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

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[1] 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. Our 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 phase, characterized by incipient subsidence and overall aggradation/progradation over a basal unconformity, 2) the Rift Climax phase, which marks maxima of tectonic subsidence and is characterized by retrogradation-progradation, and 3) the Late Rift phase, 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 phase, 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 work 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 recognizes 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.

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1. Introduction

[2] 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].

[3] 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] (Figure 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.*, 2010; *Pereira and Alves*, 2011; *Pereira et al.*, 2011] (Figure 1). These latter findings, however, revealed significant uncertainties concerning the Mesozoic rift evolution of southwest Iberia. Some of these

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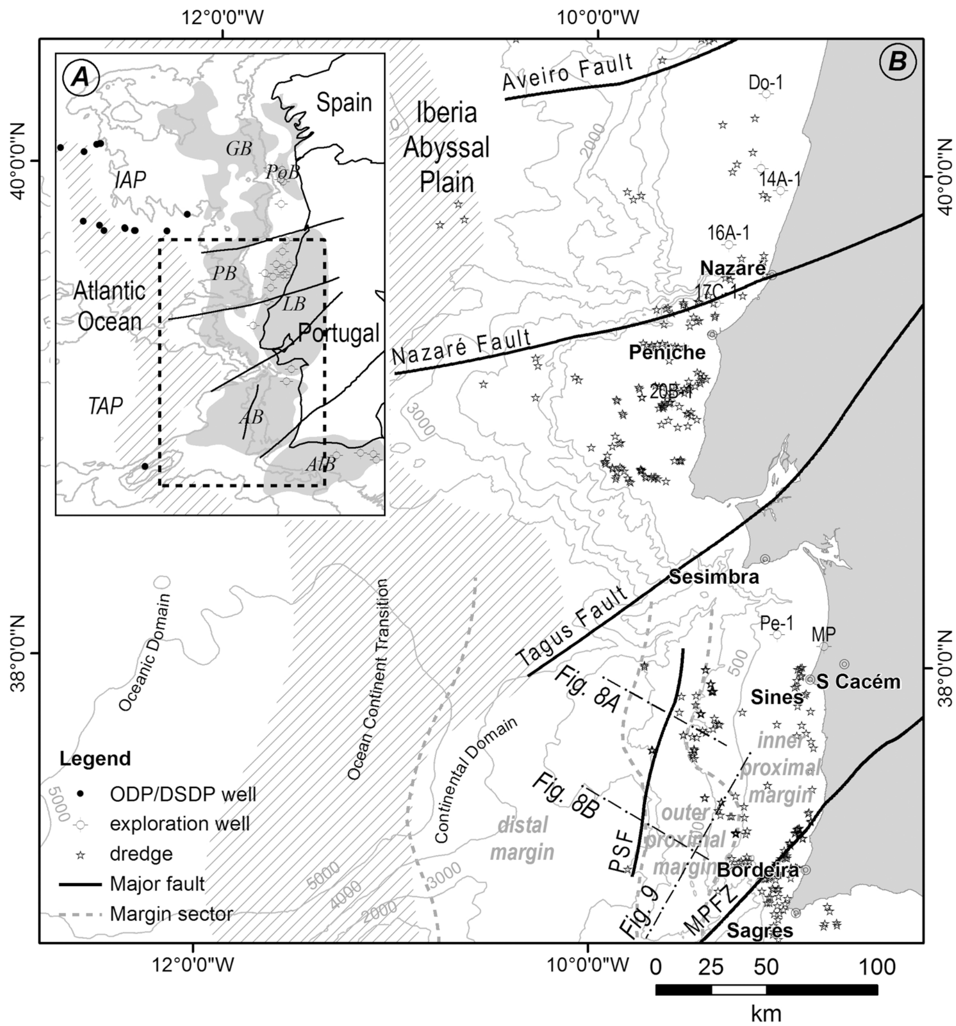

Figure 1. (a) Regional map with the location of the studied area and the main basins of the West Iberian margin and their relation with the main continental crust domains; GB – Galicia Basin, PoB – Porto Basin, PB – Peniche Basin, LB – Lusitanian Basin, AB – Alentejo Basin, AlB – Algarve Basin, IAP – 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].

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.

[4] This work 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 work to explain the complex rift-related evolution of divergent margins. The interpreted data are used to construct a solid sequence-stratigraphic 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.

[5] Our 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. We postulate that during discrete rifting episodes, a complete stratigraphic cycle comprises three distinct phases of subsidence, which are materialized by different tectonic systems tracts [e.g., *Prosser*, 1993] bounded by coeval regional unconformities. This character contrasts to

what is known from a) the distal margin of Northwest Iberia, where deep-sea drilling showed that only the final rift episode is recorded [*Wilson et al.*, 2001], and b) 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].

2. Data and Methods

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

[7] 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] (Figure 1).

[8] The zonation of the continental margin into proximal and distal sectors [e.g., *Manatschal and Bernoulli*, 1998, 1999; *Manatschal*, 2004; *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] (Figure 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] (Figure 1).

