberian margin, tied to exploration well Pe-1, showing Late Triassic-Late Jurassic growth strata (Megasequences 1 to 3) underneath post-rift depositional sequences (Megasequences 4 and 5) and syn-inversion strata (Megasequences 6, 7 and 8). Note the presence of a Late Cretaceous prograding wedge on the inner proximal margin and thick Cenozoic units showing multiple channels. Ages for interpreted Megasequences in figure 7.4. Location of the seismic line in figure 7.4.

7.4. Results

7.4.1. Tectono-stratigraphy of the MPFZ area

Originally interpreted as a region of Late Cretaceous uplift, erosion and deposition of olistoliths (Baldy, 1977; Mougenot et al., 1979; Mougenot, 1988), the seismic data in this paper reveal significant Meso-Cenozoic deposition on the Southwest Iberian margin, largely controlled by N-S to NE-SW normal faults dipping to the East and West (Figs. 7.4 and 7.5).

On the south-eastern sector of the margin, a NE-SW elongated area of crustal transcurrent strain is identified, herein referred as São Vicente sub-basin. This area is broadly defined between faults F10 and F14 (shaded area in Fig. 7.4) extends over 120 km and width of about 20-40 km, showing a fault pattern dissimilar to the remainder of the margin. Here, NE-SW (e.g. F12 and F13, the MPFZ) and NW-SE fault segments (e.g. F11) suggest the accommodation of significant lateral movements in the Southwest Iberian margin during the Mesozoic (Fig. 7.4).

Mesozoic strata within this transcurrent domain reveal the development of a highly-faulted axial trough, roughly below where the modern São Vicente Canyon incises the margin (Figs. 4.9, 7.6 and 7.7). Within the wider São Vicente sub-basin and in the MPFZ, deposition subsequent to continental rifting and breakup continued until the present day. Thus, a suite of eight meaningful seismic-stratigraphic megasequences can be identified within the study area (Fig. 7.3).

7.4.2. Syn-rift megasequences

Megasequence 1 shows chaotic to sub-parallel reflections onlapping the Paleozoic basement. It thickens only locally onto major basin-bounding faults, a character suggesting limited tectonic subsidence during this period (Fig. 7.5). Megasequence 1 comprises Carnian to Norian continental red beds and shalley-evaporitic deposits of Carnian-Hettangian age, identified at outcrop (Bordeira and Santiago do Cacém) and borehole (Go-1 and Pe-1) (Figs. 7.3 and 7.4). However, within the MPFZ there is no clear evidence of the presence of thick evaporites and halokinesis (Figs. 7.6, 7.7 and 7.8).

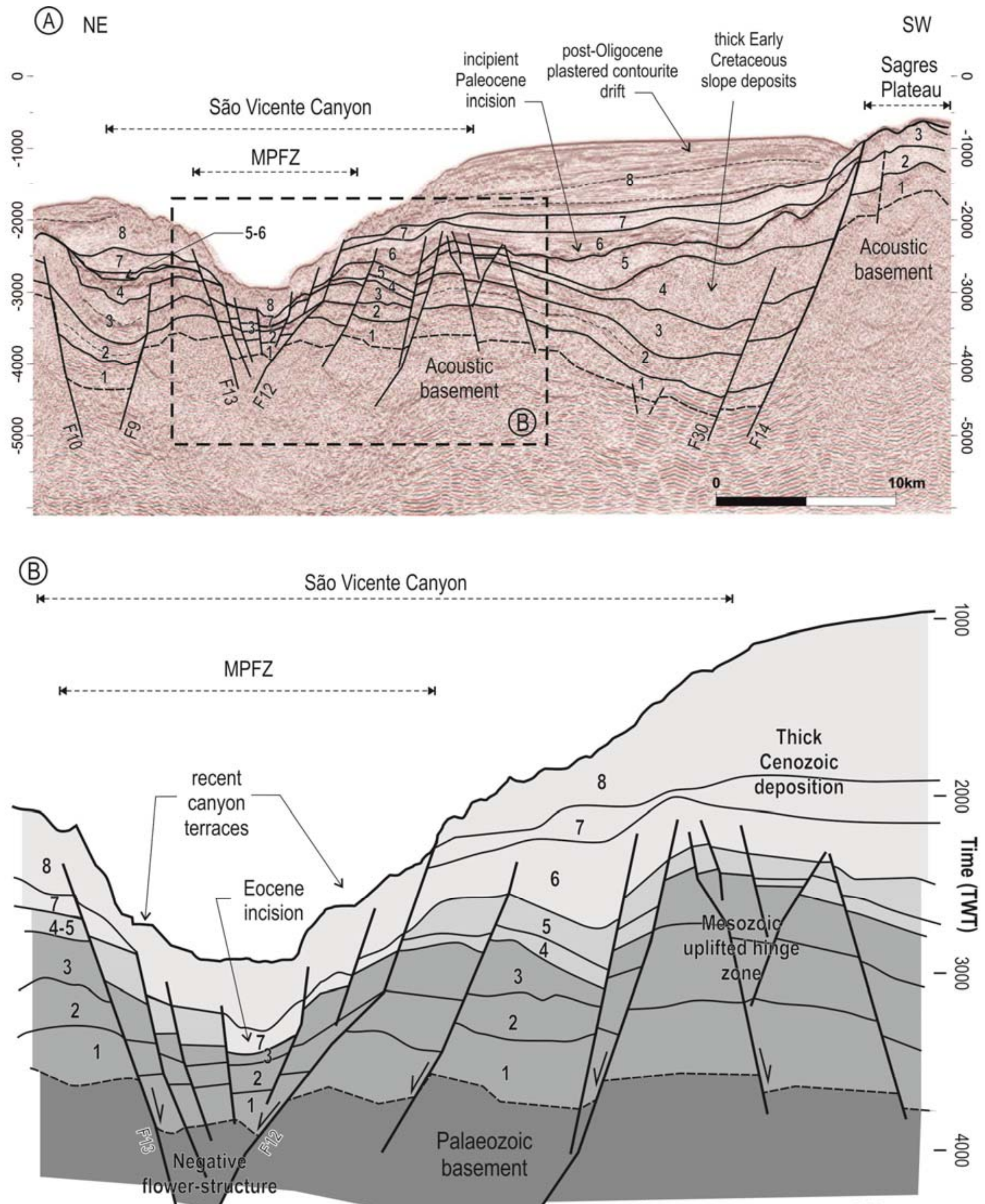

Figure 7.6 - Multichannel seismic section (A) and interpreted line diagram (B) across the offshore segment of the Messejana-Plasencia Fault Zone, revealing the architecture of a negative flower structure underneath the São Vicente Canyon.

Megasequence 2 (Sinemurian-Callovian) is generally characterized by thick growth strata deposited onto NNE-SSW to NE-SW master faults (e.g. F14, Fig. 7.5), and by divergent to sub-parallel reflections of high amplitude (Figs. 7.6, 7.7 and 7.8). The megasequence marks the progressive development of a Lower to Middle Jurassic carbonate ramp (Fig. 7.5), and denotes the progressive establishment of marine conditions in Southwest Iberia, a character that has been interpreted as representing the infill of the margin within a context of continued base-level rise (Pereira and Alves, 2012) (See chapter 6 for details).

The development of Megasequence 2 is associated with Syn-Rift phase II, which records continental extension and transition to seafloor spreading in the northern Central Atlantic margins and left-lateral (oblique) rifting in the Algarve Basin and Gulf of Cadiz (Sallarès et al., 2011; Pereira and Alves, 2012) (Fig. 7.2). Occasionally, strong reflectors within the megasequence reveal a pronounced unconformity (Figs. 7.5 to 7.8), coeval with a Toarcian-Aalenian hiatus observed at outcrop (Fig. 7.3). Megasequence 2 is truncated at its top by the regional Late Callovian to Middle Oxfordian angular unconformity (e.g. Azerêdo et al., 2003) (Fig. 7.3).

Megasequence 3 (Oxfordian-Berriasian) comprises growth strata deposited during the last episode of syn-rift subsidence in Southwest Iberia (Pereira and Alves, 2011) (Figs. 7.5 to 7.8). It reveals cyclic retrograding-prograding trends at outcrop and in well Pe-1, with a subsidence maximum recorded at the boundary between the Oxfordian and the Kimmeridgian (Wilson et al., 1989; Stapel et al., 1996; Pereira and Alves, 2012). Within the MPFZ, reflections in Megasequence 3 are chaotic to transparent, suggesting the predominance of siliciclastic deposition. In other parts of the São Vicente sub-basin, however, high-amplitude continuous reflections suggest the deposition of carbonates, in similarity to onshore outcrop locations such as in Bordeira and Santiago do Cacém (Figs. 7.5 to 7.8). In these locations, Oxfordian to Kimmeridgian organic-rich limestones, interbedded with conglomerates and breccias, mark the onset of Rift Phase III (Oliveira, 1984; Inverno et al., 1993; Pereira and Alves, 2012).

7.4.3. Post-rift Megasequences

The base of Megasequence 4 (Berriasian-Aptian) is characterised by a major change in seismic facies above an angular unconformity (Figs. 7.5 to 7.8). High-amplitude chaotic to sub-horizontal reflections, some showing downlapping terminations, suggest the predominance of siliciclastic deposits in Megasequence 4, similarly with strata drilled further north in well Pe-1 (Figs. 7.3 and 7.5). Megasequence 4 is poorly developed (or absent) on the Sagres Plateau and East of the F14 fault, a character that contrasts with the thick Early Cretaceous post-rift sequences observed on the continental slope and distal margin towards the Tagus and the Horseshoe Abyssal Plains (Figs. 7.6 and 7.8). It is therefore interpret that the MPFZ, along with other relay ramps and subordinate faults (e.g. F11), comprised preferred paths for sediment by-pass towards the distal margin during the Early Cretaceous (Fig. 7.9A).

Although absent in great part of the proximal margin, the Aptian-Maastrichtian Megasequence 5 is observed in the MPFZ and the São Vicente sub-basin. This unit is characterized by high amplitude, chaotic to sub-parallel reflections (Figs. 7.6 and 7.8). Evident thickness variations between the proximal and distal margins suggest once more significant transport of Late Cretaceous sediment towards the distal margin (Fig. 7.8C). The Late Cretaceous is also the period when a prominent prograding sediment wedge developed between F9 and F11, reinforcing the notion that significant tectonic controls were dominating the regional uplift and sediment by-pass on the margin (Fig. 7.5 and 7.9a). These tectonic controls were likely amplified by the intrusion of Late Cretaceous igneous bodies in Southwest Iberia (e.g. Miranda et al., 2009), a phenomenon related to widespread crustal movements that are associated with the onset of counter-clockwise rotation of the Iberian microplate. In the MPFZ and surrounding continental slope area, Megasequence 5 is truncated by a regional erosional surface of early Paleogene age (Figs. 7.5, 7.6 and 7.8). On seismic data, this same surface records a major change in the tectonic setting of Southwest Iberia as it marks the onset of tectonic inversion on the margin.

On the proximal margin, Megasequence 6 (Paleocene to early-mid Eocene) shows downlapping sub-parallel to chaotic/transparent reflections, whereas on the distal margin sub-parallel reflections predominate in what should represent a deep-marine succession (Figs. 7.5, 7.6 and 7.8), which contrast with dredge data from the proximal margin, where carbonate samples were collected (Fig. 2.13). Chaotic to sub-parallel seismic facies within the MPFZ suggest the occurrence of mass-wasting deposits sourced from the East. Away from the MPFZ, Megasequence 6 shows downlap onto incipient anticlines, the first evidence of crustal shortening in Southwest Iberia (Figs. 7.5 and 7.8B-C).

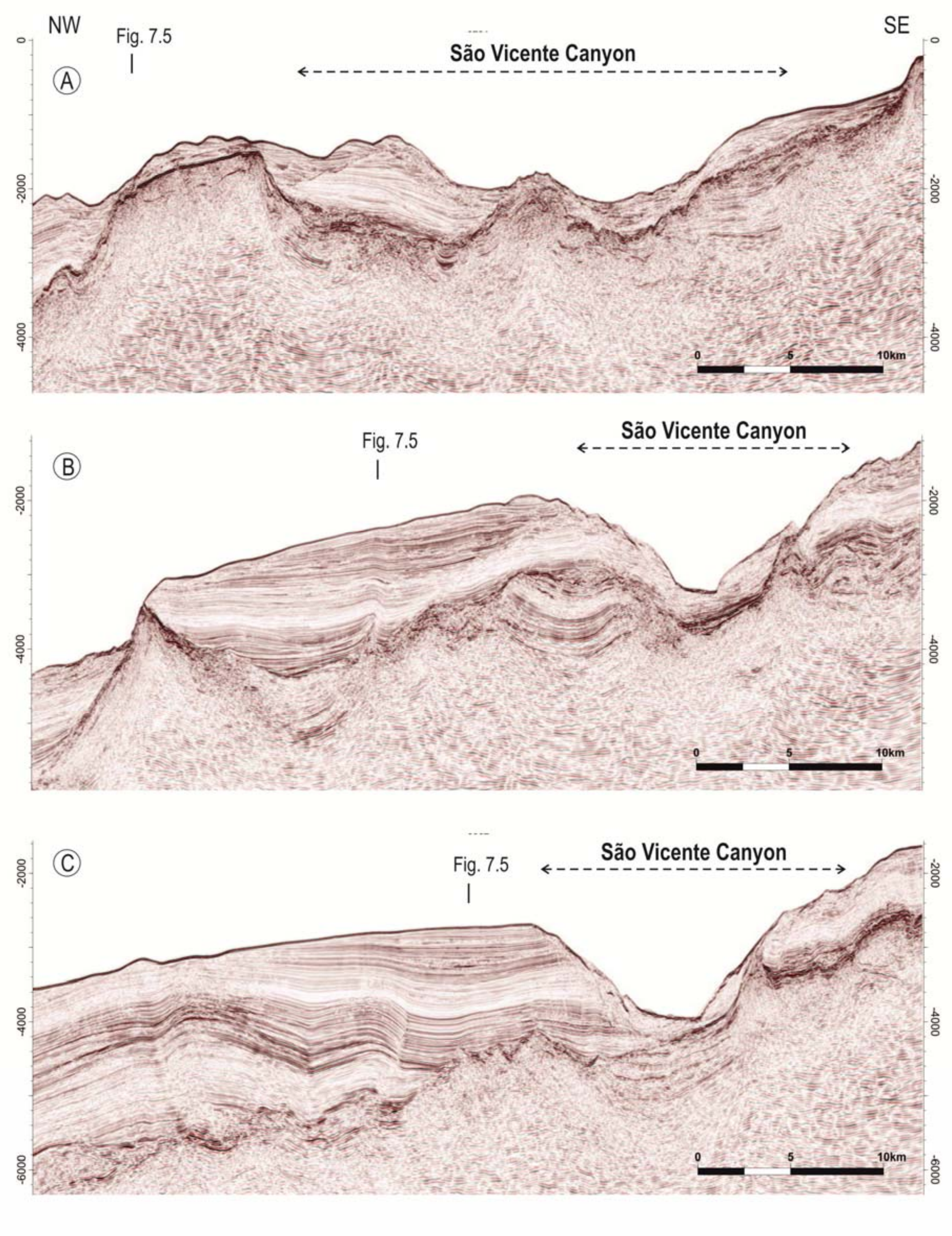

Figure 7.7 - Uninterpreted multichannel seismic sections across the proximal margin of Southwest Iberia. They evidence the transtensive geometry of the offshore segment of the MPFZ and the expression of long-lived incision of the São Vicente Canyon from the Paleogene onwards.

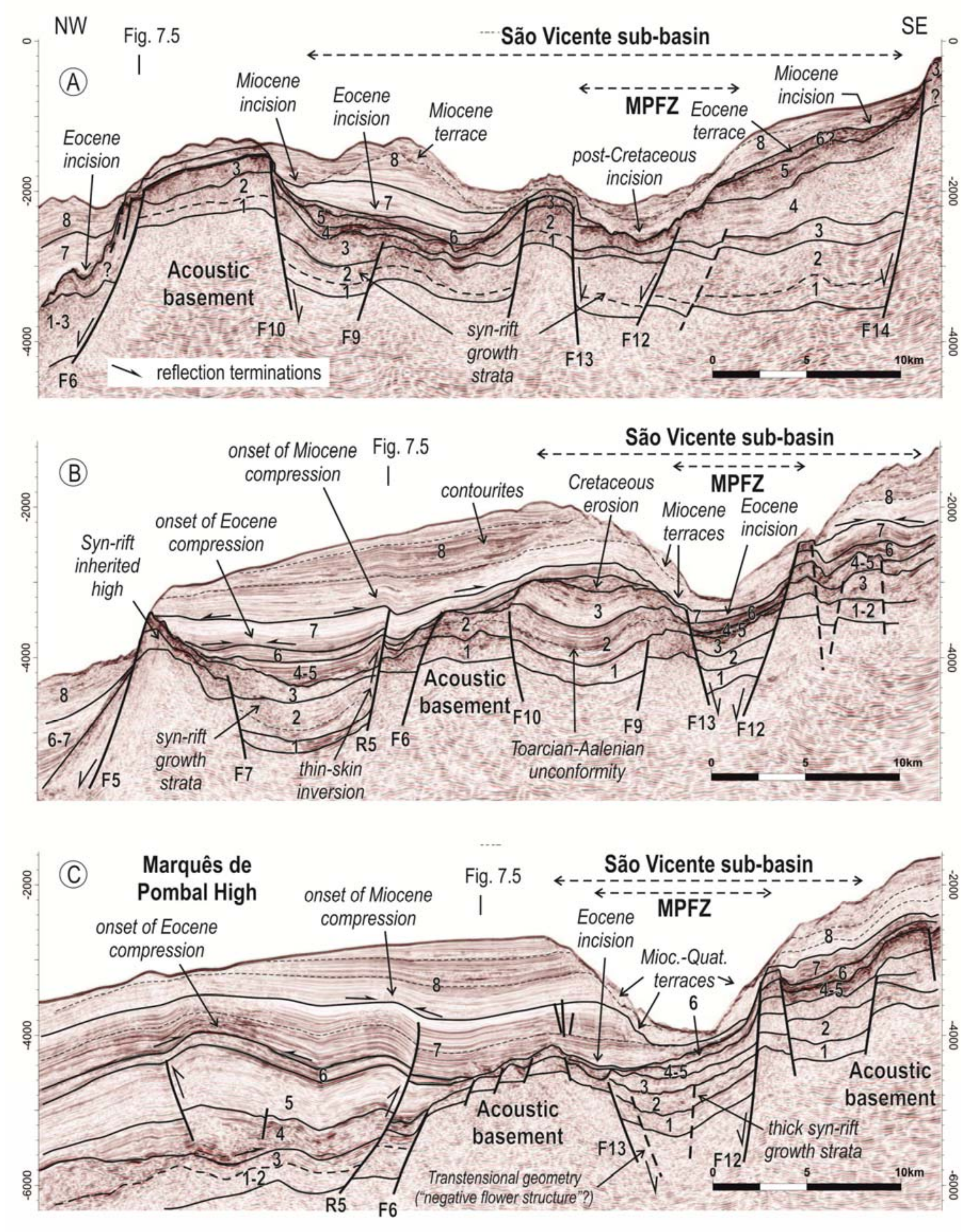

Figure 7.8 - Interpreted seismic sections from Fig. 7.7, highlighting the broad transcurrent architecture of the margin and the complex structure of the MPFZ. Note the significant erosion at Late Cretaceous level and the presence of a wide region of deformation away from the MPFZ. Relative ages for interpreted Megasequences in Fig. 7.3. Location of the seismic lines in Fig. 7.4.

Megasequence 7 (Late Eocene to Early Miocene) is essentially absent within the MPFZ, although in parts of the São Vicente sub-basin this unit is observed blanketing the margin (Figs. 7.6 and 7.8). It is characterised by significant erosion at Palaeocene-Eocene level, coeval with syn-tectonic shortening of the margin (Pereira et al., 2011 and references therein). Outside the MPFZ, its lowermost boundary shows downlap onto growing anticlines (Fig. 7.8). Internal reflections are mainly chaotic to sub-parallel on the proximal margin, whereas on the distal margin sub-parallel reflections dominate, denoting the likely occurrence of deep marine deposits (Figs. 7.5, 7.6 and 7.8).

Megasequence 8 (Miocene to recent) is characterised by significant thickness variations on the margin, which includes chaotic to sub-parallel reflections associated with the clear development of the São Vicente Canyon, erosional terraces and levees (Figs. 7.6 and 7.8). Outside the canyon reflections are sub-parallel to hummocky, revealing the occurrence of thick plastered deep-water sediment drifts and/or turbidites overlying inherited Mesozoic structural highs (Figs. 7.5, 7.6 and 7.8).

7.4.4. Geometry and kinematics of the offshore MPFZ

Seismic data show that a sector of strike-slip strain accommodation (the São Vicente sub-basin) extends from the continental shelf north of the Sagres Plateau towards the Horseshoe Abyssal Plain, including the offshore prolongation of the MPFZ, shown as a transcurrent segment with length in excess of 100 km and a width of up to 15 km (Fig. 7.4). The MPFZ comprises a group of sub-parallel faults rooted in the continental lithosphere at depths of about 20 km, whose geometry suggests the development of a negative flower structure (Figs. 4.9, 7.6 and 7.8), markedly contrasting with the reverse fault geometry typically suggested for this strike-slip (e.g. Zitellini et al., 2004; Terrinha et al., 2009). Significantly, two main normal faults (F12 and F13) were interpreted as bounding the MPFZ (Figs. 7.4, 7.6 and 7.8). The northern boundary fault F13 dips to the Southeast with an estimated maximum throw of ~1400 m, between the basement and top of Megasequence 3 (Fig. 7.10). Conversely, the southern master fault F12, the São Vicente Fault (sensu Terrinha et al., 2009), dips to the NW with a normal maximum throw of ~3400 m (Fig. 7.10). The easternmost termination of the MPFZ coincides with a N-S normal fault close to the head of the São Vicente Canyon (F14, Figs. 7.4, 7.6 and 7.8a).

The asymmetric nature of the MPFZ indicates that most of its tectonic subsidence was accommodated in its southern flank (F12), along the Sagres Plateau (Figs. 7.6 and 7.8). Additionally, throw values estimated along the MPFZ indicate that subsidence was more pronounced in its southwest section (Fig. 7.10), towards the Horseshoe Abyssal Plain, in a region of clustered earthquake activity (Fig. 7.1). Inside the MPFZ other minor sub-parallel faults are often recognizable, although their continuity cannot be traced with sufficient detail to identify precise kinematic indicators (Figs. 7.6 and 7.8c).

These data, nonetheless, allowed us to define the MPFZ as the closest structural and morphological expression of a prolonged structural lineament extending from onshore to the Horseshoe Abyssal Plain (Fig. 7.4).

The geometry of the São Vicente sub-basin and the MPFZ, together with its strata, indicate the transfer zone to have been predominantly transtensional during continental rifting, in contrast to the transpressive regime expressed at present by earthquake focal mechanisms. Other faults on the Southwest Iberian margin suggest that oblique rifting exerted a significant control in the segmentation of the Southwest Iberian margin, namely fault F11, which is shown to comprise a NW-SE normal fault dipping to the SW, with significant vertical displacement (Figs. 7.4 and 7.5). This fault lead to the deposition of thick syn-rift strata, and of an Early to Late Cretaceous post-rift prograding wedge (Figs. 7.5 and 7.8a).

Based on these concepts, an oblique left-lateral component for fault F11 is interpreted, as suggested by the arcuate pattern on the zonation of the proximal and distal margin (Fig. 7.4).

7.5. Discussion

7.5.1. Geological controls on the timing of canyon incision

Syn-rift units in the São Vicente sub-basin and MPFZ show growth strata totalling 2 km in thickness (Figs. 7.6 and 7.8). This character reveals that deposition within what was, essentially, a releasing bend and associated pull-apart basin generated during early Mesozoic oblique rifting, and present on the margin until latest Jurassic-Early Cretaceous continental break-up. Although the São Vicente sub-basin comprised a major syn-rift depocentre, there is no clear evidence of canyon incision during continental rifting. It is interpreted to have formed a major by-pass area to significant volumes of sediment sourced from the proximal margin only at the end of the Cretaceous (Fig. 7.9a). This major depositional change was likely associated with the intrusion of the Late Cretaceous igneous complexes, which local expression cannot fully explain the generalised uplift and associated sediment by-pass along the entire margin.

Seismic profiles indicate that from the Early Cenozoic onwards (Megasequences 6, 7 and 8, Figs. 7.6 and 7.8) deposition occurred dominantly on the outer proximal and distal margins, and was very limited within the MPFZ and on the inner proximal margin (Fig. 7.9b). This setting is also observed during the Paleocene-Eocene (Megasequence 6), a period marked by the inception of widespread erosional surfaces incising depositional units of Late Cretaceous age (Figs. 7.6 and 7.8).

The mid-Eocene to Oligocene (Megasequence 7) evolution of Southwest Iberia was once again dominated by enhanced erosion on the continental slope and shelf, and by downlapping of thick strata onto evolving anticlines and inverted syn-rift structures. These events were also synchronous to the formation of erosional terraces in the São Vicente Canyon and record the first unambiguous evidence of its incision on the margin (Figs. 7.6 and 7.8).

Megasequence 8 (Miocene-recent) is characterized at the base by the onset of a major regressive event coeval with the major pulse of crustal shortening and uplift on the margin. In the São Vicente Canyon, successive terraces were formed on its flanks by the accumulation of chaotic or discontinuous strata, predominantly comprising mass-wasting deposits and slope-derived axial fans (Figs. 7.6 and 7.8).

The existence of these terraces highlight that submarine canyon incision was more pronounced after the Middle Miocene, an observation that confirms previous interpretations for the ravinement of submarine canyons in Southwest Iberia (Alves et al., 2000; Roque, 2007) (Figs. 7.6 and 7.8).

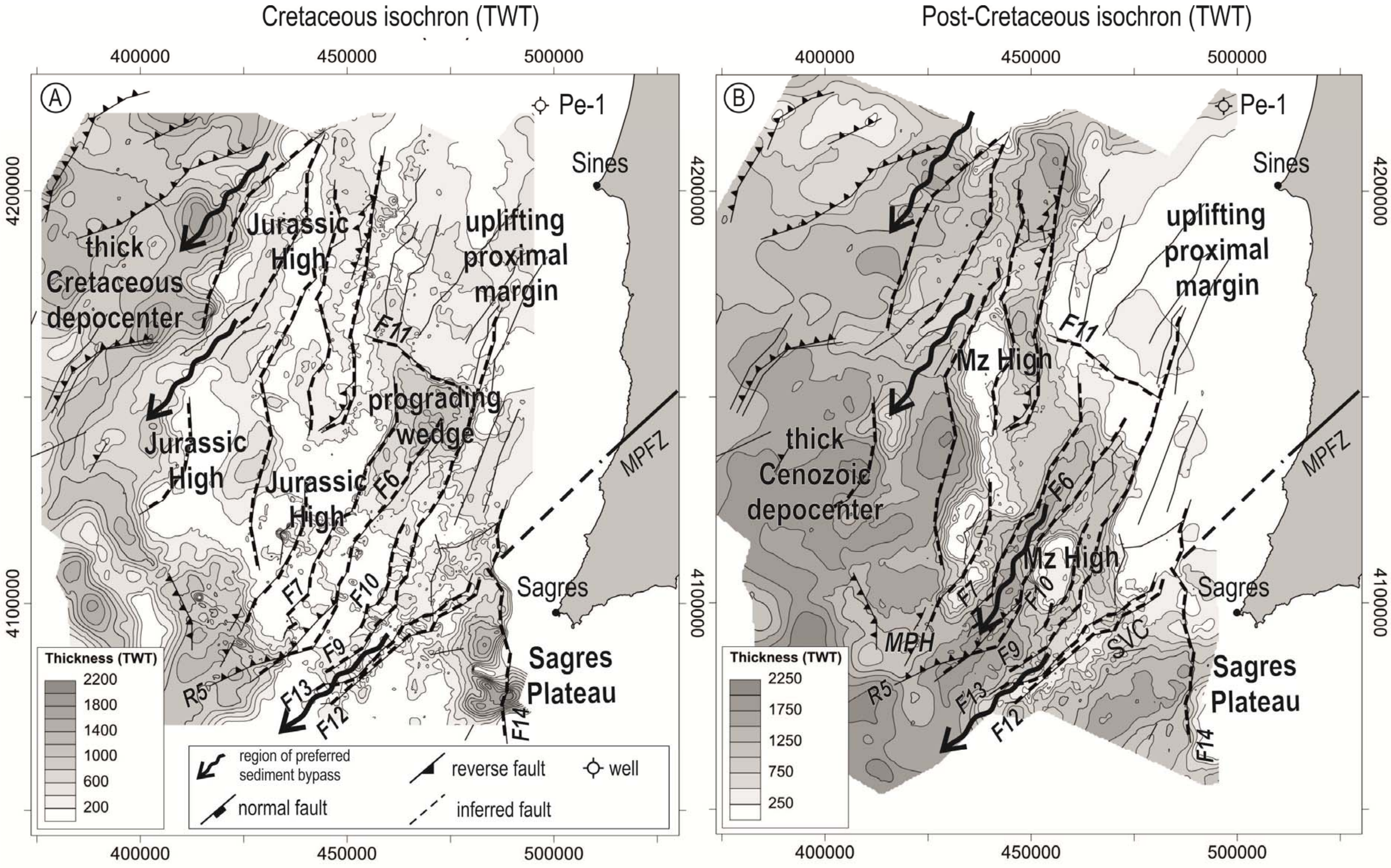

Figure 7.9 - Isochron maps showing the location of main Late Cretaceous and Cenozoic depocenters on the Southwest Iberian margin. A) Cretaceous TWTT Isochron map, highlighting the main inherited syn-rift master faults. Note the deposition of a Cretaceous prograding wedge, in relation with the uplifted domain of the inner proximal margin. B) Cenozoic TWTT isochron map revealing widespread uplifting of the proximal margin, an event controlling the sediment bypass towards the distal margin along the MPFZ. Main Eocene-Oligocene depocenters are crosscut by the inherited rift geometry and affected by local shortening, as in the case of the Marquês de Pombal High (MPH).

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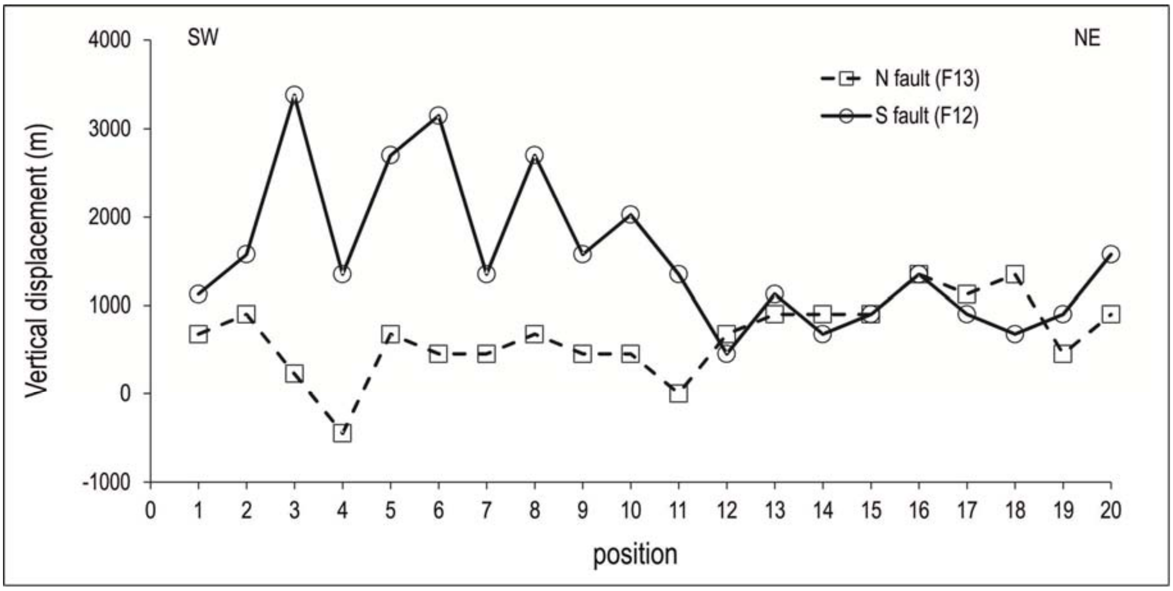

Figure 7.10 - Estimated vertical throw of master faults bounding the offshore segment of the MPFZ. The plots reveal a marked asymmetry between the proximal (NE) and distal (SW) terminations of the MPFZ, interpreted to have controlled syn-rift deposits in the study area.

However, the relative absence of Late Cretaceous strata on the proximal margin, together with the incision of latest Cretaceous-Paleogene channels, indicate the onset of incision in the São Vicente Canyon area to pre-date a Chattian-early Miocene erosional surface at the base of Megasequence 8 (Figs. 7.6 and 7.8). The limited information regarding the nature and age of the Late Cretaceous strata hinders any detailed interpretations on Mesozoic incision features, but the interpreted data points out for the generation of a proto-submarine canyon during, at least, the latest Cretaceous-Early Paleogene (Figs. 7.6 and 7.8).

7.5.2. The role of the MPFZ during the Mesozoic segmentation of southwest Iberia

Evidence of a transtensional regime controlling the Mesozoic evolution of the margin and the MPFZ can be obtained from: 1) CAMP related intrusions outcropping along the MPFZ; 2) the formation of a negative flower structure on the offshore segment of the margin, within a wider area of oblique extension. However, the absence of clear kinematic indicators on 2D multichannel seismic data, likely due to the reactivation of syn-rift structures during Late Cretaceous-Cenozoic inversion, prevents a more insightful analysis of the magnitudes and directions of displacement in the MPFZ. It is of critical importance, nevertheless, to estimate the displacement recorded by the MPFZ after the

Paleozoic. This can be attained at a larger scale through the integration of regional geodynamic criteria.

The detailed mapping of N-S to NNE-SSW rift-related faults (Fig. 7.4) suggests that the stress field recorded during continental rifting was broadly aligned E-W to NW-SE in relation with the present-day geographic position of Iberia (Fig. 7.11). These directions markedly contrast with the predominant NE-SW direction of crustal extension suggested by Mougenot et al. (1979) and Mauffret et al. (1989b), but agree with the interpretation of a NW-SE direction of oblique rifting occurring in southern Iberia (e.g. Sallarès et al., 2011).

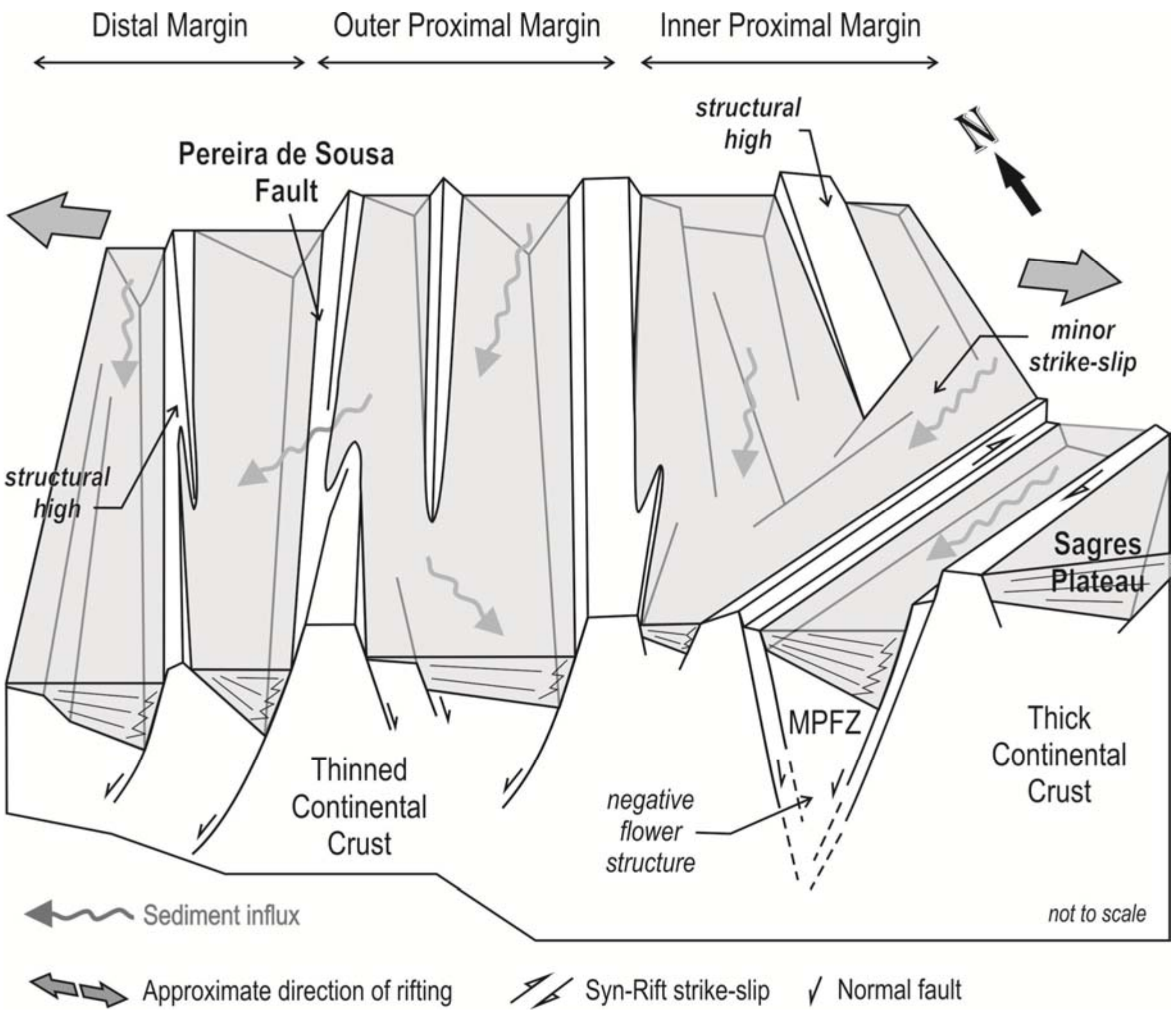

Figure 7.11 - Block-diagram depicting the regional architecture of the MPFZ during Mesozoic rifting. Interpreted growth strata are represented in grey, and where controlled by the E-W to NNE-SSW extension of the southwest Iberian margin. The Sagres Plateau is located to the south of the study area, and formed a hinge zone separating the Algarve-Gulf of Cadiz and Southwest Iberia during the Triassic to Late Jurassic.

Regional stresses associated with thinning of the Iberia-Newfoundland conjugate margins thus exerted an eastwards drag force on the Iberian plate during the Mesozoic, an event that can be confidently coupled with the westwards migration of Iberia in relation to the assumed fixed North African plate along the left-lateral Azores-Gibraltar Transform Zone (Stampfli and Borel, 2002; Sallarès et al., 2011; Schettino and Turco, 2011) (Fig. 7.12).

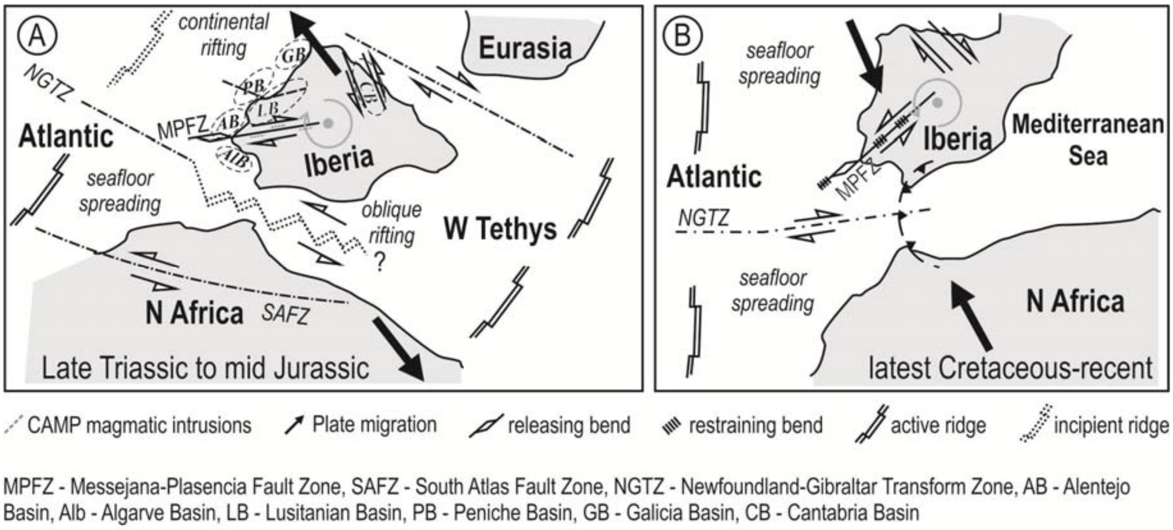

Figure 7.12 - Schematic reconstructions of the Iberia microplate relative to North Africa and Eurasia summarising the interpreted kinematics of the MPFZ during (A) Late Triassic to Middle Jurassic continental rifting and (B) latest Cretaceous to Holocene tectonic inversion. AlB – Algarve Basin, AB – Alentejo Basin, LB – Lusitanian Basin, PB – Peniche Basin, GB – Galicia Basin, CB – Cantabria Basin, NGTZ – Newfoundland-Gibraltar Transform Zone and SAFZ – South Atlas Fault Zone.

Moreover, the transcurrent regime invoked here to explain both the geometry of strata and their bounding faults, and the implications for the evolution of Iberia in the Mesozoic, concurs with the strike-slip architecture anticipated for the Late Jurassic of the Lusitanian Basin (Leinfelder and Wilson, 1989; Wilson et al., 1989). These authors, however, underestimated the contribution of larger strike-slip segments controlling the persistent readjustments of Iberia during the Mesozoic.

Another indicator of dextral movements relates with the counter-clockwise rotation of Iberia from the Cretaceous onwards (Palencia-Ortas et al., 2006; Osete et al., 2011; Vissers and Meijer, 2012), a movement accommodated along transfer zones such as the MPFZ. Hence, the extensional regime proposed for MPFZ during rifting can be explained either by: 1) continuous left-lateral movements dominating since the Paleozoic; or 2) by a temporary shift to dextral strike-slip movements during continental extension.

Based on the latter evidence, we postulate that the MPFZ predominantly comprised a dextral releasing bend during the Mesozoic, favouring the hypothesis of a temporary shift in the kynematics of the fault zone during continental extension. This postulate, combined with NW-SE extension of southwest Iberia during the Mesozoic, leads to the conservative estimate of 10 to 15 km of horizontal displacement in the MPFZ during continental rifting. Assuming this latter kinematic evolution for the MPFZ, displacement was accommodated within this first-order transfer fault in major, but kinematically distinct, stages: 1) predominant sinistral strike-slip during Variscan continental collision; 2) dextral transtension during continental extension; and 3) sinistral transpression during Late Cretaceous-Holocene convergence of Iberia with North Africa.

In the Cantabria Basin in North Iberia inherited sutures from the Paleozoic were active in the Triassic-Early Jurassic (to accommodate the sinistral opening of the Bay of Biscay) and later reactivated as dextral pull-apart basins during the Late Cretaceous (Garcia-Mondejar, 1989). The conjugate movement of the Cantabrian pull-apart in the context of Iberia agrees with the sense of displacement interpreted herein for the MPFZ during the Late Triassic-Late Jurassic (Fig. 7.12). The kinematics of the MPFZ can also be compared with its conjugate margin of Nova Scotia, along the Minas Fault Zone (Laville and Petit, 1984; Olsen and Schlische, 1990), suggesting that this type of oblique-slip accommodation of strain associated with transform zones and continental plate boundaries is far more significant than anticipated.

Ultimately, the dispersion of earthquake epicentres on the southernmost termination of the MPFZ (Fig. 7.1), and local focal mechanisms (Gràcia et al., 2003a; Geissler et al., 2010) suggest the MPFZ to terminate as a typical contractional horsetail splay, an architecture common to other transpressive segments worldwide (e.g. Cunningham and Mann, 2007). This confirms the modern MPFZ as an alternating releasing-restraining bend, a character of importance to the assessment of geohazards on the margin. In fact, first-order transcurrent features as the São Vicente sub-basin, MPFZ and Sagres Plateau are known to be of high seismogenic and tsunamigenic potential as proven offshore California (Borrero et al., 2004; Legg and Borrero, 2004), Sumatra-Andaman (Bilham et al., 2005; Malod et al., 2005; Sibuet et al., 2007a), Marmara Sea (Parsons, 2004) and Caribbean Sea (Cunningham and Mann, 2007; Mann et al., 2007). This implies that the region around the MPFZ comprises one of the structures in Southwest Iberia with the largest potential to generate large earthquakes and tsunamis, as those in the 1755 Lisbon Earthquake (e.g. Zitellini et al., 2001; Terrinha et al., 2003).

7.5.3. Hinge-zones as morphological expression of margin-scale oblique movements

This new interpretation for the MPFZ and São Vicente sub-basin as a Mesozoic releasing bend has implications for the relationship between the fault zone, the Sagres Plateau and the westernmost Tethyan region (e.g., the Algarve Basin and the Gulf of Cadiz, South Iberia), particularly in what regards the tectonic controls on the ancient Boreal and Tethysian paleogeographic domains (e.g. Terrinha et al., 2009). Our results suggest that the offshore MPFZ bounds the Sagres Plateau to the north, which forms a tectonically-induced hinge zone between the South and Southwest Iberian margins (Fig. 7.11).

Based on the observation of scarce syn-rift strata above the Sagres Plateau, this structural high is interpreted to have formed a physiographic barrier between Tethysian and Boreal waters since Syn-Rift I. Most of the syn-rift tectonic subsidence in Southwest Iberia was accommodated at this time north of the Sagres Plateau, preserving this NE-SW high as a structural divide, or hinge zone, between West Iberia-Newfoundland and West Tethys (Figs. 7.10 and 7.11). Such an interpretation explains not only the faunal isolation and the short-lived compressional periods described by Terrinha et al. (2002), but also the thickness variations recorded between poorly-developed Early-Mid Jurassic strata on the Sagres Plateau and thicker correlative units in continental slope basins to the NW and SE (Figs. 7.5, 7.6 and 7.8). A second hinge zone bounded by the Tagus and Nazaré Transfer Zones (the Estremadura Spur), is considered in this work to separate the Alentejo and the Peniche Basins. In fact, Vanney and Mougenot (1990), describe a similar architecture for the Nazaré Fault Zone and its associated uplifted hinge zone of the Estremadura Spur.