[9] On seismic data, the interpretation of unconformity bounded sequences uses the concepts of *Hubbard et al.* [1985] 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 recognized in West Iberia [*Witt*, 1977; *Manuppella*, 1983; *Oliveira*, 1984; *Ramalho and Ribeiro*, 1985; *Gabinete para a Pesquisa e Exploração de Petróleo* (*GPEP*), 1986; *Ribeiro et al.*, 1987; *Wilson*, 1988; *Inverno et al.*, 1993; *Azerêdo et al.*, 2003; *Rey et al.*, 2006] (Figure 2).

[10] 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, we apply 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 analyzed 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."

[11] 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 (Figure 3). Therefore, as with to eustasy controlled depositional systems, each of the tectonic systems tracts is used to "emphasize 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.

3. Geological Setting

3.1. Mesozoic Continental Rifting in West Iberia

[12] 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 [e.g., *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.*, 1989; *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; *Wilson et al.*, 2001; *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*, 2010, 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].

[13] The southwest Iberian margin experienced three major rift phases [*Pereira and Alves*, 2010, 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

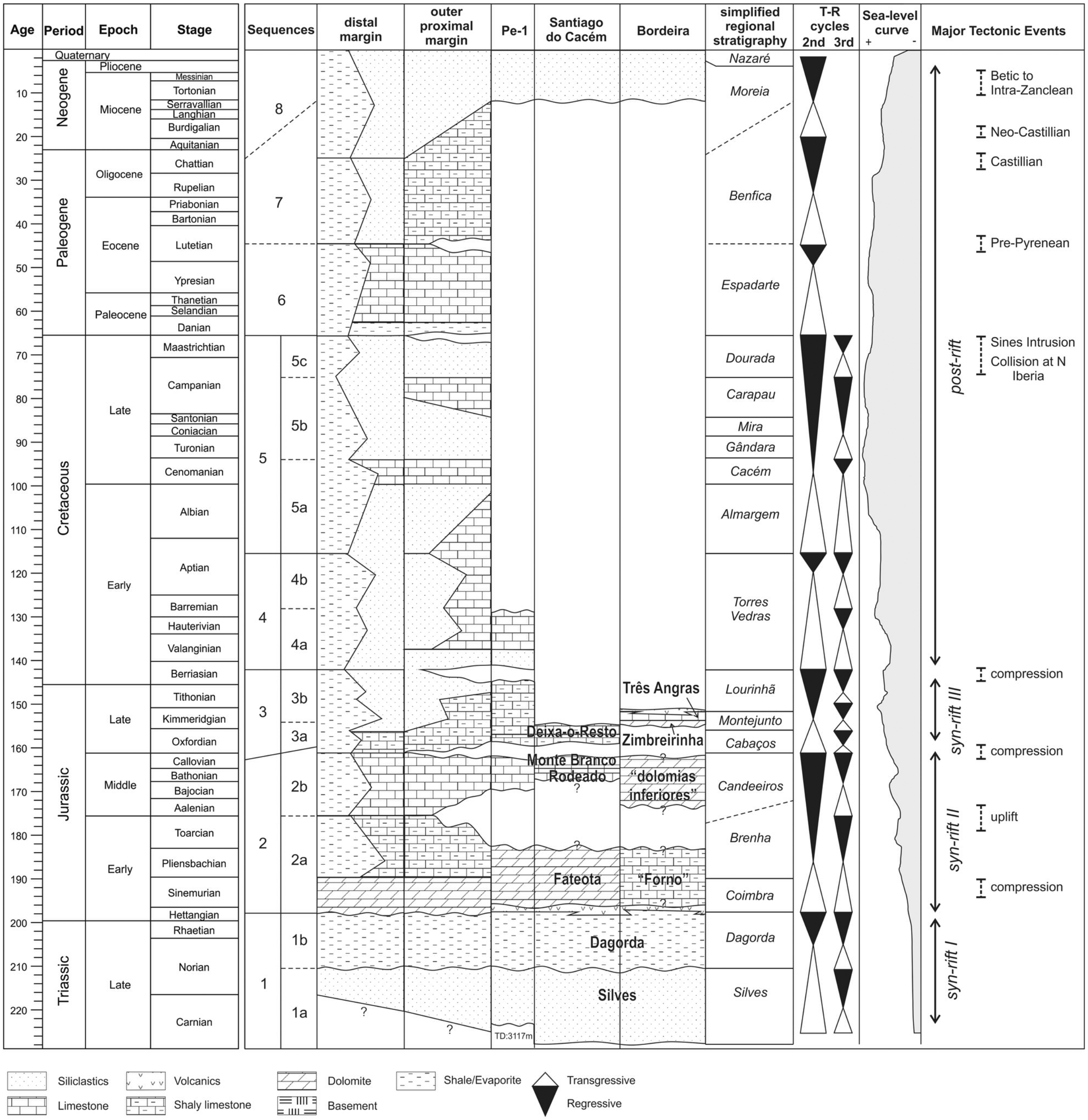

Figure 2. Simplified lithostratigraphy of the southwest Iberian margin, showing the main stratigraphic sequences and major Transgressive-Regressive (T-R) events recorded in the study area and West Iberia. Regional informal lithostratigraphy based on the works of *Witt* [1977], *Manpupella* [1983], *Ramalho and Ribeiro* [1985], *Ribeiro et al.* [1987], *GPEP* [1986], *Wilson* [1988], *Inverno et al.* [1993], *Azerêdo et al.* [2003], and *Rey et al.* [2006]. T-R events adapted from *Reis and Pimentel* [2010]. Chronostratigraphy and Mesozoic-Cenozoic sea level curve extracted from TSCreator 4.2.5, based on *Hardenbol et al.* [1998].

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.*, 1989; *Hiscott et al.*, 1990; *Pereira and Alves*, 2011].

3.2. Seismic-Stratigraphic Units in Offshore Basins

[14] Continental extension throughout the southwest Iberian margin resulted in the formation of four major regional unconformities, which bound three principal syn-rift

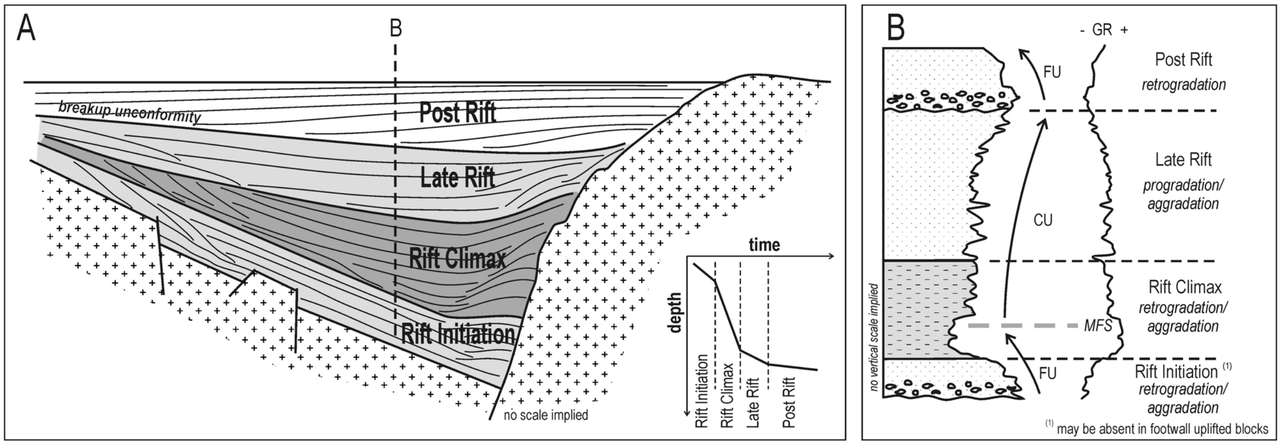

Figure 3. Schematic tectonic systems tracts (a) on a transverse seismic section and (b) on outcrop, borehole and wireline data. Based on *Prosser* [1993], *Gawthorpe et al.* [1994] and *Ravnås and Steel* [1998]. Rift subsidence curve adapted from *Gupta et al.* [1998].

Megasequences (1, 2 and 3) (Figure 2). Many of these unconformities are broadly synchronous across the Central and North Atlantic [*Mauffret et al.*, 1989; *Hiscott et al.*, 1990; *Pereira and Alves*, 2011].

[15] A basal angular unconformity separates the tightly folded Late Paleozoic (Devonian-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] (Figures 2, 4, 5a, and 5b). 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] (Figure 5c).

[16] 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] (Figure 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] (Figures 2 and 4).