In summary, the transtensive (or pull-apart) domain of São Vicente sub-basin responded to the existence of a long-lived releasing bend during the Mesozoic, contrasting significantly with its modern transpressive nature (Gràcia et al., 2003a; Geissler et al., 2010) (Fig. 7.12). The magnitude of Meso-Cenozoic subsidence recorded in the MPFZ is significantly larger than in other continental slope basins of Southwest Iberia. Based on this evidence, it is postulated that future elastic palaeogeographic reconstructions on divergent margins must take in consideration not only rift-related strain accommodation, but also the variable transcurrent record of their rifted margins through time. In this context, the MPFZ, the Minas Fault Zone, the South Atlas Fault Zone and the Cantabria Basin suggestively represent major intra-plate splay segments of neighbouring oceanic transform zones capable of accommodating significant lateral movements (Fig. 7.12).

7.6. Conclusions

The offshore segment of the Messejana-Plasencia Fault Zone (MPFZ) comprises a first-order transfer zone that controlled both deposition and strain accommodation on a broader scope of oblique rifting throughout the Southwest Iberian margin. It evolved initially as a left-lateral Paleozoic suture, later reactivated as a dextral releasing bend (and associated pull-apart basin), during Late Triassic to Early Cretaceous rifting, in which a clockwise migration of Iberia is recorded. The MPFZ was subsequently acting as a left-lateral releasing-restraining bend from Late Cretaceous onwards, accommodating significant shortening during the counter-clockwise rotation of the Iberian microplate. It is therefore concluded that:

a) Similarly to other first-order transfer zones in the Central-North Atlantic (e.g. the Minas Fault Zone, the South Atlas Fault Zone and the pull-apart Cantabria Basin) the MPFZ comprises a first-order strike-slip fault zone accommodating significant deformation within the Iberian Plate.

b) This long-lived tectonic boundary had a key impact on the formation of the Sagres Plateau, a tectonically-induced hinge zone that separated this region from westernmost Tethys since, at least, the Early Jurassic. This separation had significant impact on both faunal isolation and ocean circulation on the Southwest Iberian margin.

c) The incision of the São Vicente Canyon along the MPFZ was initiated in the latest Cretaceous-Paleocene, continuing into the Eocene and the Miocene in response to regional uplift and crustal shortening. A significant phase of Early Cretaceous erosion and sediment by-pass on the continental slope was suggestively accompanied by widespread incision of canyons systems older than the São Vicente Canyon.

d) As a result, the MPFZ should be recognised as a major tectonic feature that accommodated important combined vertical and horizontal movements on the Southwest Iberian margin, a character that must have critical impact on future elastic palaeogeographic reconstructions for the southern North Atlantic, and on future seismogenic and tsunamigenic risk analyses for this part of the Atlantic Ocean. In fact, it is herein proposed that the MPFZ and adjacent São Vicente sub-basin comprising areas capable of generating large-magnitude earthquakes and associated tsunamis

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Chapter 8

Discussion

"Science may set limits to knowledge, but should not set limits to imagination"

Bertrand Russell

Section 8.2 was partly published in "Pereira, R. and Alves, T. M. (2012). Is southwest Iberia an upper plate or a lower plate margin? 3rd Central and North Atlantic Conjugate Margins Conference, Dublin, Ireland, PIPCo RSG Ltd., 170-171".

Section 8.4 was partly published in "Pereira, R., Alves, T. M. and Cartwright, J. (2012). Tectono-stratigraphic evolution of the Southwest Iberian margin: a tail of the Central Atlantic. 3rd Central and North Atlantic Conjugate Margins Conference, Dublin, Ireland, PIPCo RSG Ltd., 75-76." and "Pereira, R. and Alves, T. M. (2012). Tectono-stratigraphy of multiphased rifting on the distal margin of Southwest Iberia (North Atlantic). Deep-water continental margins: The final exploration frontier?, London, UK, Geological Society of London, 73-74".

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8. Discussion

An integrated discussion of Chapters 4, 5, 6 and 7 is presented in this chapter with reference to the broader concepts and open questions highlighted in the introductory chapter.

Section 8.1 discusses the distinct subsidence patterns observed on each sector of the margin (Chapters 4, 5 and 6), through the construction of new burial history models, for the inner proximal, the outer proximal and the distal margin. These models demonstrate both the existence of distinct phases of rifting, and the significance of individual regional geodynamic events that controlled the rift evolution of the southwest Iberian margin.

Throughout section 8.2, an innovative approach aims to discuss the geodynamic model used to explain the evolution of the Southwest Iberian margin in the light of the broader scope of asymmetric rifted margins (sensu Lister et al., 1986). Topics addressed in this chapter include: 1) the implications to the evolution and geometry of magma-poor rifted margins (with emphasis on the Iberia-Newfoundland conjugate margins); and 2) the significance for palaeogeographic reconstructions of the Central-North Atlantic complex triple-junction.

In section 8.3, the results obtained from the seismic-stratigraphic analysis are discussed in terms of their contribution to the revision of some sequence stratigraphy concepts and their application to rifted continental margins.

Section 8.4 integrates the bulk of the results presented in this thesis and discusses the implications for the analysis of the Iberia-Newfoundland conjugate margins and for other magma-poor rifted margins.

Section 8.5 discusses the implications of the results presented in the thesis for hydrocarbon prospectivity in the Alentejo Basin.

Finally, in section 8.6 the main limitations to this work are discussed and accordingly, in section 8.7 an overview of the main open questions and suggestions for further work are presented, highlighting the chief uncertainties and forward approaches that should be developed in order to clarify unclear aspects on evolution of the Southwest Iberian margin and magma-poor rifted margins as a whole.

8.1. Multiphased rifting of the SW Iberian margin

The results presented in this work demonstrate that in common with other continental rifted margins in the Atlantic (Balkwill and Legall, 1989; Chang et al., 1992; Le Roy and Piqué, 2001; Manatschal, 2004; Lavier and Manatschal, 2006; Tucholke et al., 2007), Southwest Iberia has undertaken noteworthy crustal thinning resulting from multiphased rifting. During this process, three main structural sectors were formed and reworked during the rift-to-drift evolution to construct the present margin geometry. Each sector shows typical geometries of syn-rift strata associated with the extension of a deformed Palaeozoic metamorphic basement, above which, three rift-related Megasequences were accumulated from the Late Triassic to the Late Jurassic. Above these units, the post-rift Megasequences record the progressive drifting of the margin, followed by discrete uplift and compression periods that resulted in rift-dependent shortening architectures.

Rift architecture throughout the margin reveals that the three main sectors (i.e. the inner proximal margin, the outer proximal margin and the distal margin) record the progressive migration of the dominant locus of subsidence during the different phases of the evolution of the Iberia-Newfoundland margins (Fig. 4.5, 4.6). Each sector shows distinct patterns of subsidence/uplift, as expressed from seismic, wells and outcrop data. In Chapter 6, the inner proximal margin was modelled using exploration well Pe-1 that confirmed both the multiphased nature of extension of the margin and the significance of episodic uplifting, namely during the Toarcian-Aalenian hiatus, the Late Cretaceous generalised margin tilting and the Alpine compressive events. If this aspect could be confirmed for the most proximal segment of the margin, it remained untested for the undrilled sectors of Southwest Iberia. As demonstrated in the analysis of seismic data on the outer proximal and distal margin (Chapter 4), these sectors comprise thick growth strata pointing to dissimilar subsidence patterns to those observed on the inner proximal margin. Consequently, in order to assess the burial history in these sectors, two pseudo-wells were modelled, namely Beldroega-1 (Be-1) on the outer proximal margin and Poejo-1 (Po-1) on the distal margin (Figure 8.1). The location of these wells was selected on the basis of the occurrence of thick syn-rift strata overlain by complete post-rift sequences that could explain the complete evolution of the margin and by the good seismic-stratigraphic control of each sub-basin.

Notwithstanding significant uncertainties on the age of sequences and their unconformities, the lithology of each seismic package, the real thickness of seismic units and the palaeowater depth, the overall data presented in this work allows the constraining of most of these variables. Additional wells in the Alentejo Basin (Golfinho-1 and Monte Paio) and in the south-western Lusitanian Basin (20B-1 and 17C-1) (Fig. 8.1), were used to test the multiphased nature of continental rifting in southwest Iberia and for the first time, to document the subsidence in undrilled areas of the margin.

8.1.1. Modelling burial history on the margin

The analysis of subsidence and burial history throughout the margin was accomplished by modelling key wells on the inner proximal margin of the Alentejo and Lusitanian Basins (MP, Pe-1, Go-1 and 20B-1 and 17C-1) (Fig. 8.1), and by the tentative modelling of pseudo-wells on the outer proximal and distal margin of the southwest Iberian margin (Be-1 and Po-1) (Fig. 8.1).

Acknowledging the uncertainties on some of the input parameters used in the models, this section aims to assess the significance of subsidence variation across the margin and to estimate the importance of uplift events on the overall rift-related tectonic subsidence, as well as the relation between the principal events controlling the evolution of the margin. The detailed input parameters used in these models are presented in the Annexes.

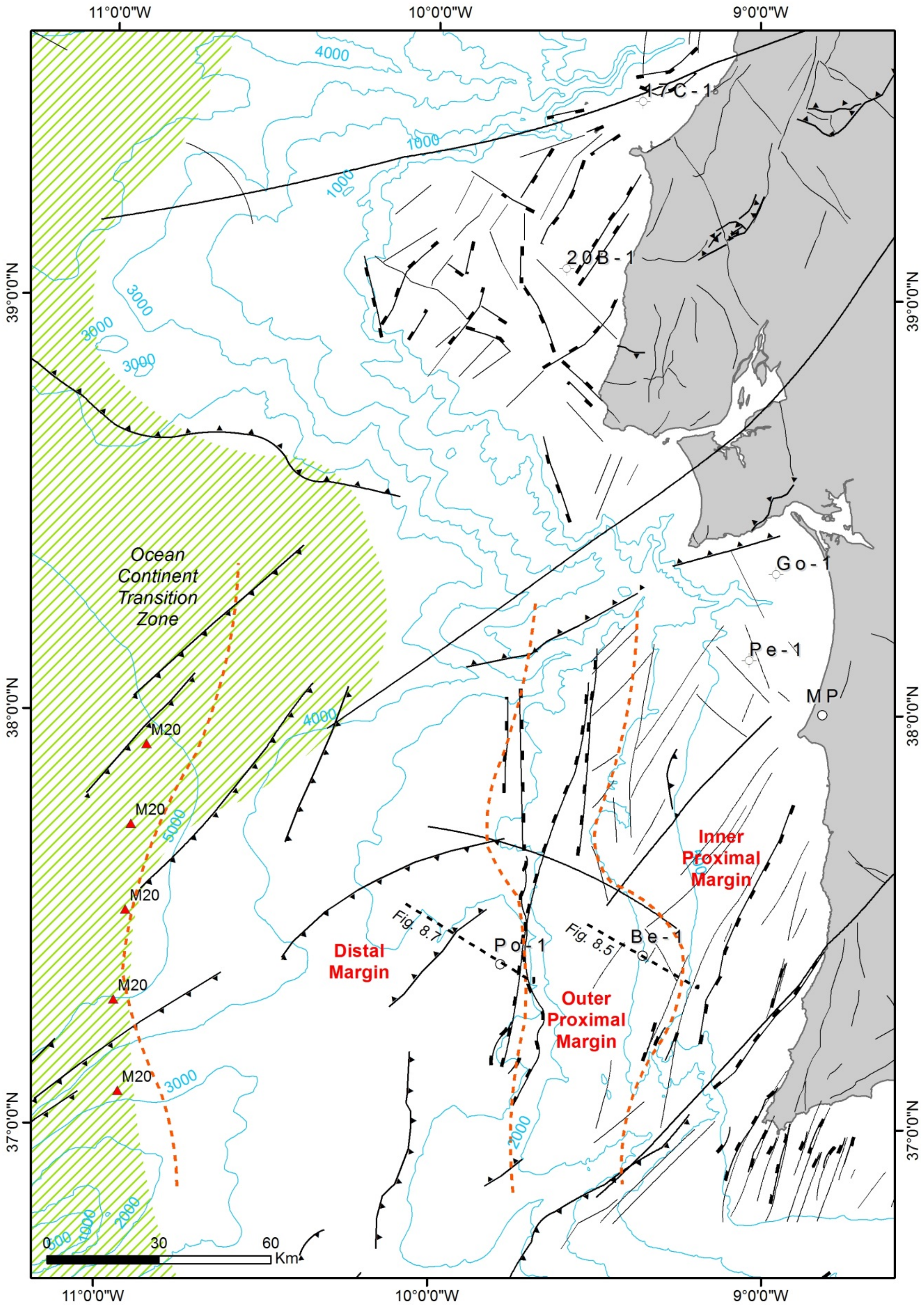

Figure 8.1 – Location of the wells and pseudo-wells used for burial history modelling on the margin, in relation with the different sectors of the margin. Outline of the Ocean-Continent Transition zone and magnetic anomalies from Rovere et al. (2004).

When possible, depths of stratigraphic markers and main unconformities were obtained from well reports (except from well MP that is based partially on unpublished information and from Inverno et al. (1993)). In pseudo-wells, sequence boundaries for each Megasequence were depth-converted using the average interval velocities obtained from the nearest shot point.

Age of sequence boundaries was obtained from well reports or interpreted in accordance with the regional lithostratigraphic framework presented in Chapter 2.

In the absence of exact paleo-water depth control, values where interpreted for key events assuming similar values used in previous backstripping studies carried out on the Alentejo and Lusitanian Basins (Stapel et al., 1996; Cunha, 2008; Cunha et al., 2009).

The magnitude and duration of erosive events was estimated for each well based either on analogue information from neighbouring wells or from seismic data. These input values are therefore revealed as the principal uncertainty factor when modelling burial history.

8.1.1.1. Syn-rift subsidence

The analysis of the burial history models carried out for the selected wells reveals that significant (yet variable) tectonic subsidence initiated by Carnian age and extends in most cases to the earliest Jurassic, in accordance with previous models elaborated for the Alentejo and Lusitanian Basin (Stapel et al., 1996; Cunha, 2008; Cunha et al., 2009). However, in wells located on the inner proximal margin (Pe-1, Go-1 and MP), a Rhaetian-Hettangian (205-198 M.a) pulse of subsidence can be identified (Figs. 8.2, 8.3 and 8.4). This pulse, although of distinct magnitude in each well, is interpreted as the onset of a new generalised extensional event, which is coeval with the onset of continental extension throughout the Central and North Atlantic margins.

On the outer proximal margin, Megasequence 1 is thick, bounded by NE-SW to N-S normal faults along which, growth strata can be observed (Fig. 8.5). Pseudo-well Beldroega-1 (Be-1) in this location reveals an estimate thickness of in excess of 2000 m (Fig. 8.6).

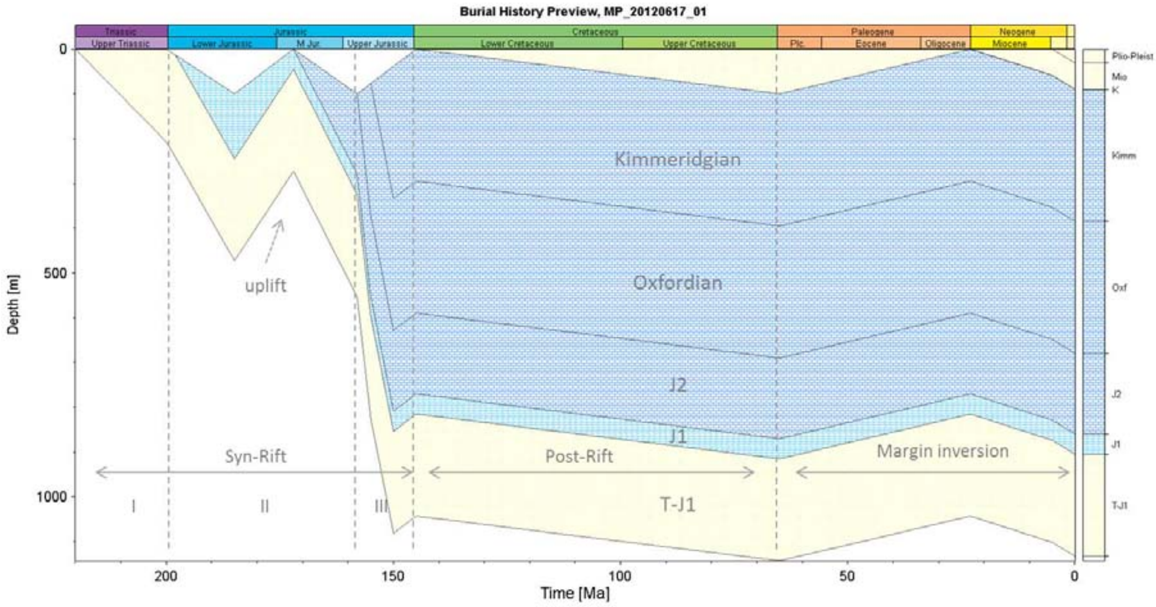

Figure 8.2 – Burial history model for the inner proximal margin in well Monte Paio. Note the effect of Toarcian-Aalenian uplift during syn-rift phase II. Subsequent to rift cessation, a period of uplift and erosion is marked by a regional unconformity (Tithonian-Berriasian).

On the distal margin, similar growth strata points to important subsidence during the Carnian-Hettangian interval (Fig. 8.7). Here, pseudo-well Poejo-1 (Po-1) shows that onset of continental extension formed a thick sub-basin that accumulated approximately 2000 m of siliciclastic to shaly-evaporitic deposits (Fig. 8.8). In well 20B-1 Megasequence 1 was not intersected (Fig. 8.9), but in well 17C-1, this unit exceeds 1000 m (Fig. 8.10), suggesting that on West Iberian margin, during this interval, continental extension and tectonic subsidence was of substantial magnitude. Rift Phase II (Megasequence 2, Sinemurian-Callovian) is expressed in all modelled wells, but shows increased significance in wells Be-1, Po-1, 20B-1 and 17C-1. In these wells 400 to 1300 m of shallow to deep marine carbonate successions were accumulated denoting the rejuvenation of tectonic subsidence during this rift phase. However, this estimation is conservative due to the Toarcian-Aalenian uplift event that affected mainly the southwest Iberian margin, which in some cases eroded a significant volume of sediments (> 100 m), as in the case of Pe-1, Go-1 and MP (see Appendix 1).

The Toarcian-Aalenian event (end of sequence 2a) is not continiously observed on seismic data imaging the outer proximal and distal margin (Figs. 8.5 and 8.7), suggesting that uplift affected dissimilarly the margin, which is interpreted as a correlative conformable event.

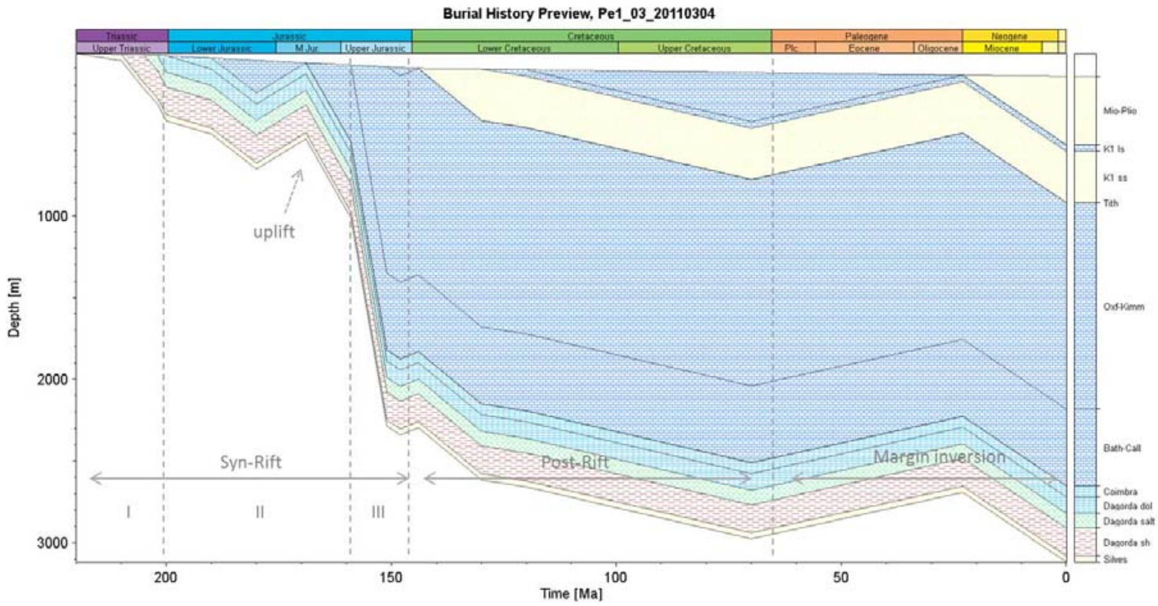

Figure 8.3 – Burial history model for the inner proximal margins in well Pe-1. Note the effect of Toarcian-Aalenian uplift during syn-rift phase II. Subsequent to rift cessation, a period of uplift and erosion is marked by a regional unconformity (Tithonian-Berriasian).

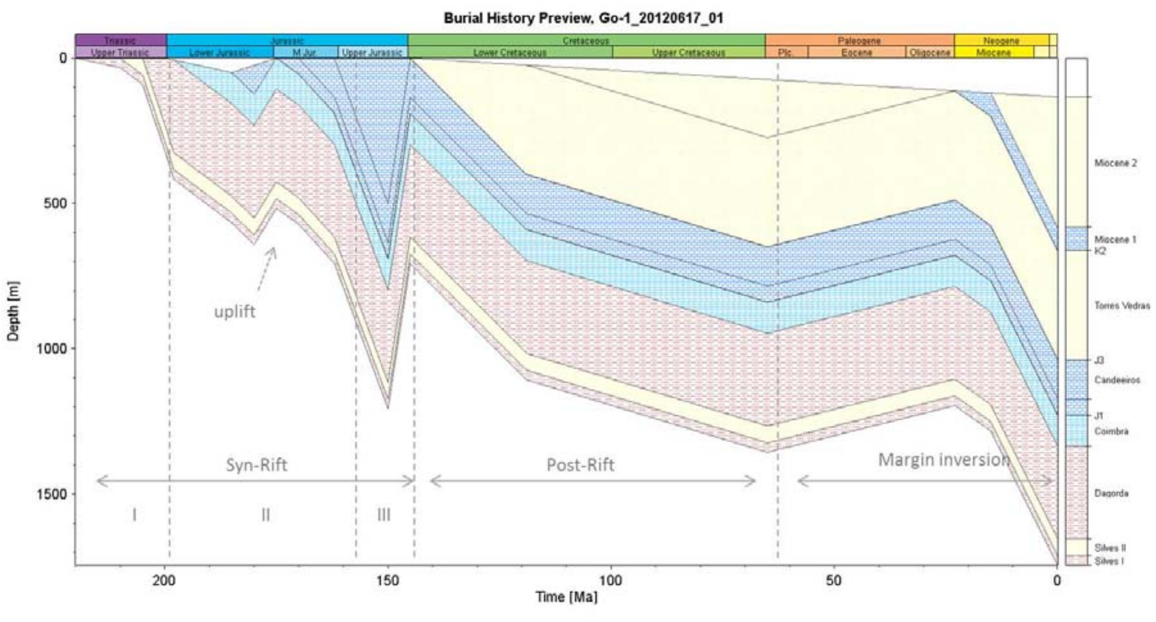

Figure 8.4 – Burial history model for the inner proximal margin Go-1. Note the effect of Toarcian-Aalenian uplift during syn-rift phase II. Subsequent to rift cessation, a period of uplift and erosion is marked by a regional unconformity (Tithonian-Berriasian).