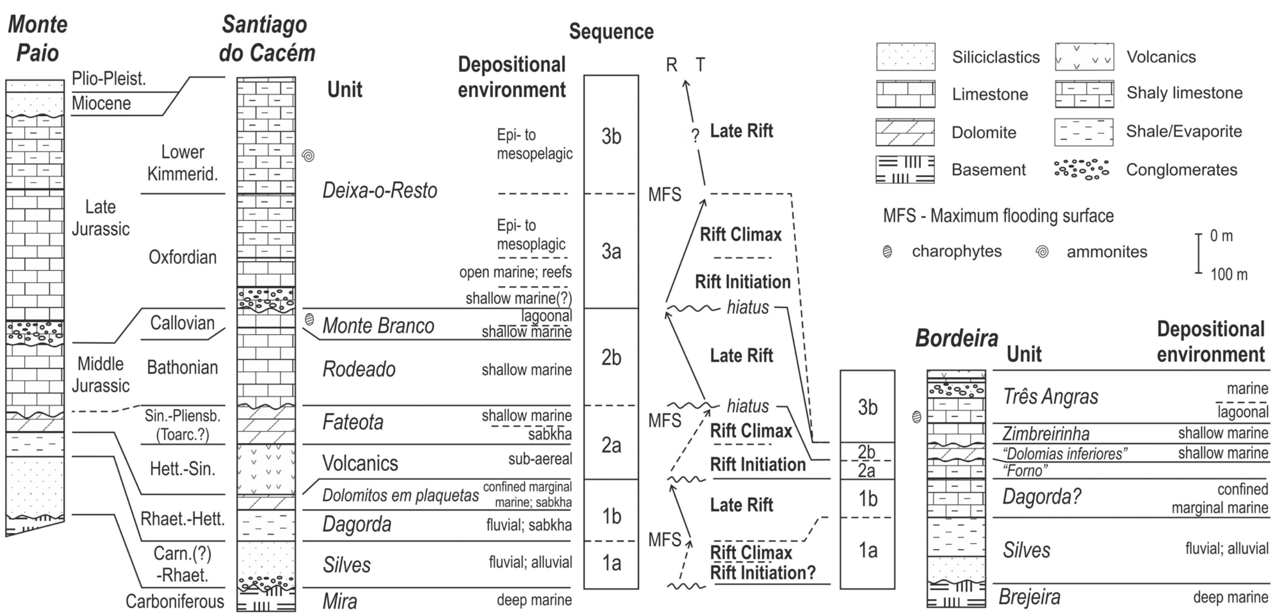

Figure 4. Schematic lithostratigraphy, depositional environments and T-R trends from outcrop locations at Santiago do Cacém, Bordeira and in well Monte Paio. Based on *Manuppella* [1983], *Ramalho and Ribeiro* [1985], *Ribeiro et al.* [1987], *Inverno et al.* [1993] and *Alves et al.* [2009].

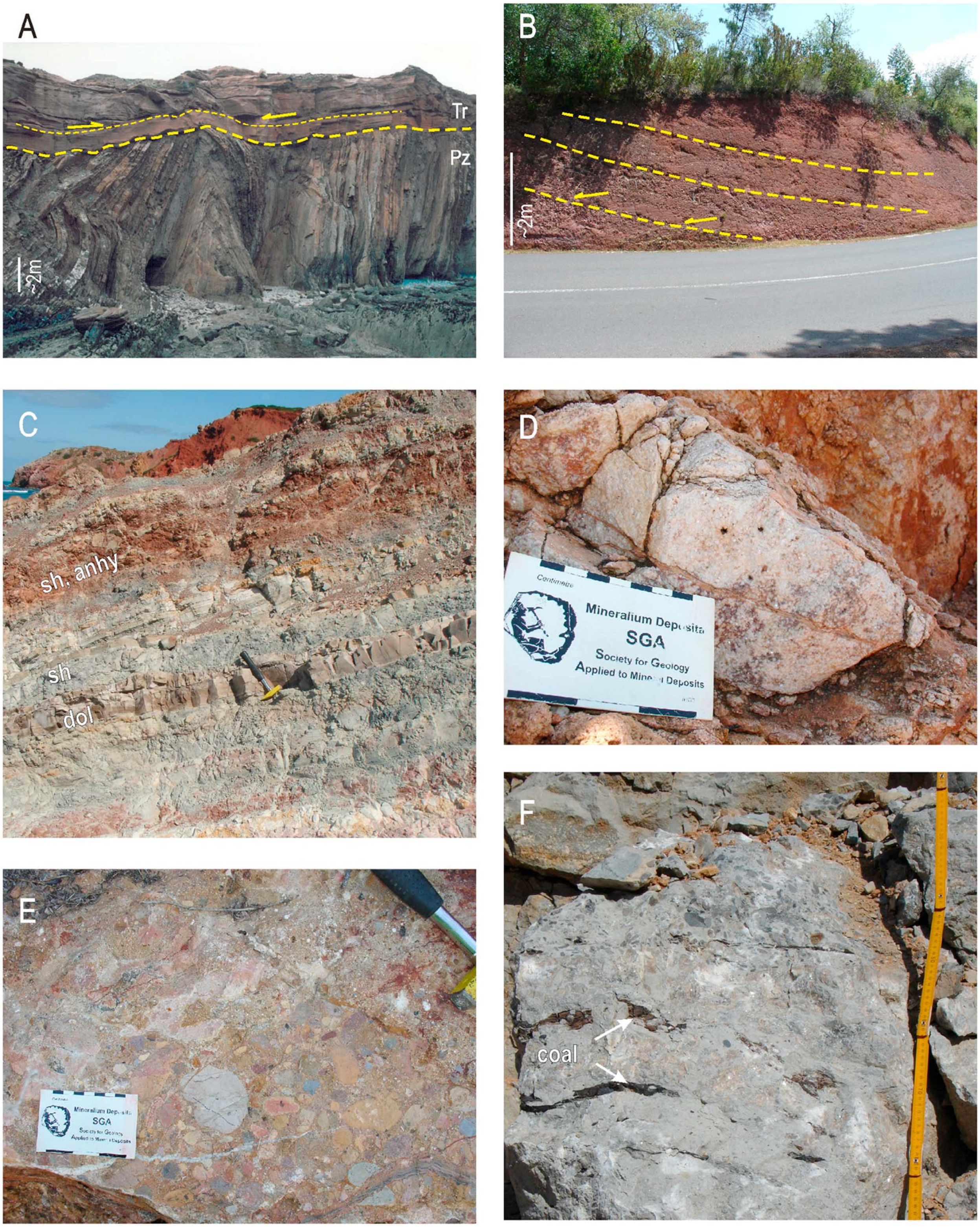

Figure 5. (a) Angular unconformity between the Late Triassic Silves formation and crosscutting the Paleozoic basement units, south of Bordeira (Telheiro beach). (b) Stratification within the Late Triassic (Silves Fm., southeast of Santiago do Cacém). (c) Dagorda formation south of Bordeira (Amado beach). (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).

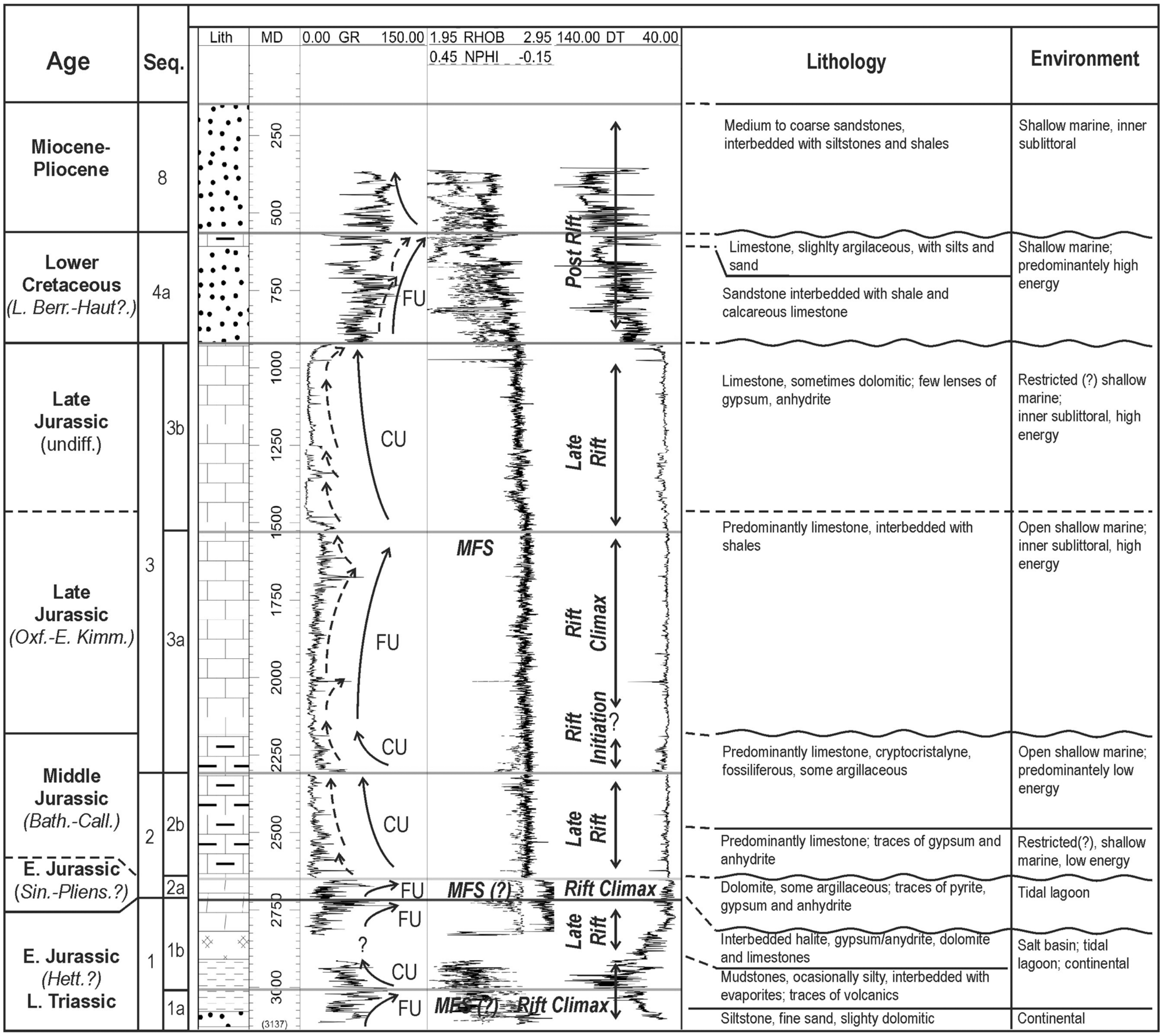

Figure 6. Interpreted wireline data and depositional trends from well Pe-1. Lithologies and depositional environments are based on the well completion report.