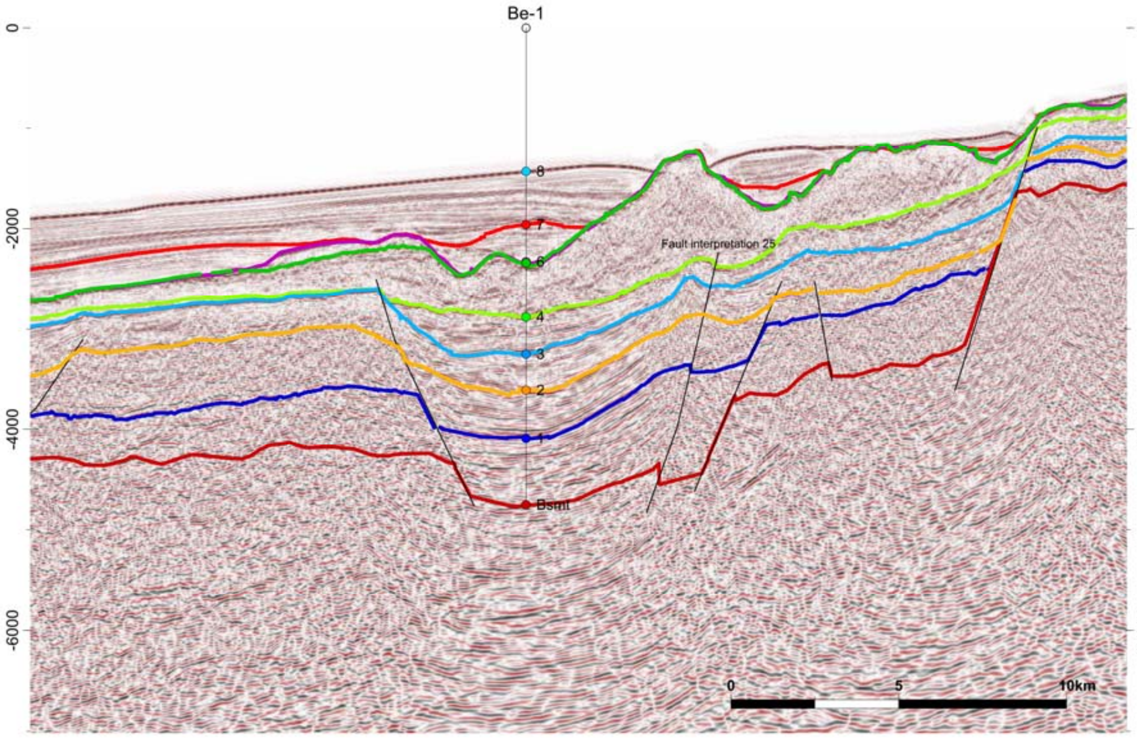

Figure 8.5 – Seismic line and location of pseudo-well Be-1 on the outer proximal margin. Note the influence of noteworthy erosion removing Megasequence 6 and the role of limited inversion affecting Megasequences 1 to 4.

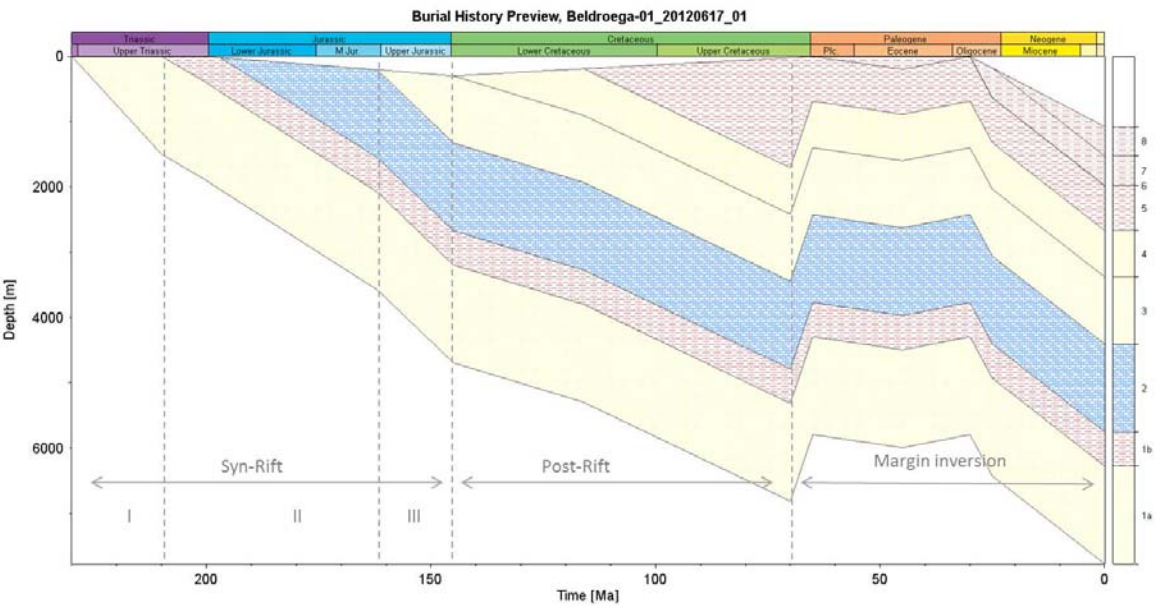

Figure 8.6 - Burial history model for the outer proximal in pseudo-well Be-1, showing continued subsidence during the distinct rift phases By the latest Cretaceous-Paleocene, a period of major uplift on the margin resulted in the erosion of large volumes of a Late Cretaceous prograding wedge.

Subsequently to the Toarcian-Aalenian uplift, tectonic subsidence resumes on the margin by the Callovian-Oxfordian, as observed in wells Pe-1, Go-1 and MP, but the paroxysmal pulse of continental extension is focused during the Oxfordian-Kimmeridgian interval (Figs. 8.2, 8.3 and 8.4). In these examples subsidence reveals the final event of extension on the southwest Iberian margin (Rift Phase III), which results in the accumulation of thick growth strata from Megasequence 3. In wells Pe-1, MP, Po-1 and Be-1 thickness of this Megasequence is estimated vary from 600 to 1300 m.

This markedly contrasts with proximal margin wells Go-1, 20B-1 and 17C-1 that lack the entire Late Jurassic interval. This suggests a differential response to the last period of rifting that during its last pulse (Kimmeridgian-Tithonian?) is interpreted to have experienced: 1) rift-related uplift of the footwall during tilt-block rotation, or 2) isostatic rebound of the proximal margin (rift-shoulder effect) during the late rifting immediately after continental breakup.

The analysis of the pseudo-wells modelled on the margin demonstrates what was previously observed on seismic data, namely the persistent subsidence during rifting. This results in a pattern of continued subsidence in burial history models (Figs. 8.8 and 8.10) revealing that from the Late Triassic to the Late Jurassic, these sectors of the margin were continuously extended during rifting.

8.1.1.2. Post-rift subsidence and margin inversion

The analysis of the post-rift sequences reveals a complex interplay of subsidence and uplift that affects dissimilarly the different sectors of the southwest Iberian margin from which, the following four main periods of uplift and shortening can be recognised (see Chapters 2 and 5 for details), namely during the Late Cretaceous (to Paleocene?), the Eocene, the Oligocene and from the Miocene to the present day.

Seismic and borehole data demonstrate that the Early Cretaceous (Berriasian-Aptian) is broadly characterised by limited subsidence, which is interpreted to have resulted dominantly from thermal readjustments of the continental crust subsequent to breakup, limited tectonic subsidence and isostatic response to sediment load into sub-basins.

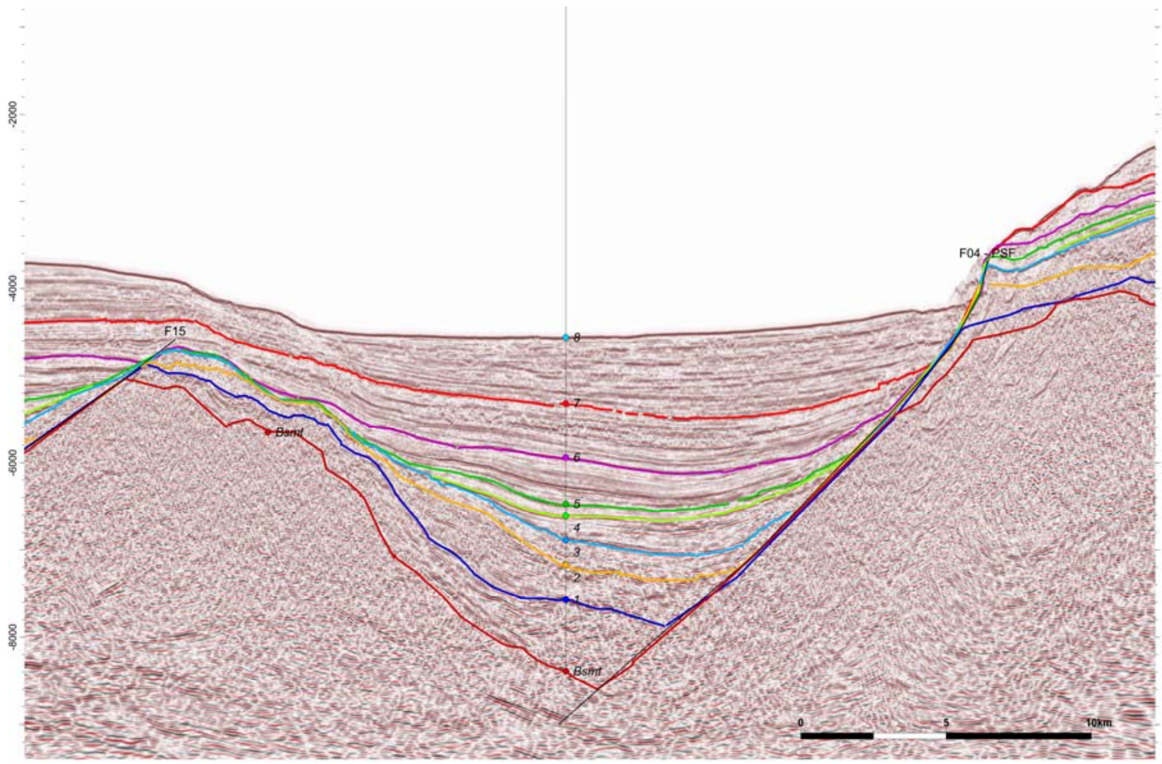

Figure 8.7 – Seismic line and location of pseudo-well Po-1 on the distal margin. This sub-basin, bounded by the Pereira de Sousa Fault (F04) reveals persistent subsidence not only during rifting, but also since the post-Chattian(?) associated with margin shortening.

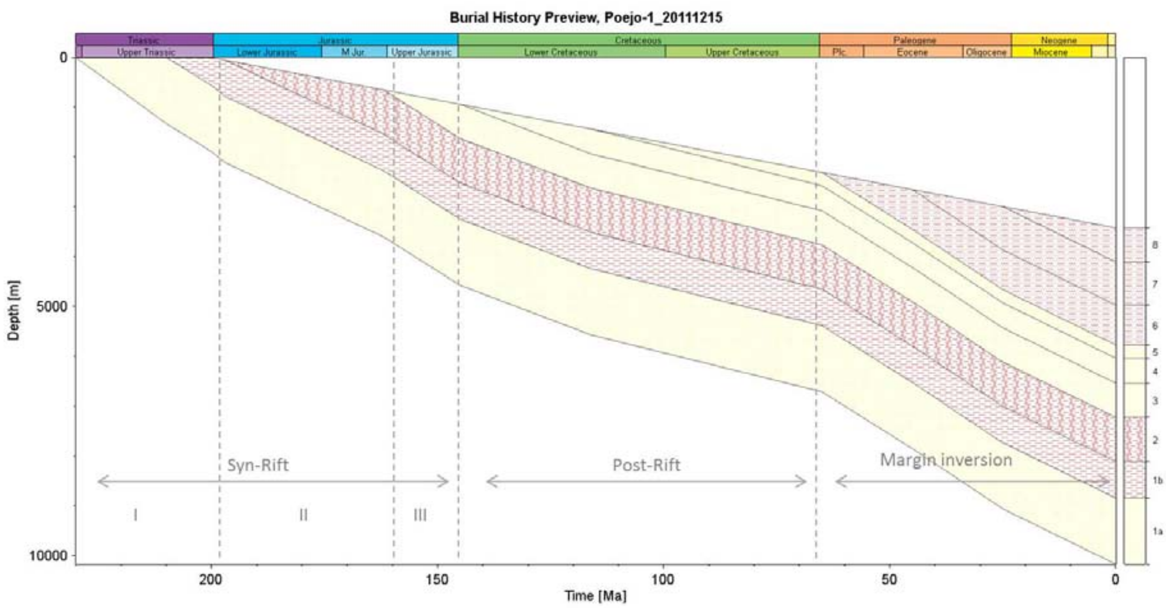

Figure 8.8 - Burial history model for the distal margin in pseudo-well Po-1, revealing the persistent subsidence of this sub-basin.

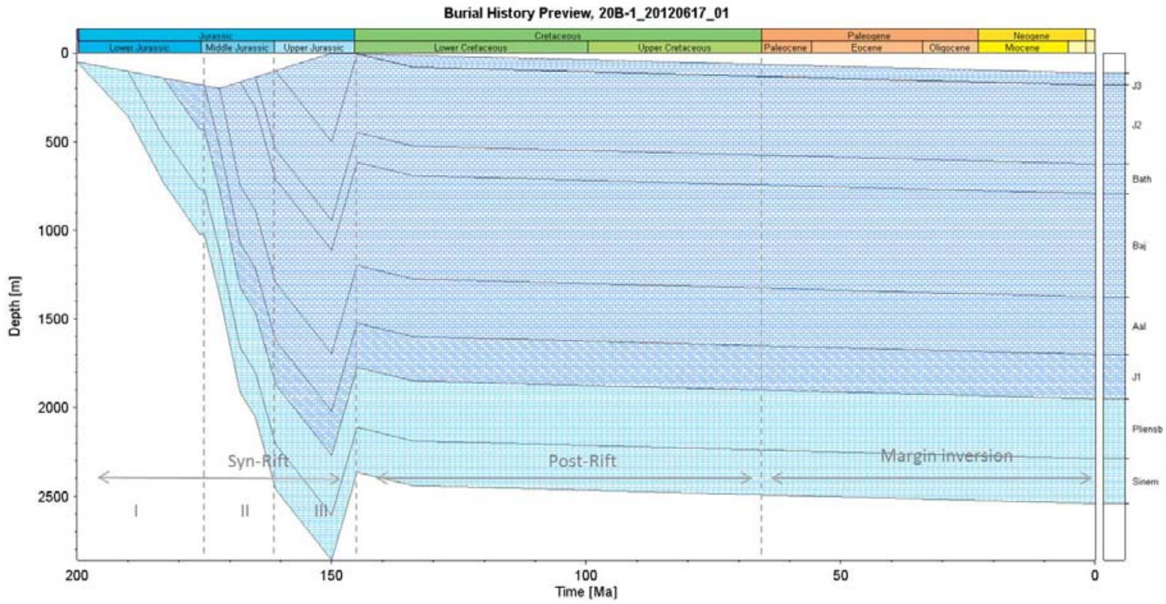

Figure 8.9 – Burial history model for the proximal margin of south-western Lusitanian Basin, in well 20B-1.

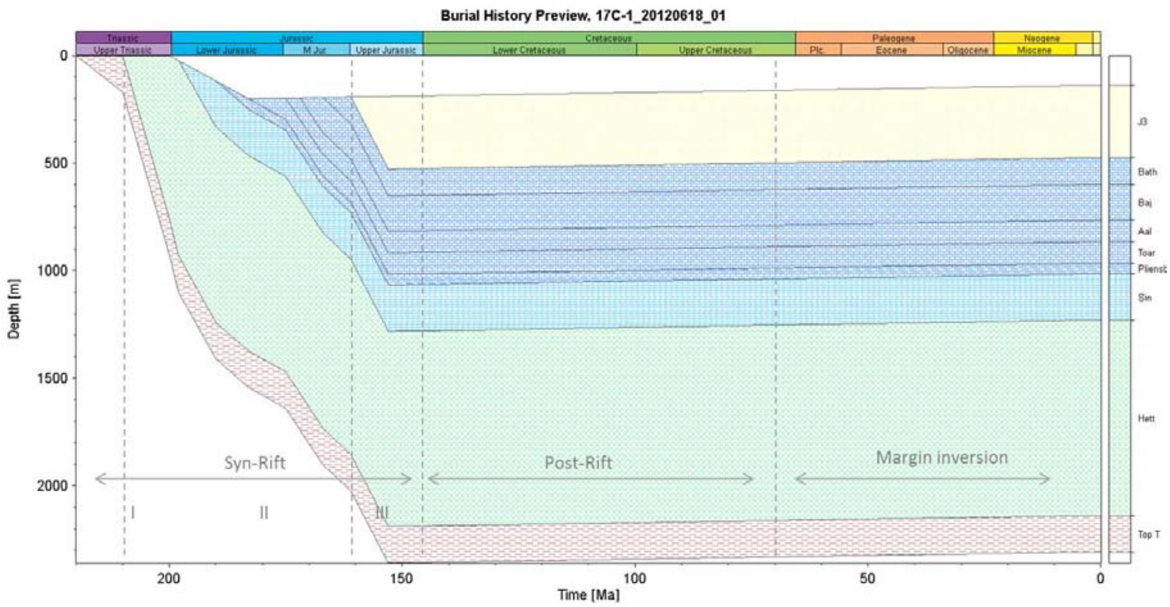

Figure 8.10 – Burial history model for the proximal margin of south-western Lusitanian Basin, in well 17C-1.

In the proximal margin, wells Pe-1 (Fig. 8.3) and Go-1 (8.4) intersected 376 to 1528 m of Early Cretaceous siliciclastics and carbonates, whereas in Be-1 approximately 710 m are estimated (Fig. 8.6). On outcrops and well MP (Fig. 8.2) this interval is absent.

The Late Cretaceous marks the first major period of uplift recorded in the margin, as observed by the significant Albian-Paleocene hiatus. Similarly to outcrops, seismic and well data (MP, Pe-1 and Go-1) show that this interval was in many places obliterated, although on the outer proximal margin, a thick Late Cretaceous prograding deltaic unit is observed, subsequently eroded by a significant incision surface, removing approximately 1000 m of sediments (Figs. 8.5 and 8.6).

Due to the limited geological controls on the margin, the Cenozoic periods and magnitude of uplift are difficult to estimate. This is the case of the models developed for wells 20B-1 and 17C-1 that do not show units younger than the Late Jurassic, thus hindering the complete subsidence analysis, which is evident by the straight burial trend from this age onwards (Figs. 8.9 and 8.10). Nonetheless, these events are clearly expressed on seismic data and were used for preliminary burial history models that reveal that inversion of the margin occurred during an extended period (and persists today), with the principal events focused on the Eocene, the Oligocene and the Miocene. Similarly to wells Pe-1, Go-1 and MP (Figs. 8.2, 8.3 and 8.4), pseudo-well Be-1 (Fig. 8.6) shows a significant period of uplift followed by post-Miocene subsidence.

The distal margin is characterised both by thick post-rift sub-basins (Fig. 8.7), and by areas of considerable hiatus associated with crustal shortening, such as in the Marquês de Pombal High (Fig. 4.13, 5.9 and 5.10). Pseudo-well Po-1 (Figs. 8.7 and 8.8), located on a resilient sub-basin reveals that subsidence in some areas of the margin can extend through long periods, even during margin shortening, namely during the marked Eocene to Miocene inversion. This same well shows approximately 3100 m of sediments overlaying rift strata (Fig. 8.8).

8.1.2. Integrated analysis of subsidence and uplift

The combined analysis of the burial history models presented for the Alentejo and southwest Lusitanian Basins demonstrates the existence of three main phases during continental rifting, interrupted by widespread but uneven events of uplift affecting the margin (Fig. 8.11). Subsequent to rift cessation a period of relative tectonic quiescence marks the drift evolution of the margin, ultimately influenced by major uplift and compression during most of the Cenozoic.

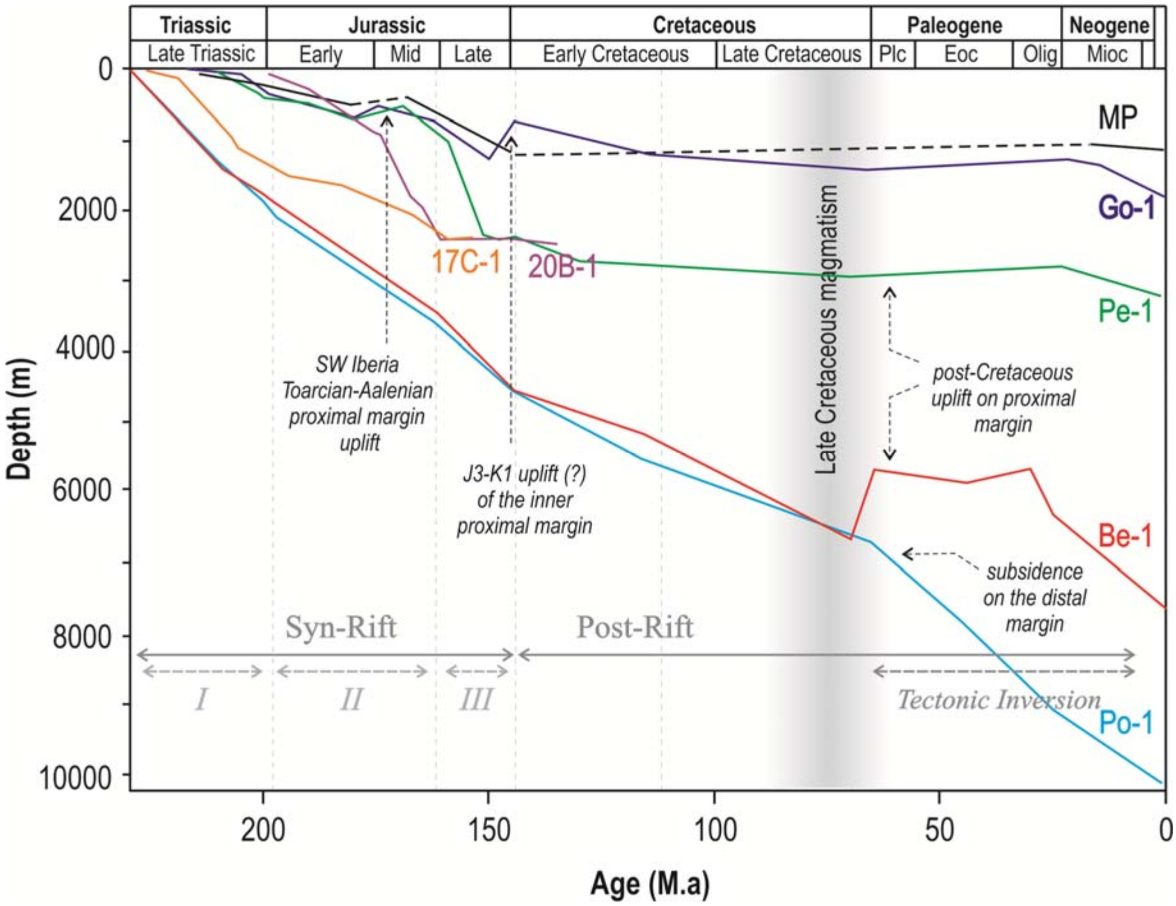

Figure 8.11 – Combined depth-to-basement burial history models of the southwest Iberian margin compared with wells from the south-western Lusitanian Basin, showing the distinct phases of rift subsidence and subsequent inversion of the margin.