[17] 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 (Figure 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] (Figures 2, 4, and 5d).

[18] 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.*, 2002]. Overlaying this unconformity, the Late Jurassic is characterized 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] (Figures 4, 5e, and 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].

[19] 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 (Figure 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].

[20] 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 et al.*, 2010, 2011].

4. Sequence Stratigraphy Analysis of the Southwest Iberian Margin

[21] 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 (Figure 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) (Figure 7a).

[22] 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 (Figure 2).

[23] In Figures 2, 4, and 6 and in Table 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.

4.1. Syn-Rift Megasequences

4.1.1. Megasequence 1 (Carnian?-Hettangian)

[24] Megasequence 1 materializes 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 inner proximal margin at this time (Figure 7b). Megasequence 1 exceeds 200 m in thickness at Santiago do Cacém (Figure 4), whereas in Pe-1 it is thicker than 380 m (Figure 6). Offshore southwest Iberia, TWT thickness maps indicate that Megasequence 1 can reach up to 1 s (~2200 m) (Figure 7b). Thickness variations in Megasequence 1 are associated with the generation of NE-SW depocenters bounded by syn-rift master faults (Figure 7b). This shows that the deposition of Megasequence 1 was controlled by an initial, but significant, phase of crustal subsidence.

[25] The occurrence of growth strata within sequence 1a is limited, suggesting minor subsidence (Figure 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 (Figures 4, 5b, and 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 (Figures 4, 5c, and 6). In this uppermost sequence no clear depositional trends are observed (Figures 6 and 8).

4.1.2. Megasequence 2 (Hettangian/Sinemurian-Callovian)

[26] Megasequence 2 is characterized 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 (Figures 7c and 8).

[27] 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 (Figure 8 and Table 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).

[28] Dolomitic and limestone strata in sequence 2a were deposited in the latest Hettangian-Sinemurian at the start of Syn-Rift II (Figures 4 and 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 60m of dolomitic deposits (Figure 6). This latter character was likely generated by a relative rise in base level at the start of Syn-Rift II.

[29] 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 (Figure 6). In well Pe-1, sequence 2b is recognized by presenting a sharp break on gamma-ray and density logs (Figure 6), whereas on seismic data this event is expressed as a correlative paraconformable boundary (Figures 8 and 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 (Figure 8). *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 (Figure 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 (Figure 2).We interpret this latter trend as denoting 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 (Figure 4). Sequence 2b is crosscut at its top by a widespread Late Callovian to Middle Oxfordian angular unconformity (Figures 4, 6, and 8).

[30] On the proximal margin, seismic data reveal a prograding/aggrading rimmed carbonate platform of probable middle Jurassic age (Figure 9). This suggests that carbonate deposition throughout the southwestern Iberian margin was widespread at this time, similarly to what has been described in the Lusitanian Basin [*Azerêdo et al.*, 2002]. Considering the hiatus recorded in Nova-Scotia and on its conjugate margin of North Africa [e.g., *Welsink et al.*, 1989], the Toarcian-Aalenian hiatus in southwest Iberia and western

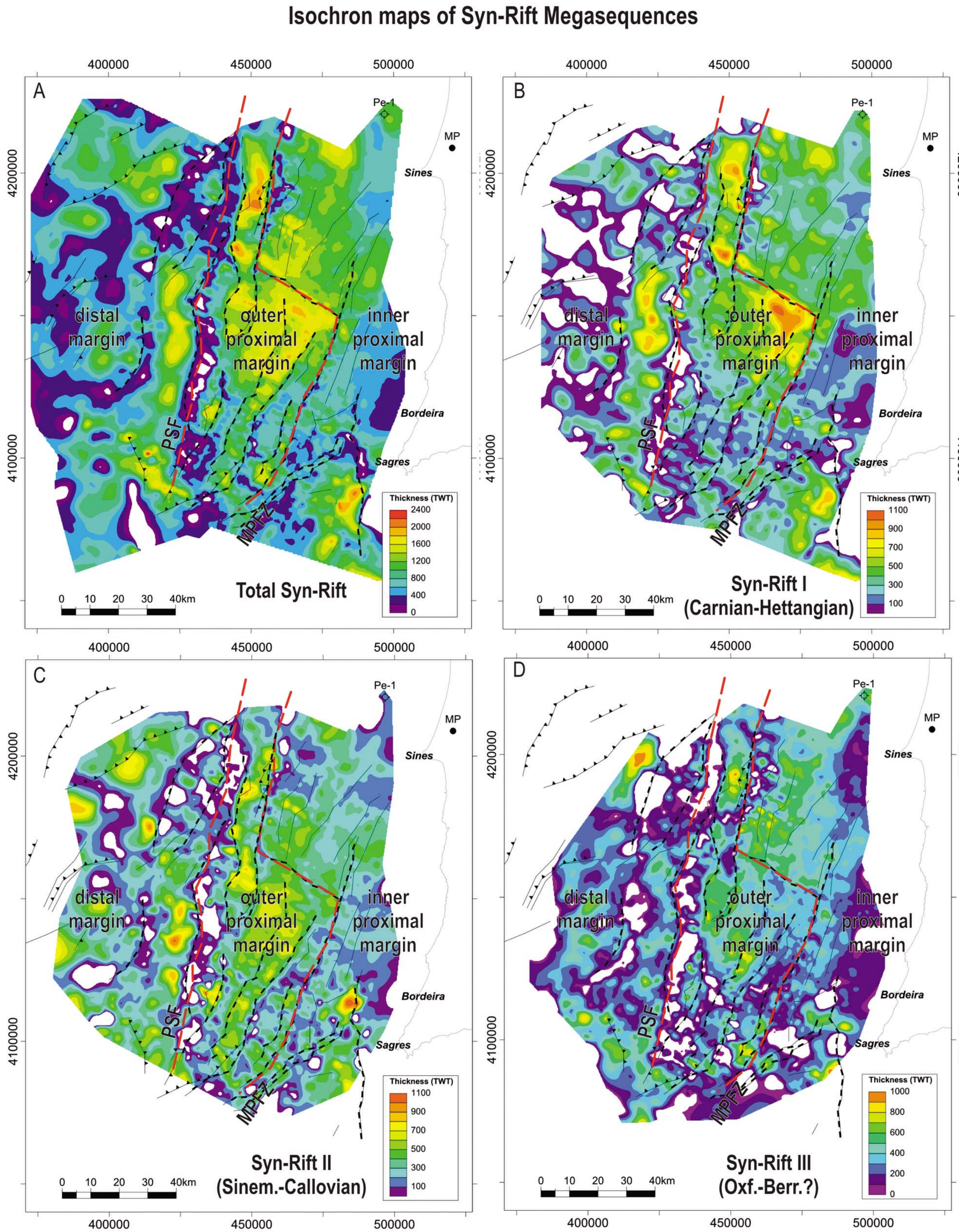

Figure 7. Maps showing the structural control and major rift depocenters throughout the southwest Iberian margin. (a) Total syn-rift thickness isochron map (TWT) of the southwest Iberian margin. (b) Isochron map (TWT) of top of Syn-Rift phase I. (c) Isochron map (TWT) of top of Syn-Rift phase II. (d) Isochron map (TWT) of the Syn-Rift phase III. Faults and margin zonation from *Pereira and Alves* [2011].

Table 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

			Lithostratigraphy				
Sequence (3rd Order)	Probable Age of Base	Seismic Stratigraphy	Regional	SW Iberia	Lithology of the Proximal Margin	Lithology of the Distal Margin	Overall Depositional Trend
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 siliciclstics	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 inferiors”	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