The first Rift Phase occurred during the Carnian (or early) to the Hettangian and is characterised by significant subsidence throughout the margin, associated with the wide rift extension mode of the Pangea supercontinent, and synchronous with the evolution of the West Tethys and the Central to North Atlantic. However, subsidence patterns obtained for this period reveal a significant uncertainty due to the limited seismic-stratigraphic and thickness control in some sectors of the margin. If in exploration wells intersecting Megasequence 1 the lithostratigraphic data allows good control of input parameters, it is of most importance to consider that for sequence 1a (the shaly-evaporitic unit), the models may not represent the effective initial thickness (such as in wells Go-1 and 17C-1), as halokinesis may have played a major role and can therefore bias the results. If so, during Syn-Rift I, burial history models may therefore overestimate the magnitude of subsidence for this period.

A new Phase of rifting initiated by the Hettangian-Sinemurian (marked at its base by the occurrence of CAMP igneous rocks), reached a subsidence peak by the Pliensbachian, as demonstrated in Pe-1, Go-1 and in Bordeira by the deep marine facies of the Forno unit (equivalent of the Brenha formation in the Lusitanian Basin). The analysis of the wells modelled for the proximal margin reveals that the Toarcian-Aalenian event played a major control in the evolution of the southwest Iberian margin initially by exhuming the Early to Middle Jurassic and subsequently by the resumed subsidence during the Bajocian-Callovian. Moreover, the models reveal that Rift Phase II was more intense on the outer proximal and distal margin (Be-1 and Po-1), suggesting the relative westwards migration of the rift locus (Fig. 8.11).

Based on results presented in this work, the Rift Phase II (Sinemurian-Callovian), can therefore be correlated in its earlier period (Sequence 2a, Sinemurian-Toarcian) with the last phase of continental extension preceding seafloor spreading occurring in the northern Central Atlantic, namely on the Morocco-Nova Scotia margins (e.g. Hiscott et al., 1990; Withjack et al., 1998). This event is interpreted to have caused the regional uplift of the southwest Iberian margin resulting in a widespread isostatic rebound that explains the major hiatus subdividing Megasequence 2.

The final Rift Phase documented in these models occurred from the Oxfordian to the Tithonian (Fig. 8.11), although already during the latest Jurassic, some parts of the proximal margin reveal significant uplift, which resulted in the removal of the uppermost Jurassic sequences. Although not fully constrained, well Pe-1 suggests that subsidence in some areas might have initiated early in the late Callovian.

Throughout the margin the Early to Late Cretaceous is characterised by overall relative tectonic quiescence and the accumulation of shallow to deeper marine deposits. The combined burial history models (Fig. 8.11), seismic data and Isochron maps (Chapter 6, Fig. 6.10) reveal that during this interval deposition occurred mainly on the outer proximal and distal margin suggesting significant sediment by-pass resultant from noteworthy uplift of the inner proximal margin and the Variscan basement in the hinterland. Similar sediment distribution in the Lusitanian Basin can be observed, which contrasts with the occurrence of growth strata on the distal margin of the Peniche and Galicia Basins, to the North (e.g. Wilson et al., 2001; Alves et al., 2006; Alves et al., 2009). However, on the proximal margin, as in other basins in West Iberia, the Late Cretaceous interval is scarce and often absent (e.g. Rey et al., 2006), denoting a period of increased uplift of the hinterland domains of the margin, which occurred some 50 My at the Southwest Iberian margin or 20-30 My after complete breakup on the northern segment of West Iberia.

The Late Cretaceous Megasequence 5 observed on seismic and, modelled in pseudo-well Be-1 (Fig. 8.5, 8.6 and 8.11) includes a lowstand prograding delta-type seismic package that suggests a relative base-level fall subsequent to cessation of rifting, which contrasts with the global eustatic curves that indicate that during this period sea level was rising. If this interpretation is valid, subsidence patterns for the Cretaceous cannot therefore be fully explained by eustasy or by simple tectonic post-rift subsidence, nor can simultaneously explain the widespread uplift of the inner proximal margin, which must then present external distinct controls for the Aptian?-Paleogene hiatus. Accordingly, a group of factors is presented as possible explanations of the extent and magnitude of the uplift that include: 1) Late Cretaceous magmatism, 2) Post-rift exhumation of passive continental margins, or 3) ocean-continent convergence.

The first argument reveals that in contrast with the northern West Iberian margin (i.e., North of the Nazaré Fault Zone), only Southwest Iberia records the effects of Late Cretaceous magmatism (94-62 M.a; see Chapter 2.2.3). The ascent of substantial volumes of igneous rocks must have therefore resulted in an un-quantified thermal uplift of the inner proximal margin. However, the distribution and size of alkaline batholiths and sills formed during this process are somewhat localised in space and present little significance as a whole, to explain the magnitude of the uplift event.

A second possible explanation for the post-rift widespread uplift has been described for other passive margins, such as NE Brazil, Greenland or offshore Norway (Japsen et al., 2012b). In Greenland, following post-rift subsidence, these same authors showed that an elevated plateau formed approximately 50 M.y after continental breakup, with similar timeline occurring for the NE Brazilian passive elevated continental margin (Japsen et al., 2012a). This model suggests that after rifting, margins which are characterised by elevated plateaus of 1-2 Km above sea-level, were formed by up-warping and folding of the lithosphere, associated with compressive stresses operating in the lower crust-mantle transition (Japsen et al., 2012b). Using this time frame, assuming continental breakup west of the Tagus Abyssal Plain by 145 M.a (*ca.* M20-17 magnetic anomalies time frame), Cretaceous margin uplift would have initiated by 95 M.a, i.e., broadly coinciding with the age of ascension and subsequent consolidation of Late Cretaceous magmatism and the first clear record of widespread margin uplift. Whether a similar process controlled or not the uplift of the southwest Iberian margin still needs further investigation, as so far no detailed data or analysis can verify this correlation. Moreover, a Late Cretaceous (to early Paleogene?) erosion surface is so far untested, although the widespread absence of these deposits in the mainland and their correlative abundance in the offshore, could point to a similar physiography.

A third and alternative mechanism that might explain the Late Cretaceous-Paleogene uplift on the margin could be related with the onset of counter-clockwise rotation of Iberia, collision with the Pyrenees and the convergence of the oceanic and continental domains, through the thrusting of deep rift-related detachments underlying the continental crust, as suggested for the southwest Iberian margin by Neves et al. (2009). Although, these authors suggest that such convergence only initiated by the Late Miocene (the last and best recorded compressive phase in Iberia), it has been demonstrated by the evidence of canyon incision and large amplitude folding on the distal margin presented in this thesis that shortening along the southwest Iberia initiated as early as the latest Cretaceous, but was more important since the Eocene (see Chapters 5 and 7).

Whether a single process, or the conjunction of the above governed Late Cretaceous uplift remains an open question. However, data and reasoning presented herein, favour that although with different magnitude, each of these processes could have contributed to the overall uplift of the mainland and the inner proximal margin.

Subsidence and uplift during the prolonged Cenozoic inversion were related with continental collision of the Iberia microplate with Eurasia and North Africa during the different stages of the Alpine orogeny. The first major pulse of inversion and shortening occurred in the Eocene as a result of the collision with the Pyrenees, followed by Oligocene and Miocene increasing pulses of crustal deformation. Burial history models capture these events but due to lack of information these discrete pulses cannot be investigated in detail. Nonetheless, the models presented corroborate the conclusions presented in Chapter 5 that point to different magnitude of crustal deformation, as observed from the different patterns of basement subsidence throughout the margin (Fig. 8.11).

8.1.3. Implications for estimating the age of continental breakup on the SWIM

The models presented for the southwest Iberian margin reveal that from the Early Cretaceous onwards, tectonic subsidence was significantly diminished and ultimately interrupted by margin inversion (Fig. 8.11). However, the burial history models developed for the outer proximal and distal margin (Be-1 and Po-1) indicate that during this same period these sectors of the margin continued to subside, contrasting with the interpretations that pointed to the cessation of rift by Tithonian-Berriasian times (Mauffret et al., 1989b; Srivastava et al., 2000).

From these observations, two possibilities arise regarding the age of continental breakup on the Southwest Iberian margin: 1) Continental breakup is Tithonian-Berriasian in age, coeval with M20-17 magnetic anomalies and previous interpretations, pointing to the early onset of seafloor spreading west of the Tagus Abyssal Plain (Mauffret et al., 1989b; Srivastava et al., 2000; Tucholke et al., 2007); or 2) Continental breakup occurred during the Barremian-Aptian, similarly to the Galicia and Northern Newfoundland margins (e.g. Pinheiro et al., 1996; Tucholke and Sibuet, 2007; Bronner et al., 2011).

Consequently the following must be considered:

- Late Cretaceous sediments (collected from seafloor sampling) overlay the Early Cretaceous sub-parallel reflectors on the outer proximal margin;

- The Early Cretaceous seismic package (megasequence 4) overlays three superimposed growth strata interpreted to represent the principal Rift Phases documented both for the Lusitanian and Alentejo Basin. A fourth Rift Phase is only unequivocally described on the distal Galicia and Peniche Basins (Alves et al., 2006; Tucholke et al., 2007; Tucholke and Sibuet, 2007; Alves et al., 2009 and references therein);
- The Early Cretaceous units identified on seismic are poorly constrained and their real thickness (which was estimated from average velocity models) can be overestimated, thus biasing subsidence for this period;
- The different Rift Phases are dissimilarly expressed throughout the margin. As such, although continental breakup on the SW Iberian margin might have occurred during the Jurassic-Cretaceous transition, the Early Cretaceous effect of isostatic compensation resulting from the final Rift Phase in the NW Iberian margin could have induced subsidence in the study area;
- The proximal margin is depleted in Cretaceous deposits and therefore sediment bypass and accumulation on the outer proximal and distal margin generated increased lithostatic overburden over the syn-rift, thus increasing subsidence during this period. This, associated with thermal post-rift subsidence resulted in significant accommodation space, promptly infilled by these deposits;
- Post-rift inversion of the margin is interpreted to have resulted in differential accommodation of shortening, which associated with a rift-related deep-crustal detachment subsequently inverted to thrusting, lead to the continued rotation of the inherited tilt-blocks and the uplift of the footwall. Therefore, a syn-rift depocentre was continuously reactivated even during margin inversion (Fig. 8.7).

Considering the above, the first hypothesis is presented as the most feasible, suggesting therefore, a Late Jurassic to earliest Cretaceous continental breakup occurring West of the Tagus Abyssal Plain.

8.2. Southwest Iberia as an upper-plate margin

West Iberia and Newfoundland are type-examples of asymmetric magma-poor rifted margins in the North Atlantic that underwent prolonged continental extension since the Late Triassic until the Early Cretaceous, when continental breakup ultimately gave place to the formation of oceanic crust (Manatschal, 2004; Tucholke et al., 2007). However, the evolution of its southern province (the Southwest Iberia and South Newfoundland conjugate margins), is still poorly investigated and key questions remain unclear, such as: 1) the exact nature, extension and geometry of the continental crust, 2) the processes controlling the transition to the oceanic domain, 3) the significance of first-order transfer zones on intra-plate stress accumulation and, 4) the role of inherited crustal heterogeneities on post-rift shortening. Such aspects regarding the geodynamic evolution of the Southwest Iberian margin are discussed in the context of the large scale model of asymmetric rift margins, namely the upper-plate or lower-plate tectonic setting (sensu Lister et al., 1986).

Within the Iberia-Newfoundland conjugate margins it has been interpreted that its northern segment represent a typical example of asymmetric rifted margins, where the northern Newfoundland and the Lusitanian-Galicia basins represent respectively an upper-plate and a lower-plate (e.g. Wilson et al., 1989; Reston et al., 1995; Froitzheim and Manatschal, 1996; Whitmarsh et al., 2001).

However, during the outcome of this work it became unclear if the lower-plate setting described for north-western Iberia was applicable for the whole Iberian margin and if this could explain some of the dissimilarities found on the Whale-Alentejo conjugate margins. Accordingly, a group of major distinctive features are described ahead, in order to verify the hypothesis that the Southwest Iberia represented an upper-plate margin.

8.2.1. Contrasting architecture of conjugate margins

The multiphased segmentation of the continental crust during rifting resulted in the formation of discrete structural styles, broadly coinciding with the distinct sectors of the margin, i.e., the proximal and distal margin (Chapter 4).

The architecture of the crustal tilted blocks and their related growth strata shows distinct subsidence patterns, contrasting with the geometry of its conjugate of South Newfoundland and those from the Galicia margin (Fig. 8.12). The southwest Iberian margin is characterised by a relatively narrower proximal margin of 50-100 km, and by approximately 100-150 km on the distal margin of the Alentejo Basin, when compared with southern Newfoundland.

In Whale and Horseshoe Basins the proximal margin extends across a region of about 150 km (Enachescu, 1992), whereas in the distal margin of the Carson, Salar and Bonnition basins, it extends over 200 km (Wielens et al., 2006). Moreover, on the Southwest Iberian margin the geometry of growth strata and their estimated subsidence reveal not only the multiple events of extension, but also the ocean-wards rift locus migration, in a mechanism interpreted to have similar genesis as in Newfoundland. Such segmentation is related with the geometry of the continental crust and the model invoked to explain the asymmetry of these Atlantic margins.

The conjugate margins of Iberia and Newfoundland also differ in the volume of Carnian-Hettangian evaporites deposited, with the Whale-Horseshoe basins showing a thick evaporite unit (Balkwill and Legall, 1989), whereas on the Southwest Iberian margin these are nearly absent or include a mixture of shales and interbedded evaporite sequences.

Throughout the study area, the tilt block geometry of the outer proximal and distal margin reveals that listric master faults are likely rooted at an upper continental crust level (Fig. 8.12). The analysis of high-quality 2D multichannel seismic data imaging the SW Iberian margin reveals an East dipping lower continental crust detachment, above which the thickness of the continental crust varies landwards from about 5 km on the distal margin, to over 25 km on the proximal margin (Fig. 5.8 and 5.13). This deep crustal reflector can be traced throughout the margin and ends near the Ocean-Continent Transition zone.

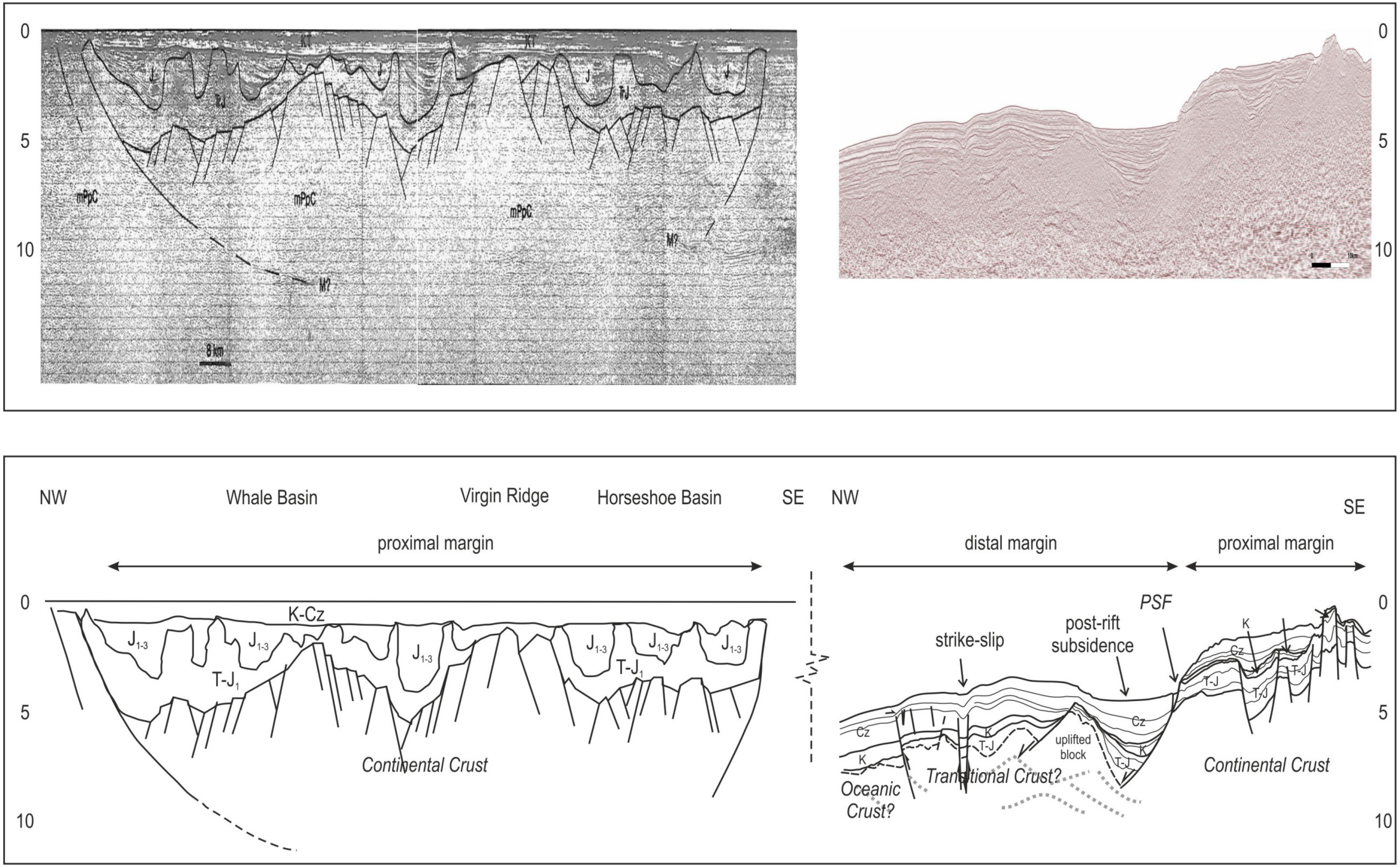

Figure 8.12 – Compared seismic sections on the Alentejo Basin (Southwest Iberian margin) and Whale Basin (South Newfoundland) and their interpretation. Seismic section and interpretation of Whale Basin modified from Balkwill and Legall (1989).

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8.2.2. Evidence from magmatic activity

Although commonly described as a magma-poor rifted margin, the southwest Iberian margin reveals several events of magmatism since the Triassic-Jurassic boundary, which contrasts markedly with what has been described from other areas in Northwest Iberia and Newfoundland (e.g. Azerêdo et al., 2003; Tucholke and Sibuet, 2007).

In fact, on the Southwest margin of Iberia, igneous activity includes the extrusive tholeiitic basalts of Central Atlantic Magmatic Province (e.g. Martins et al., 2008; Cirilli et al., 2009), the Late Jurassic dykes (Oliveira, 1984), the gabbros and other magmatic suites from the Gorringe Bank (Schärer et al., 2000; Conti et al., 2004 and references therein), the tholeiitic-to-alkaline proximal margin igneous intrusions and volcanics of the latest Cretaceous (Miranda et al., 2009) and the Madeira-Tore Rise (e.g. Merle et al., 2009). Moreover, the Late Cretaceous magmatic features documented in SW Iberia, not only show striking similarities on their overall geochemical signature, but also on their alignment NW-SE along the proximal margin, which can also be observed on the Earth Magnetic Anomaly grid Map (Fig. 8.13A). Ribeiro et al. (1990) suggested that these Late Cretaceous igneous features are the result of a dextral strike-slip crosscutting the continental margin.

Contrariwise, it is postulated here for the first time that these Late Cretaceous intrusions can result from underplating, given the adequate upper mantle conditions and a suitable geodynamic setting.

Considering the existence of a thick 25-30 km highly segmented continental crust on the Southwest Iberian margin, as demonstrated in Chapter 5 and by Afilhado et al. (2008) and Neves et al. (2009), some of the preliminary conditions for post-rift lithospheric uplift and consequent adiabatic melting could have been achieved (Fig. 8.14). If such a deep crustal magma source is feasable, this might therefore explain the persistent igneous activity in this specific domain of the North Atlantic.

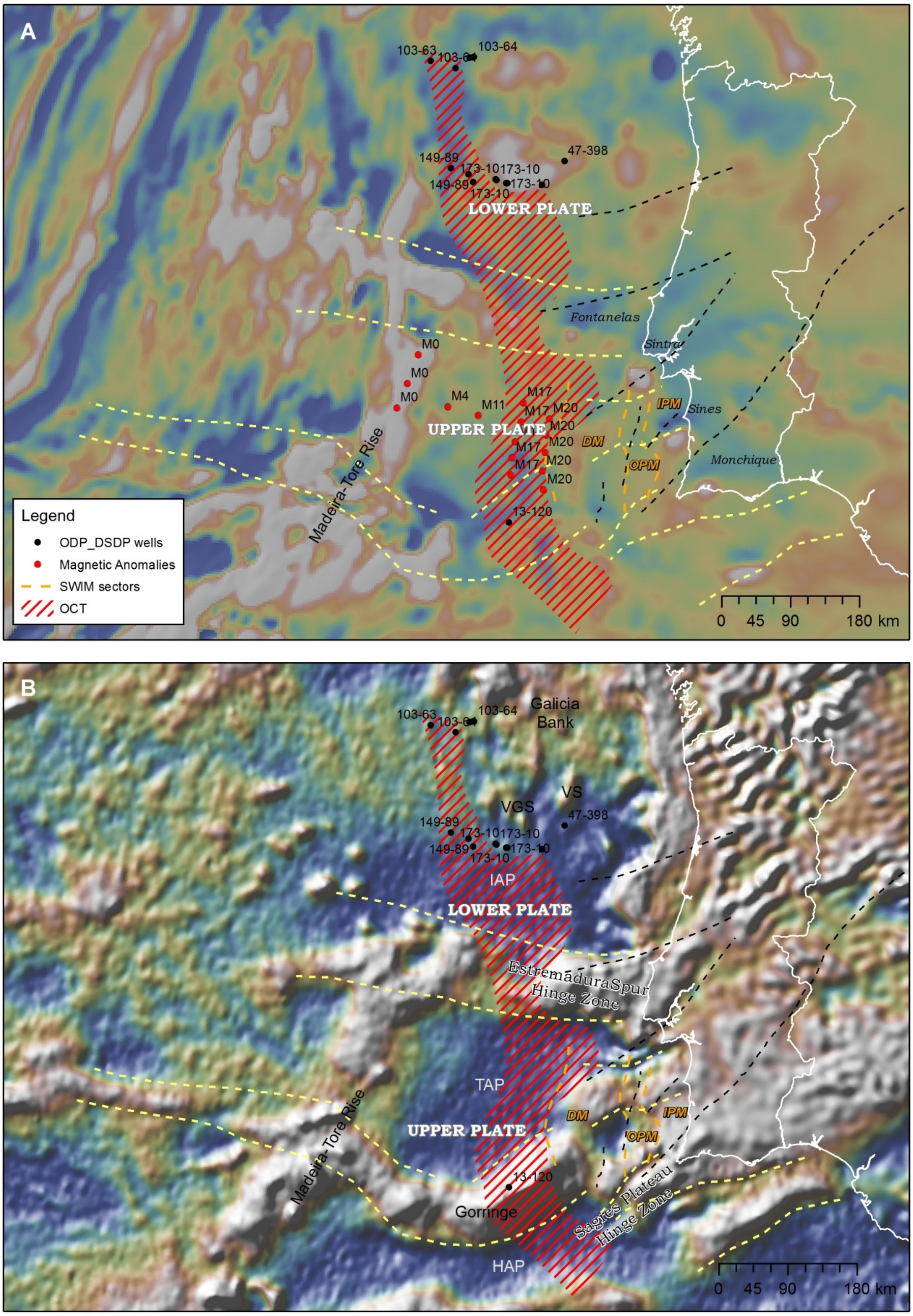

Figure 8.13 – Geophysical maps and evidence for changing polarity of the asymmetric rifted margin of Iberia in relation with the major interpreted lineaments. A – Map of Earth Magnetic Anomaly Grid showing oceanic magnetic anomalies and OCT (Rovere et al., 2004). B – Free-air gravity anomalies (Sandwell and Smith v18.1). Images obtained from GeoMapApp 3.3.0.

This mechanism concurs with the occurrence of underplated material predicted by depth-dependent models explaining asymmetric rifted margins (Wernicke, 1981; Lister et al., 1986) and the updated and revised versions of these models (Manatschal and Bernoulli, 1998, 1999; Manatschal, 2004). Schärer et al. (2000) explain asymmetric rifting with the occurrence of asthenosphere igneous material underlying the thinned and highly segmented continental crust of Iberia, which in a later stage experienced unroofing of the lithospheric mantle. However an integrated vision of such geodynamic scenario has not been comprehensively presented so far.

On the Namibian margin, high velocity zones underlying the thinned continental crust are associated with underplated material (Fernàndez et al., 2010). Similarly to what is suggested here for the Late Cretaceous intrusion of deep-sourced igneous bodies, these authors also document sub-volcanic intrusions in the thick continental crust.

According to the model of Lister et al. (1986) and Etheridge et al. (1989), underplating is predicted only for the upper-plate margin, thus suggesting that Southwest Iberia to represent this type of setting.

An increase in temperature at deep crustal levels causing magma ascent also allows clarifying the uplift and/or tilting of the margin (likely since the Early Cretaceous) and the resulting increased sediment supply towards the distal margin, as evidenced by the occurrence of thick post-rift strata deposited in a continuously subsiding basin. The burial history models presented above additionally concur to hypothesis that persistent Cretaceous-Tertiary uplift of the proximal margin was controlled by crustal uplift resulting from inherited rift geometry, i.e. the broad scale geodynamic upper-plate architecture.

8.2.3. Evidence from crustal architecture

Another significant aspect reinforcing the upper-plate setting is the role of first-order transfer fault zones bounding the SW Iberian margin, namely the Nazaré Fault Zone (NFZ) to the North, and the Messejana-Plasencia Fault Zone (MPFZ) to the South (Fig. 8.13). Each of these first-order transfer zones, are respectively accompanied by the occurrence of uplifted hinge zones, i.e. the Estremadura Spur and the Sagres Plateau (Fig. 8.13), which acted as major oceanic barriers since the early times, thus clarifying the tectonic controls that allowed the tethysian-boreal connectivity of the early Atlantic Ocean.

The NFZ is interpreted to have worked as the northern boundary for the polarity change between the upper-plate geometry of SW Iberia advocated here, and the lower-plate setting proposed for NW Iberia (Reston et al., 1995; Froitzheim and Manatschal, 1996; Alves et al., 2009) (Fig. 8.13). On gravimetric data the Estremadura Spur and the Sagres Plateau emerge as prominent crustal highs reinforcing this interpretation (Fig. 8.13). The models that postulated such geometry (Lister et al., 1986; Etheridge et al., 1989; Wernicke and Tilke, 1989), are herein supported by the polarity shift of the margin. Similarly with the upper-plate setting of the Moroccan margin (Piqué and Laville, 1996), the interpretation of Southwest Iberia as an upper-plate margin thus results in the increased evidence that this segment of the North Atlantic has strong affinities with the Central Atlantic, which therefore points to a revision of the role of Iberia in the wider context of the Atlantic. The analysis of gravity and magnetic anomalies geophysical data on the West Iberian margin reveals that these hinge zones as noteworthy features dividing the northern lower-plate margin of NW Iberia and the upper-plate margin of SW Iberia (Fig. 8.14). The analysis of the free-air gravimetric data in the study area also reveals striking correlation with the interpreted sectors of the continental crust presented in the chapters above (Fig. 8.13B). The inferred transfer fault segmenting the proximal margin is therefore revealed as a probable left-lateral strike-slip (Fig. 8.1). Although kinematic indicators are unclear for this lineament, the geometry of the continental crust indicates that it may relate with the recent movement described for the MPFZ.

The upper-plate geometry of SW Iberia also explains the compressive geometries and distinct shortening rates across the margin, which dominantly include the reactivation of Hercynian and syn-rift faults, with the formation of both thick-skinned and thin-skinned tectonic features.

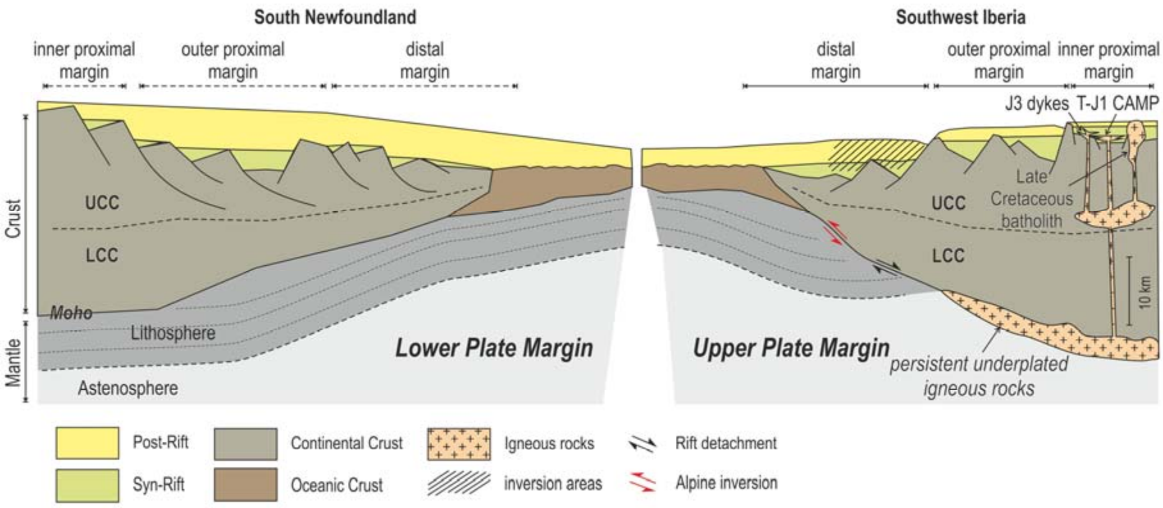

Figure 8.14 – Schematic model of the Southwest Iberian margin as an upper-plate continental margin, showing the distinct rift-related subsidence geometry, the preferred areas of post-Cretaceous shortening, the inversion of movement of the crustal detachment and the postulated underplated source for persistent magmatism. Based on the model of Lister et al. (1986).

Such geometry contrast with the inversion architecture on the NE Iberian margin as described by Masson et al. (1994), which is characterised by gentle folding of the post-rift units. The lower continental crust detachment formed during rifting (Chapter 5, and Figs. 8.12 and 8.14) is herein invoked to be the preferred locus for the inception of convergence between the oceanic and continental domains, which resulted from collision of Iberia with the North Africa and Eurasian plates. Thus, the crustal indentor invoked by Neves et al. (2009) coupled with the numerical modelling of Nikolaeva et al. (2010), may therefore represent one of the few documented cases of onset of subduction, an hypothesis long suggested by Ribeiro (1998), which comes herein supported by new data and interpretations. Similar relation between underplating and basin inversion was described for the Britain and the East Irish Sea (Brodie and White, 1995).

In conclusion, the postulate that southwest Iberia depicts an upper-plate margin setting explains not only the N-S and E-W asymmetry of the southernmost Atlantic conjugate margins, the late Cretaceous magmatism and its distribution, but also the structural architecture during post-rift inversion.

Moreover, this model brings light for future palaeogeographic reconstructions of the Central-North Atlantic, as it reveals the important implications for the assessment of possible petroleum provinces, namely on the variation of heat flow throughout the margin, the extension of source rocks and reservoirs, the regional stress field or the integrity of seals.

The model proposed in this work does not aim to resolve the lower-upper-plate paradox (Reston et al., 1995; Rosenbaum et al., 2008 and references therein), but is therefore a contribution for this question.

8.3. Can sequence stratigraphy be applied to rift basins?

In Chapter 6, an original combined seismic and sequence stratigraphic analysis of the main tectono-sedimentary units of the southwest Iberian margin is presented. In this chapter a comprehensive framework was erected in order to establish the basis for the understanding of the overall stratigraphic evolution of this domain of the Atlantic in relation with neighbouring continental rifted margins of North Africa, North America and Northwest Europe.

Since the revolutionary creation of the sequence stratigraphic analysis of depositional sequences (e.g. Mitchum et al., 1977a; Mitchum et al., 1977b; Vail et al., 1977; Van Wagoner et al., 1988), limitations to the application of such methodology where grounded on the complex interplay between eustasy and tectonic controls, mainly in geodynamic settings governed by intense rift subsidence. Despite the significant contributions based on marine and non-marine environments, both from ancient and modern examples from the North Sea, the East African Rift System, or the Gulf of Suez (Frostick and Steel, 1993; Prosser, 1993; Gawthorpe et al., 1994; Ravnås et al., 1997; Ravnås and Steel, 1998; Martins-Neto and Catuneanu, 2010), a unique approach to a hierarchy and framework is still is to be achieved.

The current discussion aims to analyse these concepts, based on examples from the southwest Iberian margin presented in this thesis and to promote the debate of the methodologies that could explain an insightful sequential tectono-stratigraphic description of rift basins.

In rift basins, tectonics is the principal control in the creation of new accommodation space that is to be filled with sediments, either sourced from afar or formed within the depocentre. Moreover, the drainage network that constantly evolves during the persistent changing geometry of the basin during rift subsidence, along with climate controls, exert a significant role in the nature and depositional geometry of sediments accumulated. These aspects combined, result in the overall wedge-shape geometry of syn-rift strata commonly used in the interpretation of such basins. However, the hierarchy of unconformities, the internal geometry and their related deposits, either continental or marine, despite well characterised remains unclear in what regards their sequence stratigraphic framework, which contrasts with the comprehensive models derived for eustasy-controlled passive margins

8.3.1. Syn-Rift unconformities

The foundations of a sequence stratigraphy framework suitable for depositional analysis of rift basins, must account for the primordial role of sequence bounding unconformities and how these stratigraphic boundaries can be used to relate the distinct depositional trends within and along the hierarchy of sequences.

Unconformities should therefore be identified and classified into distinct orders of importance or magnitude, aiming to depict the regional geological and stratigraphic context, and should be later used to distinguish the principal sequences comprising the evolution of basins.

The basal regional angular unconformity, or proto-rift unconformity (sensu Nøttvedt et al., 1995), thus consisting of the foundation criteria to interpret sequence stratigraphy in extensional settings, is often well observed on seismic data, or correlated between wells and outcrops, as it is separates the previous sequences from the Rift Initiation deposits. As a result, the first deposits overlaying this unconformity can by identified by the downlapping reflections of sedimentary beds, which are independent on the position they occupy on the rotational tilt block, i.e. the subsiding hangingwall or the uplifted footwall. In the study area, the basal unconformity marking the first phase of rifting bounds the folded Paleozoic metasediments and the Late Triassic red beds, clearly observed in the Bordeira area (Fig. 6.5A). The second phase of rifting, initiating by the Rhaetian-Hettangian is marked by an angular unconformity, above which CAMP related volcanics overlay the shaly-evaporitic unit of the Dagorda formation. The third rift phase in the basin, denoting the final and more intense period of subsidence is characterized by the regional hiatus and regional angular unconformity of the Callovian-Oxfordian.

In contrast, the last unconformity commonly identified within a rift sequence, thus depicting the cessation of continental extension is characterised by downlapping strata overlaying the last tilted sediments resulting from rift subsidence. In the case of the onset of seafloor spreading this unconformity can be assigned as the breakup unconformity (sensu Driscoll et al., 1995). However, because the last deposits accumulated during rifting, when tectonic subsidence is markedly diminished, the exact identification of such strata especially on seismic data may sometimes be difficult, as both late-rift and the early post-rift sequences are often characterised as sub-parallel reflections. Moreover, the exact timing of this unconformity may be diachronous in relation with formation of the OCT and the true onset oceanization, thus suggesting the existence of a Lithospheric Breakup Sequence (LBS) (Bronner et al., 2011; Soares et al., 2012 and references therein). On the Southwest Iberian margin the breakup unconformity is interpreted as Tithonian-Berriasian in age and can be observed on seismic data, with Early Cretaceous sub-parallel reflections draping the superimposed growth strata (Fig. 4.5 and 8.12; see Chapter 4).

Both the pre-rift unconformity and the rift cessation (or breakup) unconformity, broadly considered first-order unconformities, thus bounding the high-order Megasequences (sensu Hubbard et al., 1985a; Hubbard, 1988) occurring during a rift phase. If such unconformities can be clearly identified and their record be traced unevenly throughout a basin, problems may arise when considering the extension, correlation and significance of minor unconformities that bound the distinct sequences within a Megasequence. Moreover, such unconformities are expressed dissimilarly both in type and magnitude, and are slightly diachronous throughout a basin and their conjugate margin.

The second-order unconformities (and consequently their unconformity bounded sequences) develop mainly during periods of tectonic subsidence and occur dominantly on the footwall of the tilt block near the fulcrum synchronous with the creation of new accommodation space in the depocentre (Fig. 8.15). Accordingly, the unconformity in the subsiding areas may therefore be absent and or be revealed as paraconformable boundary that cannot be detected on seismic. However, on wells and outcrops, sediment variations and their related palaeontological content, records this transition (Fig. 6.13 and 6.14). Additionally, the expression of the footwall unconformity differs in the case of fully or partly submerged basins (e.g. Ravnås and Steel, 1998). In the second case, these unconformities and sequences boundaries are characterised by erosion and incision on the footwall, accompanied by correlative forced-regression deposits that accumulate basinwards (Fig. 8.15).

These unconformities mark the transition between the different major pulses of tectonic subsidence and therefore can allow identifying the boundary between the rift initiation and the rift climax, and between the rift climax and the late rift depositional packages. Examples of footwall unconformity may explain the significant Callovian-Oxfordian hiatus, which in some areas of the proximal margin seems to last longer than in other settings of the basin.

8.3.2. Tectonic Systems Tracts and sequence stratigraphy

The work of Prosser (1993) for the North Sea firstly introduced the concept of Tectonic Systems Tracts coupled with the insightful description of the internal geometry of seismic stratigraphic sequences. Subsequent studies on rift basins throughout the world have addressed a hierarchy that could explain the distinct sequences within a rift basin (e.g. Gawthorpe et al., 1994; Nøttvedt et al., 1995; Ravnås and Steel, 1998; Ravnås et al., 2000; Martins-Neto and Catuneanu, 2010). However, the foundation criteria devised by these authors lack consensus in methodology, terminology and knowledge dispersal and therefore its application remains incomplete.

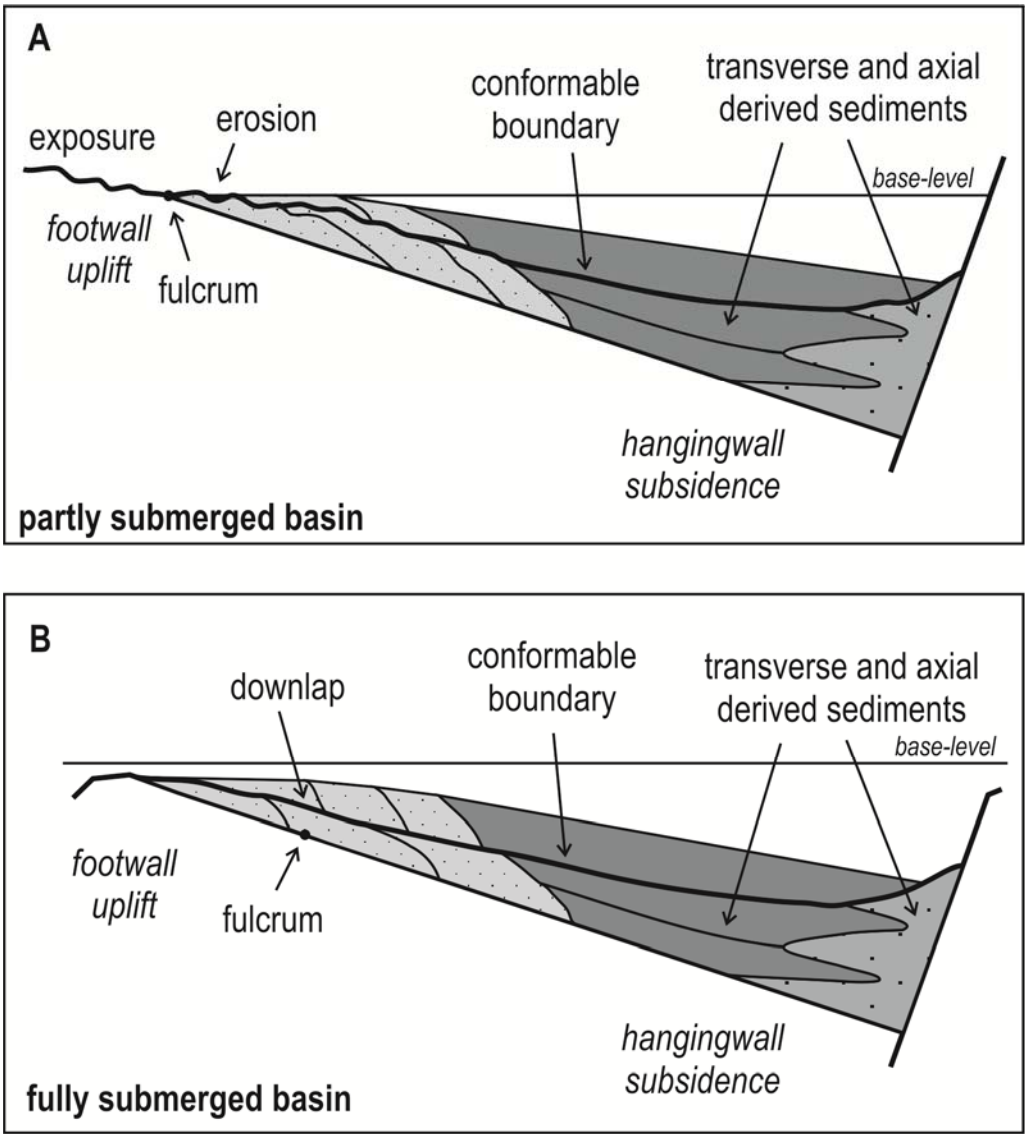

Figure 8.15 – Schematic expression of minor unconformities bounding the tectonic systems tracts in relation with the submergence of a sub-basin. A – Partly submerged sub-basin; note the coeval expression of truncation and conformable boundaries. B – Fully submerged sub-basin showing the overall unconformity on the footwall and conformable at the depocentre.

Research results presented in this work consider that similarly with the framework developed for depositional systems tracts, in basins controlled by tectonic subsidence, a group of equivalent terminology with tectono-stratigraphic significance can be applied. As such, a compromise between Prosser's original nomenclature and those suggested by the latter authors was applied to the description of the tectono-sedimentary units from Southwest Iberia. In summary, these include the Rift Initiation Systems Tract (RIST), the Rift Climax Systems Tract (RCST) and the Late Rift Systems Tract (LRST) that can be correlated with the main pulses of subsidence within a rift phase (Fig. 8.16). Accordingly, each of these Tectonic Systems Tracts (which must show a flawless depositional pattern and evolutionary significance), are then revealed, both as a descriptive but also as a predictive tool for the investigation of extensional basins. The RIST thus refers to the stratigraphic sequence associated with the initial pulse of tectonic subsidence, the RCST to the rift pulse showing maximum tectonic subsidence throughout a basin and ultimately, the LRST, which comprises the final subsidence pulse prior to the onset of post-rift deposition or a renewed extensional phase (Fig. 8.16).

The application of these terms differs from the traditional sequence stratigraphy nomenclature. The main reason for this approach is based on the concept that the depositional controls in rift basins are distinct from those in drift margins. More significantly, this results from the fact that in rift basins simultaneous uplift and subsidence occur, which contrasts with drifting settings that account for a relatively stable tectonic setting controlled mainly by eustasy.

	Episode	**Phase** *Sequence*	**Pulse/** *Tectonic Systems Tract* *unconformity*
Order	1st order	2nd order	3rd order
Duration	>10's My	3-20 My	0,5-5 My
Tectonic event	Continental Rifting	Rift Phase 2 *Megasequence*	*breakup unc.* Late Rift *LRST* *late rift unc.*
			Rift Climax *RCST* *rift climax unc.*
			Rift Initiation *RIST* *pre-rift unconf.*
		Rift Phase 1 *Megasequence*	Late Rift *LRST* *late rift unc.*
			Rift Climax *RCST* *rift climax unc.*
			Rift Initiation *RIST* *pre-rift unc.*

Figure 8.16 – Correlation of the discrete phases of continental rifting and their related Megasequences and Tectonic Systems Tracts, as a tool for construction of a sequential tectono-stratigraphic framework in continental rifted margins. Modified from Catuneanu (2006), Nøttvedt et al. (1995), Prosser (1993), Ravnås et al. (2000).

Accordingly, the concept of tectonic systems tracts are herein synthesised into a meaningful framework, grouping the discrete depositional sequences giving them a tectono-stratigraphic significance and discussed in the scope of rift basins worldwide (Fig. 8.16). As such, the term sequence to be used in this framework follows the widely accepted definition of a repeatable depositional unit bounded by unconformities and their correlate conformable boundaries (sensu Mitchum et al., 1977b).

The nature of the sediments accumulated within these sequences is not addressed as they can vary significantly depending on the several external controls, such as climate or sediment supply. Accordingly, the brief description presented ahead focus mainly on the unique depositional features that can be found on both non-marine and marine settings, independently of the bathymetry of the basin or sub-basins.

8.3.2.1. Rift Initiation Systems Tract (RIST)

The Rift Initiation Systems Tract refers to the first depositional sequence deposited in response to the early tectonic subsidence recorded in a basin. In contrast with the eustasy dominated basins, this first systems tract (as in the subsequent rift-related depositional sequences) is characterised both by a relative base-level rise on the downslope and a base-level fall on the upslope.

The base of the RIST is marked by a regional angular unconformity (the pre-rift unconformity), above which the depositional trend is characterised by overall aggradation/retrogradation, in sedimentary response to the recently created accommodation space. The new basin often shows limited volume for sediment accumulation, which relates to the minor subsidence rates encountered for this rift phase (e.g. Fig. 8.11).

Deposits within this sequence can be diverse in nature and geometry and are dominated in the proximity of the master fault bounding a basin, by the accumulation of axially derived sediments such as alluvial fans on continental dominated environments or submarine fans in marine setting. Towards the depocentre finer sediments tend to accumulate, mainly including transverse derived deposits resulting from the incipient re-organization of the drainage network. On the uplifted areas above the fulcrum, sediments are progressively eroded and axially sourced towards the back-tilted footwall showing aggradation or retrogradation. On seismic data the RIST is characterised by chaotic to planar divergent reflection showing limited subsidence. On wireline data (mainly in the Gamma Ray), the RIST shows progressive deepening-upwards trend, broadly defining retrogradation.

Occasionally, the RIST shows at its base a minor prograding trend that records the onset of tectonics subsidence and the first sedimentary response to base level rise.

The RIST can be similarly considered equivalent to the Lowstand Systems Tract (LST). In both systems tracts the relative base-level fall often generates forced regression in a shallower segment of a basin and correlative accumulation of coarse deposits on the deeper parts of the depocentre. However, in the case of the LST the area recording erosion or limited deposition is located landwards and the coarser deposits accumulated basinwards. Conversely, in the RIST due to the complex architecture of rift basins that often show constant polarity change of the subsiding hangingwall, this criterion is not valid and may be misleading when trying to predict facies variations. Moreover, the source of sediments is also distinct as they can be derived from both sides of the newly created rift basin, which contrasts with the relatively stable input of sediment from the continent in eustasy dominated settings.

8.3.2.2. Rift Climax Systems Tract (RCST)

The transition to the Rift Climax Systems Tract is marked by a second-order angular unconformity (or group of unconformities) that is usually well expressed on the uplifted tilted area of the hangingwall, but tend to be absent towards the depocentre or merely represented by a paraconformity. It is therefore the second depositional sequence found in rift basins and has significant importance for the prediction of the occurrence of possible source rocks, a chief element in the analysis of petroleum systems.

The RCST is characterised by marked tectonic subsidence on burial history models and is accompanied by retrogradation that progressively leads to the deepening of a basin and therefore results in the formation of a Maximum Flooding Surface (MFS), which is the dominant locus for the accumulation of deep-water facies rich in organic content. Such sediments coexist laterally with coarser deposits derived axially or through transverse drainage systems, resulting from the degradation of adjacent exhumed rotated blocks.

During the period of paroxysmal tectonic subsidence, this systems tract may record the successive events of tectonic subsidence that result in the accumulation of thick aggrading to retrograding sequences. Also, during this pulse, tectonics often outpaces deposition resulting in the formation of underfilled basins.

On wireline data and outcrops, this period is marked by increasing gamma-ray and the occurrence of clay-rich deposits, broadly forming a retrograding trend in response to a relative base-level rise. Accordingly, a typical bell or serrated trends may form on the deepest parts of the basin, whereas on basin edges, other retrograding patterns may be recorded.

The identification of the uppermost limit of the RCST may sometimes be difficult to pin-point, as the overall depositional trend may not be comprehensively developed. Whether the maximum gamma-ray profile should define the MFS and similarly with the TST mark the boundary of this sequence or if a noticeable depositional contrast should be considered as a limit is uncertain. However, the integrated analysis of lithology, paleontological content and wireline data must be taken into account for such decision. Additionally, the RCST must represent a period of maximum tectonic subsidence and therefore, must correlate with the overall facies within a basin. It must also be considered that the RCST relates to a tectonic pulse and that accordingly, deposition is a response to this event, which in some cases may not be immediate and a time lapse may occur between the tectonic pulse itself and the resulting sedimentary response. In chapter 6 (Fig. 6.12), the Rift Climax is interpreted to include the MFS and extend until a clear sediment variation (e.g., an hardground and/or erosional features) or wireline data break, ultimately represented by a minor unconformity denoting the onset of a new (yet less intense) period of tectonic subsidence or variation of eustatic level.

8.3.2.3. Late Rift Systems Tract (LRST)

The Late Rift Systems Tract represents the final event of deposition within a rift phase and similarly with the Highstand Systems Tract (HST) is characterised by dominant progradation that progressively fills the previously generated accommodation space. The lower boundary of the LRST may be represented by a minor angular unconformity or by a paraconformity denoting a new (yet minor) pulse in tectonic subsidence.

During the LRST, the diminished tectonic subsidence allows the formation of new depositional settings dominantly characterised by progressive influence of non-marine or marine-filled environments. Depending on the overall balance between sediment supply and accommodation space, the basin can vary from being underfilled, balanced or overfilled (Ravnås and Steel, 1998). Accordingly, fluvial to shoreline deposits may accumulate and in some cases, fully continental and exposure may be anticipated.

Whether tectonics plays a dominant control during the Late Rift subsidence pulse or eustasy governs the deposition processes must be assessed individually for each basin (or sub-basin). Within this tectonic systems tract, higher order unconformities often relate with eustatic controls, a case documented for the proximal margin wells, offshore the Lusitanian Basin (see chapter 6).

The uppermost boundary is characterised by an unconformity above which, the overall depositional trends indicate typical post-rift accumulation that on seismic are revealed as widespread and continuous sub-parallel reflections. Such unconformity may be overlain by a new rift cycle or represent the continental breakup of the margin.

8.3.3. Final remarks

The integration of multiple datasets from the Southwest Iberian margin and the models presented has allowed generating a comprehensive sequence stratigraphy framework that associates information from large-scale geodynamic models (geographically and in age) with small-scale depositional patterns. It is then suggested that the multiple phases of rifting should include each of these Tectonic Systems Tracts (Fig. 8.17), although the magnitude and significance of their expression can differ in the distinct sectors of the margin, thus pointing to a detailed analysis of specific aspects that explain their variability.

The generalised application of this revised sequence stratigraphy framework still needs to be tested in other well studied basins throughout the world. Nonetheless, the results obtained in this work along with the validation based on examples from the North Sea and the Newfoundland point to a wider applicability of such criteria.

In conclusion, this work suggests that future assessment of rift basins can therefore include detailed sequence stratigraphy analysis in order to present meaningful tectono-stratigraphic description of extensional basins.

8.4. Tectono-stratigraphic evolution of the Southwest Iberian margin in the context of the Central and the North Atlantic

Southwest Iberia, located on the transitional domain of the Central and North Atlantic Ocean, records the complete rift-to-drift evolution of a magma-poor rifted margin, which is revealed herein as a key province to understand the intricate evolution of this domain of the Atlantic and to elucidate unclear aspects of other continental margins.

The Southwest Iberian margin evolved within the context of a complex geodynamic setting of an oceanic triple point bounded by the Azores-Gibraltar transfer zone to the South and the Atlantic ridge to the West. Henceforth, the rift evolution of the margin was controlled by the E-W to NW-SE continental extension, which resulted in an elaborate interplay of N-S to NNE-SSW normal and listric faults, and basin-bounding transfer zones, confirming the oblique nature of continental extension in some areas of southwest Iberia. Throughout the margin, rifting resulted in the formation of three distinct structural sectors that record the progressive westwards rift locus migration, controlled by the coeval main phases of rifting.

The analysis of the discrete tectonic architectures throughout the margin shows that rift geometry is controlled by continental extension, which thinned the lithosphere over a deep detachment at Moho level.

As a result, eight meaningful Meso-Cenozoic Megasequences with tectono-stratigraphic and lithostratigraphic affinities can be identified, each defining second-order sequence stratigraphic cycles (Fig. 8.16). Megasequences 1, 2 and 3 combined, comprise the first-order episode related with continental rifting of the margin that extended from the Carnian to the Tithonian-Berriasian, when ultimately sea-floor spreading was attained West of the Tagus Abyssal Plain. The second episode, thus refers to the post-rift evolution of the margin (Valanginian to Maastrichtian), which can itself be subdivided into Megasequences 4 and 5, representing the quiescent dirft evolution of the margin. A third and final episode groups Megasequences 6, 7 and 8, which comprises the subsequent inversion of the margin, spanning from the latest Cretaceous to the present.

8.4.1. From the onset of continental extension to breakup

8.4.1.1. Syn-Rift Phase I

Onset of continental crust segmentation (Rift Phase I) initiated in the Late Triassic, associated with the fragmentation of Pangea, within a generalized wide rift mode extension throughout the West Tethys and the Central and North Atlantic. By this time the Iberian micro-plate was migrating to the northwest away from northern Africa, associated the combined tensors of E-W North Atlantic rifting and with oblique rifting that was occurring on the westernmost termination of the Tethys.

The interplay between rift extension and plate migration resulted in the formation of several distinct sub-basins, which accommodated unconformable Carnian to Norian widespread continental siliciclastic red beds over the folded Palaeozoic metasediments (sequence 1a), later overlain by shales and evaporites of Norian-Hettangian age (sequence 1b) (Fig. 8.16). Deposits from this period extend unevenly throughout the margin, denoting a period of limited but enduring tectonic subsidence, similar to other regions in northern Africa and the North Atlantic (e.g. Balkwill and Legall, 1989; Hiscott et al., 1990; Enachescu, 1992; Carr, 2003).

Such observations are corroborated by the new burial history models generated for representative areas across the margin, which demonstrate the first episodes of tectonic subsidence on the discrete sectors of the margin.

The interaction of the dominant stress fields controlling lithospheric extension during rifting onset, likely resulted in the reworking at early stages of the ancient Messejana-Plasencia Fault Zone and the Nazaré Fault Zone, as first-order transcurrent features with significant impact in controlling forthcoming deposition, margin segmentation and intra-plate deformation.

8.4.1.2. Syn-Rift Phase II

A new phase of extension (Rift Phase II, Hettangian-Callovian) reveals the substantial Central Atlantic controls on the evolution of the SW Iberian margin, not only by a renewed phase of tectonic subsidence that has a rift climax by the Sinemurian-Pliensbachian, but is also associated with the occurrence of latest Triassic to earliest Jurassic magmatic activity of the Central Atlantic Magmatic Province (CAMP), and the inception of indisputable marine deposition (Fig. 8.16). During this period striking similarities can be found on all neighbouring continental margins, along which widespread carbonate ramps were formed on the proximal margin, whereas on the distal margin deep marine shales and siliciclastics are typical to occur (e.g. Balkwill and Legall, 1989; Welsink et al., 1989; Magoon et al., 2005) (Fig. 8.16).

Seismic-stratigraphic units and burial history models reveal that during this phase tectonic subsidence was most significant on the outer proximal and distal margin, which allowed the formation of thick growth strata during the Sinemurian-Pliensbachian Rift Climax (sequence 2a) (Figs. 8.3 and 8.11). During the Toarcian-Aalenian deposition was disrupted in the proximal margin resulting in the formation of a durable hiatus. This event is interpreted to represent the isostatic rebound coeval and synchronous with lithosphere breakup occurring at the northern Morocco-Nova Scotia conjugate margin, from where similar tectono-stratigraphic evolution is recorded (e.g. Sable Basin, Nova Scotia and Essaouira Basin, offshore NW Morocco).

This rift phase is also characterised by the continued evolution of the MPFZ as a fully-developed dextral releasing bend, controlling the northern boundary of the Sagres Plateau, which is demonstrated as an important hinge zone separating the South and south-western margins of Iberia, with impact both on episodic isolation of newly formed Boreal and Tethysian oceanic domains and in accommodating part of the isostatic rebound.

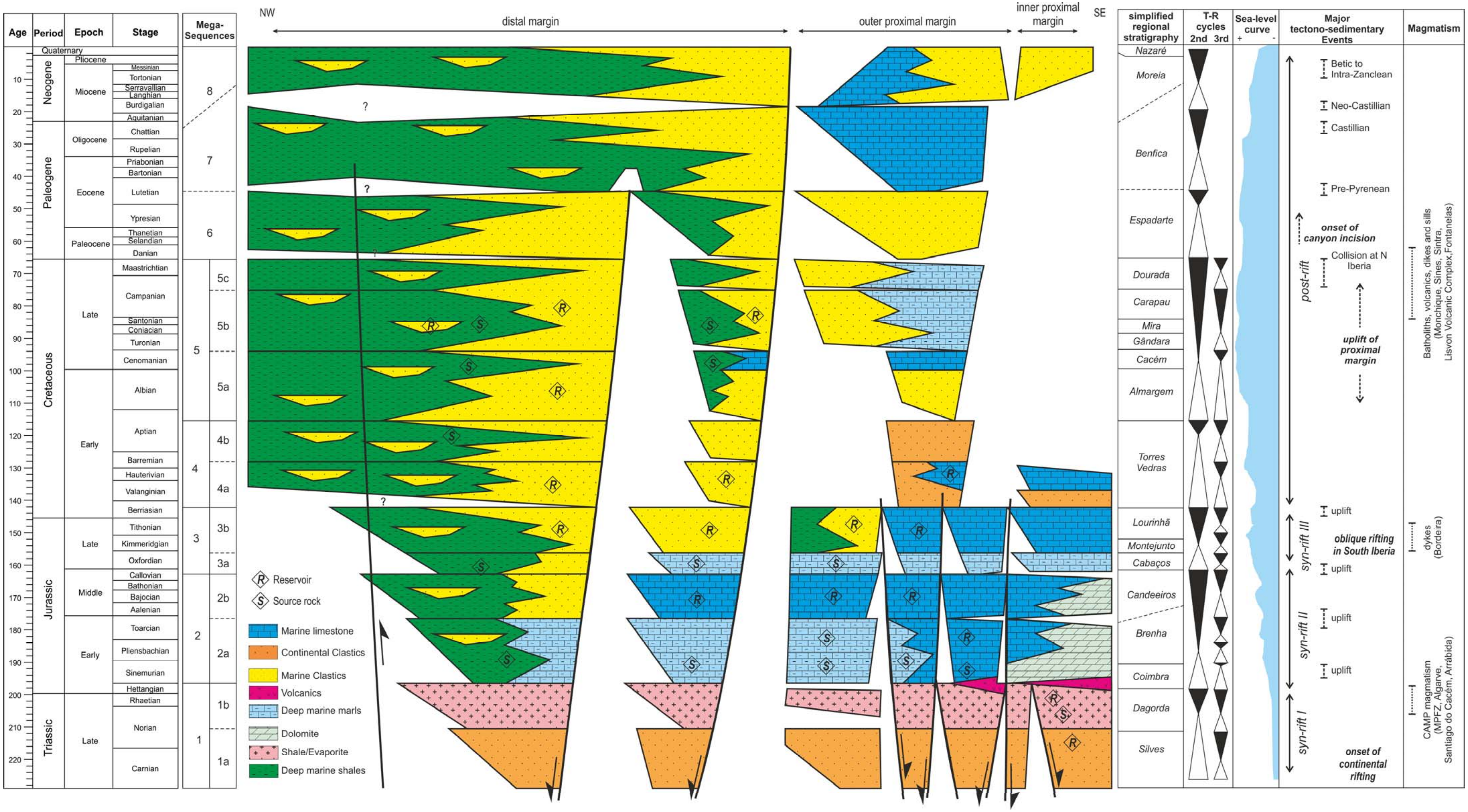

Figure 8.17 – Schematic Wheeler diagram constructed based on the interpretation of line in figure 5.8, showing the predominant interpreted lithologies, major tectono-stratigraphic and magmatic events. Speculative petroleum system elements, source rock and reservoir based on well and dredge data. Transgressive-regressive events based on the regional events from the West Iberian margin (Duarte, 2007; Reis and Pimentel, 2010) in relation with the sea-level eustatic curves from Hardenbol et al. (1998) in TSCreator 4.2.5.

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Deposition resumed on the proximal margin by the Bajocian (sequence 2b), with the accumulation of a widespread prograding carbonate ramp revealing a Late Rift pulse with limited tectonic subsidence and the increased control of eustasy in sedimentation. Locally rimmed carbonate build-ups can be identified, revealing cyclic variations of the base level. Ultimately, the progressive infill of the margin is marked by a widespread unconformity of Callovian-Oxfordian age.

8.4.1.3. Syn-Rift Phase III

The last phase of continental extension recorded in the SW Iberian margin (Syn-Rift III), occurs from the late Callovian to the earliest Cretaceous (Berriasian?). This phase is broadly synchronous to the extension occurring in northwest Iberia, Newfoundland or the North Sea and the formation of oceanic crust in the oblique rifting in south Iberia. It is mainly expressed on the outer proximal and distal margin by the formation of thick growth strata (Megasequence 3), thus recording the transition to seafloor spreading occurring West of the Tagus Abyssal Plain. The RIST are identified since the latest Callovian, progressively recording the final phase of continental extension with its paroxysmal maxima (the Oxfordian-Early Kimmeridgian the Rift Climax) that resulted in the formation of a Maximum Flooding Surface. From the Kimmeridgian to the Tithonian (Berriasian?) reduced subsidence throughout the margin records a LRST, marked at the top by a widespread unconformity interpreted to depict the end of continental extension. In contrast, rift subsidence continues in the northern distal basins of the West Iberian margin (Peniche, Porto and Galicia) until the Aptian-Albian, when ultimately, lithospheric breakup is attained in full on the Iberia-Newfoundland conjugate margins. This phase also marks the combined influence of oblique rifting between the westernmost Tethys and the southernmost North Atlantic during the relative westwards clockwise migration of Iberia in relation with North Africa.

8.4.2. Post-Rift quiescence and inversion

The post-Rift evolution of the Southwest Iberian margin (Berriasian-Aptian) is characterized by generalized progradation of siliciclastics towards the distal margin (Megasequence 4), which is interpreted as the result of relative tectonic quiescence and limited uplift subsequent to latest Jurassic seafloor spreading in SW Iberia and prior to continental breakup occurring in the Iberia Abyssal Plain by the end of this period.

As the conjugate margins of Iberia and Newfoundland digress from each other during the Albian to Maastrichtian(?) interval, the margin records the progressive accumulation of deltaic to deep-marine siliciclastics and limestones (Megasequence 5), independent from the controls of neighbouring basins, but dominantly affected by eustasy. On the Southwest Iberian margin, this is a period of significant sediment by-pass controlled by the continued uplift of the proximal areas and the inception of primordial canyon systems crosscutting the margin.

The latest Cretaceous uplift and tilting of the margin is likely associated with the combined effects of: 1) punctuated magmatism, 2) the initiation of the counter-clockwise rotation of Iberia, and 3) in an un-quantified manner, by the post-rift creation of widespread areas of elevated passive continental margins. However, it is by the Palaeogene that the first evidence of inversion and shortening are recorded, which is characterized by widespread and intense erosion on the proximal margin and voluminous bypass of sediment towards the distal margin, coupled with the left-lateral reworking of the MPFZ as a major strike-slip, accommodating significant deformation and controlling canyon incision on across the margin.

From this period onwards, eastwards migration of the Iberian plate and its collision with Eurasia and North Africa, results in generalized deformation and shortening, which affects dissimilarly and diachronically the distinct sectors of the margin and largely affects the Cenozoic deposition on the continental margin. Shortening of the margin is not only controlled by the reactivation of a deep continental crust detachment, but also by the distinct rheological behaviour of inherited growth strata and the fragmented continental crust, that resulted in the reactivation of rift-related faults, revealing localized thin-skin and thick-skinned tectonics.

Cenozoic deposition thus comprises three discrete Megasequences (6, 7 and 8) bounded by two main unconformities denoting the major pulses of shortening throughout the margin, namely during the middle Eocene and the Oligo-Miocene. Deposition in these intervals is characterized not only by the extensive accumulation of deep-water contourites or turbidites off the continental shelf, but also by the noticeable incision of the São Vicente Canyon, largely dependent of the activity of the recent MPFZ as a major restraining bend.

8.4.3. Final remarks

The integrated analysis of a varied and extensive dataset allowed the comprehensive characterisation of the complex rift-to-drift evolution and subsequent inversion of the Southwest Iberian margin.

Evidence from the tectono-stratigraphic framework together with the variable geometry of the highly thinned continental crust show that Southwest Iberia evolved as an asymmetric magma-poor rifted margin, bounded by first-order transfer zones. The margin is also characterised by the occurrence of deep crustal reflections, suggesting the existence of a detachment at Moho level that controlled thinning of the continental crust through depth-dependent stretching. The presented results concomitantly allowed the improved understanding of the position of the Ocean-Continent Transition offshore Southwest Iberia by identifying the discrete zones that record the progressive rift locus migration. A similar approach was applied on the northwest Moroccan continental margin, where similar zonation and conclusions were described. This work suggests that the South Newfoundland Canadian margin should be reassessed in the light of the new findings reported for Southwest Iberia. A comprehensive understanding of the evolution of the Canadian area would allow refining some of the aspects that still require clarification in this work (see sections 8.5 and 8.6).

The margin, segmented during three major rift phases shows the occurrence of associated structural sectors, each with discrete architecture and their associated tectonic systems tracts. These sectors were later reworked during inversion and incipient continent convergence in a process likely associated with the mega-thrusting of the continental crust indentor, which explains the discrete convergence architecture of the syn- to post-rift sequences. This approach additionally allowed demonstrating one of the few known examples where incipient ocean-continent convergence and onset of subduction might be occurring.

The comprehensive description of the rift architecture of the continental crust throughout the margin and their related growth strata, the post-rift shortening patterns coupled with a meaningful construction of a tectono-stratigraphic framework allowed to postulate that the southwest Iberian margin is an example of an upper-plate margin. The application of this postulate to the this domain of the West Iberian margin allows explaining: 1) the asymmetric geometry in relation with the conjugate south Newfoundland margin and the contrasting geometry with NW Iberia, 2) the preferred location of igneous rocks on the south-western segment of the margin, which can be explained by underplating and episodic magma ascension through a thick continental crust; 3) the position of the Ocean-Continent Transition zone in the Tagus Abyssal Plain, 4) the discrete patterns of prolonged post-rift shortening over a deep continental crust thrusting, and 5) the role of first-order transfer zones and their related crustal hinges, in the segmentation of specific domains of Central-North Atlantic.

The novel results and reasoning additionally reveal that the analysis undertaken for the SW Iberian margin can be applied to other continental rifted margins, either magmatic or magma-poor, as the vast majority of the processes reported in this work can be individually decoupled for such settings, independent of the magmatic context. This is especially true for the detailed zonation of the margin, by recognising how many rift phased controlled continental extension, the areal extent of such sectors and its implications for identifying the transition to unquestionable oceanic crust. This, along with the construction of sequence stratigraphy framework for rifted margins will allow clarifying the timing of lithosphere breakup in areas with limited well control, such as current exploration deep-water continental frontier areas.

The sequence stratigraphy approach revised herein specifically for continental rifted margins is revealed as a prospective powerful tool to analyse extensional settings, as for the first time presents a combined view of classic works. It is demonstrated for the Southwest Iberian margin that such approach can be successfully applied to estimate, the facies, events and hierarchy of the principal sequences and their related unconformities.

The notion presented in chapter 7, that first-order transfer zones act like dominant zones of margin transcurrent deformation is demonstrated to represent a critical area to understand the palaeogeographic evolution of the southernmost North Atlantic and how intra-plate deformation was accommodated during the rift-to-drift transition of this and other continental margins.

8.5. Implications for the hydrocarbon potential of SW Iberia

The widespread offshore area of the southwest Iberian margin is one of the least explored hydrocarbon provinces of the North Atlantic and its true potential remains undiscovered, contrasting with known commercial discoveries in neighbouring margins (e.g. northern Morocco, Newfoundland and Nova Scotia or the Irish Sea).

Although a significant quantity of seismic data has been acquired throughout the margin mainly in the 70's, 80's and in recent years, only two exploration wells targeted possible reservoirs in the northern area of the Alentejo Basin. These wells, along with dredge data proved the existence of an effective petroleum system, revealing oil and gas shows in the Late Triassic, the Early and Late Jurassic and in the Early Cretaceous. However, these same wells drilled in the 70's were proven to be non-commercial and since this exploration effort, no further drilling tested the remaining potential of the margin.

This section does not aim to serve as an exploration guide, but more importantly, relates the new findings resulting from the present research with a revised insight to future hydrocarbon exploration in this province.

The analysis of seismic-stratigraphic units has revealed that during continental rifting three main phases of rifting segmented the margin into discrete sectors and related sub-basins, each with individual subsidence and burial history patterns. This segmentation bears major implications for the creation of new accommodation space and the accumulation of thick depositional sequences that may constitute both source rocks and reservoirs.

The three phases of continental extension, each with well-defined pulses of tectonic subsidence relate with the different tectonic systems tracts formed within basins.

Source-prone rocks are likely to be accumulated during the retrograding cycles of the Rift Initiation Systems Tract, but more significantly during the Rift Climax Systems Tract which typically, in marine basins usually accumulate organic rich shales and fine sediments overlain by coarse deposits, which are likely to constitute good-quality reservoirs. Examples of possible source rocks can be found during the mild to intense extension periods of the Early Jurassic (sequence 2a) and the Late Jurassic (sequence 3a). Possible source rocks from the Early Jurassic include the marly deposits of the southern Alentejo Basin similar to those found in Bordeira. Late Jurassic organic-rich sequences include the Deixa-o-Resto marls. However, the source potential of the margin may differ significantly as it is demonstrated that the preferred areas of subsidence are located in the outer proximal and distal margin. The contrasting burial history models for this interval suggest that the inner proximal margin did not attain sufficient subsidence to generate relevant volumes for expulsion. Exploration wells drilled in this sector revealed limited indications of hydrocarbons, thus suggesting limited source rock efficiency.

Deposits likely to develop good reservoir quality can be dominantly associated with the Late Rift Systems Tract, in result of increased sediment supply into newly formed depocentres and their flanks. However, the asymmetric nature of the tilted blocks results in rapid lateral facies change and in some cases, the complete uplift and exposure of the footwall above the fulcrum and therefore limiting or hampering deposition. During the Rift Initiation Systems Tract and the Rift Climax Systems Tract, reservoir rocks are likely to accumulate, mainly associated with intermediate pulses of subsidence and related sediment influx in to the troughs. The nature of the sediment and therefore, the quality of the reservoir within these sub-basins varies significantly and depends on the proximity to the continental areas, climatic controls and the re-organisation of the drainage systems to the new geometry of the margin during continental extension. In the Alentejo Basin, evidence of probable reservoirs can be found on Rift Initiation deposits of the earliest Jurassic (the dolomites from sequence 2a in well Go-1, equivalent to the high-porosity dolomitic unit of the Fateota-Santa Cruz formation in Santiago do Cacém) (Fig. 6.5D), and in the Late Jurassic dredges in the outer proximal margin that samples oil stained limestones.

Despite the scarce direct evidence of good-quality reservoirs, these are expected to occur in different setting of the margin and during distinct intervals (Fig. 8.17). These include the Rift Climax to Late Rift sequences of the Middle Jurassic carbonate platform and the siliciclastics of the Late Jurassic, which are interpreted to exist on the outer proximal and distal margin, formed in result of the progressive infill of the margin during the transition to seafloor spreading.

Additional source rocks and reservoirs are likely to be found on the post-rift Cretaceous depositional sequences that were identified mainly on the outer proximal and distal margin. The widespread uplift of the hinterland and associated sediment by-pass towards the deeper domains of the margin during this period may have prevented the adequate conditions for these petroleum system elements to occur. Conversely, towards the West, the existence of thick Late Cretaceous deposits associated with a relative eustatic high, may have created the conditions for source rock accumulation. Examples of equivalent Late Cretaceous organic-rich sequences are described in the deep-sea drilling wells in off the Galicia margin, namely in DSDP 47-398 (Deroo et al., 1979), and on proven petroleum provinces from equatorial Atlantic. Consequently, the Late Cretaceous (Megasequence 5) siliciclastics and carbonates may comprise good quality reservoirs, possibly sourced from the latter units or ultimately, the deep marine turbidites and contourites from the Oligo-Miocene.

A summary of the main intervals contributing to a petroleum system are depicted in figure 8.16, by identifying possible source rock and reservoir depositional units.

8.6. Limitations of this research

The present work is the result of the integrated analysis of multiple datasets, from which a dense grid of 2D migrated multichannel seismic data comprised the vast majority of information that allowed the comprehensive tectono-stratigraphic interpretation of the study area. These data, together with existing information and new results derived from exploration boreholes, outcrop and dredges resulted in the construction of an insightful geodynamic and depositional framework that explains previously unclear aspects of the evolution of the southwest Iberian margin. However, if the seismic grid was revealed sufficient for a detailed interpretation of the Meso-Cenozoic strata on the margin, a group of relevant aspects prevented a more detailed investigation of the study area.

The main limitation to the research has its foundation on the availability of well data that allows tying seismic data with control points on distinct sector of the margin. The only wells existing in the Alentejo Basin are located to the northern area thus leaving a vast area of the margin without any direct information that allows reducing the uncertainty of interpretation away from well control. Moreover, these wells show significant depositional hiatus, which significantly hinder the interpretations of coeval strata on other sectors of the margin.

A second factor limiting a more insightful analysis of the area pertains to the insufficient lithostratigraphic and chronostratigraphic control of the principal depositional units and their related unconformities at outcrops. Although these outcrops are of significant exposure quality, the scarce work detailing the stratigraphy, palaeontology and structural geology have hampered a significant part of the interpretations presented in this thesis. The absence of detailed data has profound implications for accurate dating of the main tectono-stratigraphic events, which ultimately may result in inexact conclusions in some structurally complex areas. Dredge data in this situation was revealed of uttermost importance to calibrate key areas of the margin absent of well data. However, the validity of some information was questionable as it was revealed to be vague or in some cases, inaccurate. Moreover, a significant extent of the study area was not sampled or most of the times collected recent sediments that were shown to bear limited application for the investigation of older strata, such as the case of the Mesozoic successions that comprised the predominant scope of this thesis. The creation of burial history models that explain subsidence patterns on the margin suffered largely from the limited stratigraphic controls.

Some of the postulates presented herein, although grounded on both direct and indirect evidence lack some geological constraints. This is the case of the upper-plate margin model proposed in the discussion chapter that acknowledges the limitations on detailed petrological analysis regarding the nature and processes responsible for the ascent of magma during the distinct phases of the rift-to-drift evolution of the southwest Iberian margin. More significantly, the underplating model invoked in previous studies on the margin and reinforced in this study, is still far from full clarification.

Contrasting with the northwest Iberian margin that has been a preferred area for the study of magma-poor rifted margins through intense deep-sea drilling programs, Southwest Iberia (herein revealed as a major province that could contribute to the explanation of the processes and architecture of similar geodynamic settings), remains a poorly investigated segment of the North Atlantic. In the study area, only DSDP site 120, Leg 13 in the Gorringe Bank was carried out to investigate the nature of the continental and oceanic crust and subsequently to elucidate on the age and processed controlling sea-floor spreading in this area. Additionally, magnetic anomalies in the Tagus Abyssal Plain that could explain continental breakup also remain a matter of debate. The broad geodynamic model present in this work therefore could largely benefit from additional information in this subject.

8.7. Further work

Despite the answers resulting from this work, a variety of other puzzling aspects remains unclear or is referred here for the first time, which therefore opens the path for subsequent studies towards the insightful understanding of the southwest Iberian margin, the transitional segment of the Central-North Atlantic and other rifted passive margins.

A key subject that can bring clarification to the understanding of the evolution of the margin relates with a more detailed lithostratigraphic, chronostratigraphic and paleontological controls that allow dating the main subsidence events resulting from continental extension. To achieve this, exhaustive fieldwork should be carried out on well exposed outcrops existing in the mainland. Results from such task would have major impact on: 1) dating the exact age of the main regional depositional units and their related widespread unconformities, thus allowing to better constrain the subsidence periods on the margin, as well as their variable magnitude, 2) the understanding of facies variations throughout the margin and within distinct sub-basins, 3) the assessment of the potential for the existence of a commercial hydrocarbon province and, 4) the precise kinematic controls of strike-slip Mesozoic deformation along the onshore segment of the Messejana-Plasencia Fault Zone.

Further investigation is required in what concerns the exact position and nature of the Ocean-Continent Transition on the southwest Iberian margin and the Tagus Abyssal Plain. Future deep-sea drilling campaigns should be planned to target the continental crust in distinct areas of the margin that would ultimately contribute to: 1) the tectono-stratigraphic control on the main rift phases segmenting the continental crust, 2) dating of unclear magnetic anomalies existing on the Tagus Abyssal Plain that could clarify the exact age of continental breakup in the area, 3) clarifying the extension of the continental crust and their related Mesozoic sediments, which would have impact on the prospectivity of hydrocarbons, and 4) insightful models of palaeogeographic reconstructions that explain the evolution of the Eurasia-Africa complex triple-junction, which should account for multi-tensors and intra-plate stress accommodation.

Another aspect that needs additional investigation pertains the generation of solid burial history models that can fully explain the distinct subsidence patterns anticipated in this work. Future exploration or scientific drilling on the margin, independent on the location of the borehole, would clarify some of the uncertainties already mentioned above, namely the stratigraphic controls that allow dating the main unconformities. Such approach would have impact on clarifying the age of the main events of rifting and shortening throughout the margin and consequently on basin modelling for delineating prospective areas for hydrocarbon exploration.

Future work is suggested also on the analysis of post-rift inversion, not only on the broad architecture of the margin by enhancing the conclusions presented in this thesis with implications on the understanding of the mechanisms controlling convergence with the oceanic domain and its potential to generate destructive earthquakes and tsunamis. Such subject would also benefit from in-depth investigation of the MPFZ as a major transfer zone associated with seismogenic potential.

This thesis also evidenced the potential of the syn-rift sequence stratigraphy analysis through the compilation and tentative update of the principal concepts and methodologies that can be applied to extensional settings. However, the terminology and widespread application of such fundaments is far from straightforward. Considering the local application of this approach additional validation of the method must be proven in other extensional settings worldwide.

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Chapter 9

Conclusions

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9. Conclusions

The integrated tectono-stratigraphic and broader geodynamic analysis of the Southwest Iberian margin (also referred as Alentejo Basin), records the complete evolution since the onset of lithospheric extension to seafloor spreading, the transition to a passive drifting margin and ultimately, its subsequent tectonic inversion. This segment of the West Iberian margin is revealed to record the complex rift-to-drift evolution of an oceanic triple junction that bounds the Central and North Atlantic and the westernmost Tethys Ocean.

The use of a dense grid of high quality multichannel 2D seismic data, together with outcrop, well and dredge information demonstrates that the architecture of the rifted continental crust is segmented into three discrete N-S structural sectors, each comprising distinct superimposed growth strata, denoting the multiphased nature of extension of the southernmost Iberia-Newfoundland conjugate margin.

The three structural sectors, *i.e.* the inner proximal margin, the outer proximal margin and the distal margin, show individual tilt-block rotation and growth strata bounded by major unconformities that can be correlated throughout West Iberia, Newfoundland and Nova Scotia, the North Sea and North Africa.

The proximal to distal margin of the Alentejo Basin is dissimilar with its well-studied counterparts from the Galicia margin, since it is characterised by a nearly continuous hyper-extension of the continental crust, where outer highs or detached segments of the crust overlaying the transitional crust are not observed. This suggests a distinct architecture than the latter area, with implications on the detailed model of lithospheric thinning.

The distinctive tectono-stratigraphic characteristics of each segment of the margin allows to conclude that rift-related subsidence was persistent since the Late Triassic to the latest Jurassic (or earliest Cretaceous), and that it can be subdivided into three major Rift Phases, with their correlative Megasequences (1, 2 and 3), which respectively include: 1) the Norian-Hettangian Rift Phase I that records the generalised opening of the Pangea super-continent on a wide rift mode; 2) the Sinemurian-Callovian (Rift Phase II), which is associated with the continental extension and transition to seafloor spreading in northwest Africa; and 3) the Oxfordian-Tithonian (Berriasian?), that records the opening of the North Atlantic on the Iberia-Newfoundland conjugate margins, prior to the last rifting phase that occurred on the northern segment of the conjugate (Galicia, North Newfoundland and the Iberia Abyssal Plain), by the Aptian-Albian.

The analysis of burial history models on different sectors of the margin, supporting the results from the tectono-stratigraphic analysis strikingly show that during each Rift Phase, prominent pulses of subsidence had different expression. This reveals that continental extension thinned the crust into preferred areas of tectonic subsidence, with the higher values located oceanwards on the outer proximal and distal margin, thus denoting rift locus migration during continental extension. Transition to seafloor spreading ultimately occurred, with the final evidence of tectonic subsidence during the Tithonian-Berriasian on the outer proximal and distal margin.

Subsequent to the formation of oceanic crust that occurred on West of the Tagus Abyssal Plain, the margin evolved as a passive margin from the Early Cretaceous to the latest Cretaceous (or Paleogene). During this episode, two post-rift Megasequences (4 and 5) show the progressive infill of the margin with sediments driven from the mainland in the East. Noticeable sediment by-pass towards the outer proximal and distal margin occurred, reflecting the progressive tilting of the margin.

From the Late Cretaceous onwards, widespread uplift and shortening of the margin was accommodated differently through the proximal and distal margin, revealing that deformation styles and geodynamic controls depend on: 1) the inherited fabric of the continental crust and overlying strata; (2) the rheological behaviour of both continental crust and syn- to post-rift megasequences; and (3) the variable directions of shortening recorded during convergence between Iberia, North Africa and Eurasia. The distal margin records the vast majority of shortening, through the formation of both thin and thick-skin tectonics, coinciding with the location of the ultra-thinned continental crust.

The thinned continental crust on the outer proximal and distal margin is underlain by a deep continental crust detachment that controlled both the depth-dependent extension during rifting and was ultimately reworked as a mega-thrust during Cenozoic inversion and recent ocean-continent convergence.

The analysis of the post-rift Megasequences accumulated during the last depositional episode on the margin (Megasequences 6, 7 and 8), show that uplift, shortening and inversion to have occurred since the Late Cretaceous. Moreover, the recognition that shortening and overall deformation initiated early during post-rift, from which two main tectonic pulses in the Eocene-Oligocene and the Miocene, separated by intermediate but persistent minor events of margin convergence, is longer than anticipated. Prolonged uplift and shortening of the margin is the combined result of: 1) Late Cretaceous magma emplacement at sub-crustal levels and associated volcanism; and 2) margin westwards tilting resulting from elastic rebound subsequent to rifting; 3) collision of Iberia with the Pyrenees during the Late Cretaceous and counter-clockwise rotation and collision with North Africa during the Miocene to the present day.

The integrated analysis of the distinct sectors of the margin, both during rift extension and post-rift inversion allowed estimating the position of the Ocean-Continent Transition zone. Results show that the OCT is positioned along the distal margin, in a distance of 80–100 km of the present-day shoreline, with the westernmost limit coinciding with magnetic anomalies in the Tagus Abyssal Plain, thus reinforcing the notion that seafloor spreading, West of the Alentejo Basin, initiated by the Tithonian-Berriasian.

Results showed that during the multiple syn-rift phases the architecture of Megasequences shows similar depositional trends that can be recognised and grouped into meaningful Tectonic Systems Tracts, each with distinct pulses of subsidence, namelly: 1) the Rift Initiation Systems Tract, comprising the early stages of limited tectonic subsidence and tilt-block formation; 2) the Rift Climax Systems Tract, denoting the event of paroxysmal subsidence and base level rise, with the formation of a Maximum Flooding Surface; and 3) the Late Rift Systems Tract, which marks the final pulses of subsidence, prior to a new Rift Phase or the complete cessation of continental extension preceding seafloor spreading.

The use of Tectonic Systems Tracts, as presented in this work, allowed building a comprehensive tectono-stratigraphic framework, which describes not only the evolution of the Southwest Iberian margin, but can be also applied to other rifted margins such as Newfoundland, the North Sea and the South Atlantic. Furthermore, this sequence stratigraphic framework allows estimating, away from well control, the chief depositional controls in deep-water continental margins.

The Rift Initiation Systems Tract (RIST) was identified in all rift-related Megasequences namely, during the Carnian-Norian, the Hettangian-Sinemurian and the late Callovian-Oxfordian and marks the onset of tectonic subsidence within a rift pulse, which is characterized by overall aggradation/retrogradation overlying a basal regional unconformity. The Rift Climax Systems Tract is characterized by alternate retrograding/prograding trends, from which the transition to progradation coincides with a Maximum Flooding Surface, as in the case of the Sinemurian-Pliensbachian and the Oxfordian-Kimmeridgian. The Late Rift Systems Tract (LRST), progressively infilling the margin, is commonly characterized by aggradation and/or progradation, recording also the variations in eustasy. Late Rift pulses are recognized during the Rhaetian-Hettangian, the Toarcian-Callovian and the Kimmeridgian-Berriasian.

Results additionally allow concluding that the Southwest Iberian margin, dissimilarly to the evidence from Northwest Iberia, experienced marked syn-rift subsidence and subsequent significant uplift during the Toarcian-Aalenian with the formation of a regional unconformity, coeval with the transition to seafloor spreading in the Morocco-Nova Scotia conjugate margins. Thick Early Jurassic growth strata and this widespread hiatus, confirms the southernmost segment of the North Atlantic as a province that evolved in strong dependence with the Central Atlantic and the West Tethys.

The Southwest Iberian margin records a complex and long-lived influence of transcurrent deformation since the Paleozoic, from which, inherited first-order transfer zones accommodate extension not only during rifting, but also during post-rift inversion. This is the case of the Messejana-Plasencia Fault Zone (MPFZ) that during Atlantic rifting acted as a dextral releasing bend, and was later reworked as a sinistral strike-slip. The MPFZ, together with the Nazaré Fault Zone comprise two major tectonic boundaries and their relative hinge zones (the Sagres Plateaus and the Estremadura Spur), delimiting the southern and northern segments of West Iberia. The recognition of alternating strike-slip movements is similar with other major transfer zones in dependence of the Azores-Gibraltar Transfer Zone (*e.g.,* the Minas Fault zone in Nova Scotia), which allows to conclude that intra-plate stress accommodation within these transcurrent zones bear major implications for future elastic paleogeographic reconstructions of the Central-North Atlantic triple junction.

During the latest Cretaceous, but more significantly from the Palaeocene onwards, the MPFZ additionally controls channel deposition and canyon incision. It is also interpreted as a dominant location for sediment by-pass across the margin, with large volumes of sediment being transferred from the hinterland to the more distal domains of the margin, during most of these periods. The MPFZ is also considered a zone of significant risk for generating destructive earthquakes and tsunamis.

The overall integration of results into the broader geodynamic model of asymmetric magma-poor rifted margins suggests that the thinned continental crust of Southwest Iberia represents an Upper-Plate margin. This interpretation explains not only the contrasting architecture of the Alentejo Basin and the geometric dissimilarities with the conjugate margin of South Newfoundland, but also the preferred areas of crustal shortening during inversion and the polarity shift to a Lower Plate margin in Northwest Iberia through first-order transfer zones. Moreover, the Upper-Plate postulate expounds the persistent magmatic activity that is interpreted to result from a possible deep crustal underplated magma source that episodically fed the multiple events of magmatism occurring almost exclusively on the Southwest Iberian margin.

The integrated analysis presented in this work bears implications to the insights of speculative petroleum systems known occur on the margin and ultimately demonstrates Alentejo Basin as an highly prospective area.

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Annexes

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Table A - Input parameters for the burial history model of borehole Monte Paio.

Monte Paio	**Top (m)**	**Base (m)**	**Thickness (m)**	**Eroded Thickness (m)**	**deposition**		**erosion**	
					from (M.a)	**To (M.a)**	**from (M.a)**	**To (m.a)**
Pliocene-Pleistocene	0	31	31		5	0		
Miocene	31	90	59		23	5		
Cretaceous	90	90	0	100	145	23	65	23
Kimm.	90	385	295		155	145		
Oxfordian	385	680	295		158	155		
J2	680	860	180		172	158		
J1	860	905	45	100	198	172	185	172
T-J1	905	1133	228		220	198		

Age (M.a)	**PWD (m)**
0	0
145	0
158	100
172	0
185	100
200	0

Table B - Input parameters for the burial history model of borehole Go-1.

Go-1	**Top (m)**	**Base (m)**	**Thickness (m)**	**Eroded Thickness (m)**	**deposition**		**erosion**	
					from (M.a)	**To (M.a)**	**from (M.a)**	**To (m.a)**
Miocene 2	134	582	448		15	0		
Miocene 1	582	662	80		23	15		
K2-Pg	662	662	0	200	119	65	65	23
Torres Vedras	662	1038	376		145	119		
J3	1038	1038	0	500	162	150	150	145
Candeeiros	1038	1173	135		170	162		
J2	1173	1173	55		175	170		
J1	1228	1228	0	100	185	180	180	175
Coimbra	1228	1335	107		198	185		
Dagorda	1335	1654	319		205	198		
Silves II	1654	1712	58		210	205		
Silves I	1712	1745	33		220	210		

Age (M.a.)	**PWD (m)**
0	134
145	0
175	0
183	50
200	0

Table C - Input parameter for the burial history model of borehole Pe-1.

Pe-1	**Top (m)**	**Base (m)**	**Thickness (m)**	**Eroded Thickness (m)**	**deposition**		**erosion**	
					from (M.a)	**To (M.a)**	**from (M.a)**	**To (m.a)**
Mio-Plio	149	567	418		23	0		
K2-C2	567	567	0	300	120	23	70	23
K1 ls	567	607	40		130	120		
K1 ss	607	921	314		144	130		
J3 (Tith.)	921	2182	1261	50	159	144	148	144
J2 (Bat.-Cal.l)	2182	2652	470		169	159		
J1 (Hett.-Toar.)	2652	2652	0	200	190	169	180	169
Coimbra	2652	2719	67		200	190		
Dagorda dolomites	2719	2820	101		202	200		
Dagorda salt	2820	2910	90		205	202		
Dagorda shales	2910	3080	170		210	205		
Silves	3080	3117	37		220	210		

Age (M.a.)	**PWD (m)**
0	149
144	100
202	20
220	10

Table D - Input parameters for the burial history model of borehole Be-1.

Be-1	Top (m)	Base (m)	Thickness (m)	Eroded Thickness (m)	deposition		erosion	
					from (M.a)	To (M.a)	from (M.a)	To (m.a)
8	1076	1523	447		25	0		
7	1523	1979	456		30	25		
6	1979	1979	0	200	65	45	45	30
5	1979	2665	686	1000	116	70	70	65
4	2665	3377	712		145	116		
3	3377	4403	1026		162	145		
2	4403	5746	1343		197	162		
1b	5746	6271	525		210	197		
1a	6271	7768	1497		230	210		

Age (M.a)	PWD (m)
0	1076
30	0
65	0
145	300
200	0

Table E - Input parameters for the burial history model of borehole Po-1.

Po-1	**Top (m)**	**Base (m)**	**Thickness (m)**	**Eroded Thickness (m)**	**deposition**		**erosion**	
					from (M.a)	**To (M.a)**	**from (M.a)**	**To (m.a)**
8	3420	4104	684		25	0		
7	4104	4972	868		45	25		
6	4972	5772	800		65	45		
5	5772	6039	267		116	65		
4	6039	6540	501		145	116		
3	6540	7226	686		162	145		
2	7226	8115	889		197	162		
1b	8115	8847	732		210	197		
1a	8847	10175	1328		230	210		

Age (M.a)	**PWD (m)**
0	3420
200	0

Table F - Input parameters for the burial history model of borehole 20B-1.

20B-1	**Top (m)**	**Base (m)**	**Thickness (m)**	**Eroded Thickness (m)**	**deposition**		**erosion**	
					from (M.a)	**To (M.a)**	**from (M.a)**	**To (m.a)**
Valanginian	113	181	68		145	134		
J3	181	181	0	500	161	150	150	145
J2	181	625	444		165	161		
Bathonian	625	793	168		168	165		
Bajocian	793	1375	582		172	168		
Aalenian	1375	1700	325		175	172		
J1	1700	1950	250		183	175		
Pliensb.	1950	2288	338		190	183		
Sinemurian	2288	2541	253		200	190		

Age (Ma.)	**PWD (m)**
0	113
150	0
172	200
200	0

Table G - Input parameters for the burial history model of borehole 17C-1.

17C-1	Top (m)	Base (m)	Thickness (m)	Eroded Thickness (m)	deposition		erosion	
					from (M.a)	To (M.a)	from (M.a)	To (m.a)
J3	138	475	337		161	153		
Bathonian	475	600	125		167	161		
Bajocian	600	765	165		172	167		
Aalenian	765	865	100		175	172		
Toarcian	865	965	100		183	175		
Pliensb.	965	1015	50		190	183		
Sinemurian	1015	1230	215		198	190		
Hettangian	1230	2138	908		210	198		
Triassic	2138	2308	170		220	210		

Age (M.a.)	PWD (m)
0	138
183	200
200	0