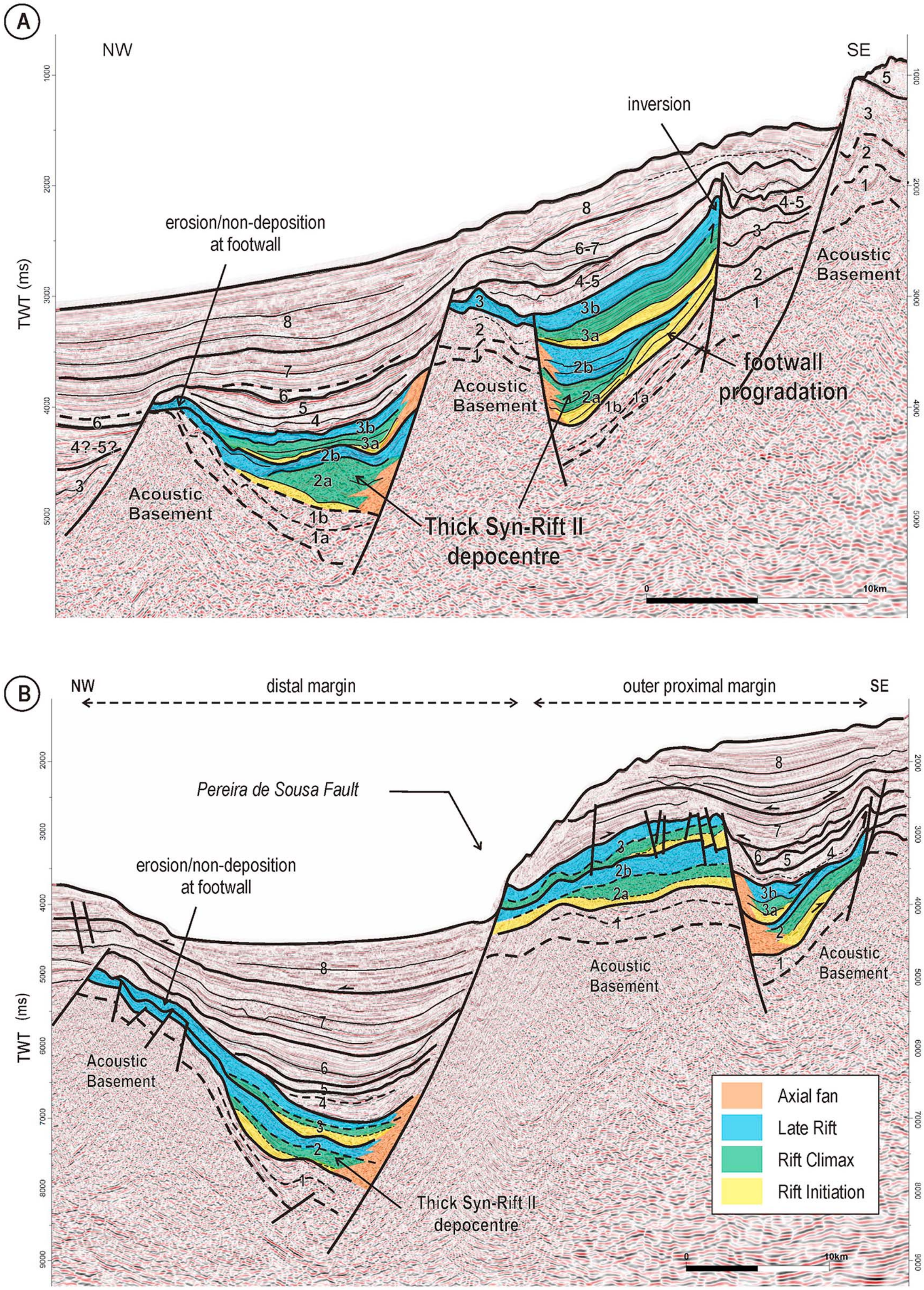

Figure 8. Interpreted migrated multichannel 2D seismic section across the (a) outer proximal and (b) distal margin, evidencing the tectonic systems tracts described in this paper and thick syn-Rift II depocenters. Note the early Jurassic rift initiation footwall progradation and the limited deposition over uplifted footwalls. Data courtesy of TGS.

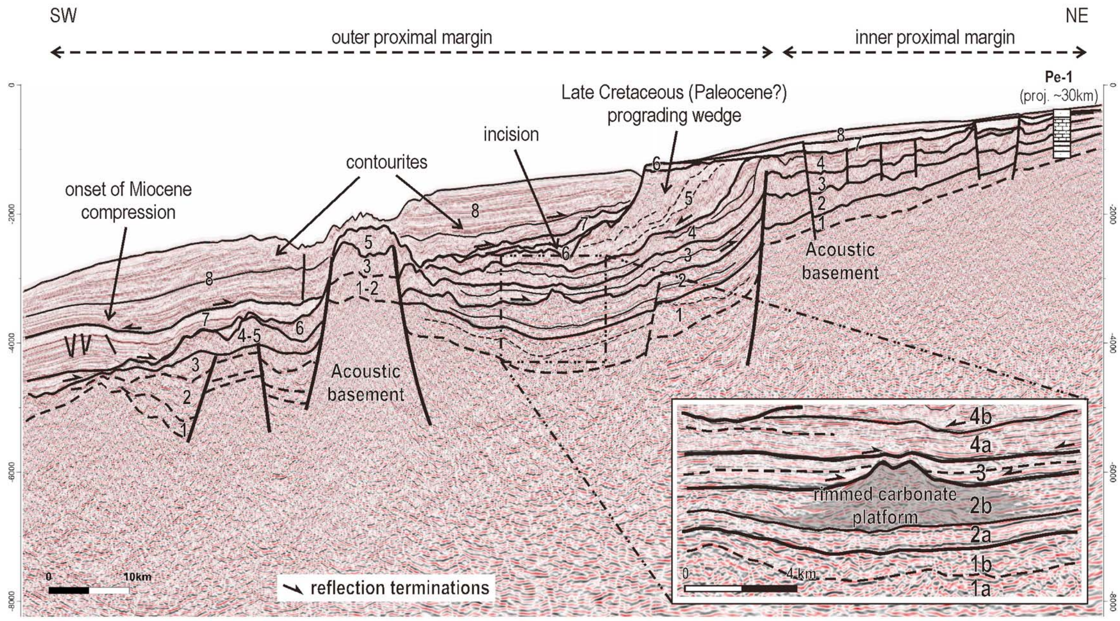

Figure 9. Interpreted multichannel 2D seismic section across the proximal margin, showing a probable mid Jurassic prograding rimmed carbonate platform. Deposition of the Late Cretaceous (Paleocene?) prograding wedge is controlled by a paleo-shelf break, subsequently eroded during the Paleocene-Eocene (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. Data courtesy of TGS.

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 (Figure 2).

4.1.3. Megasequence 3 (Callovian-Berriasian)

[31] The Callovian-Oxfordian regional angular unconformity defines the base of Megasequence 3 (Figures 2 and 4). At Pe-1, Megasequence 3 is characterized 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 (Figure 6 and Table 1).

[32] On the distal margin, growth strata indicate that important subsidence continued at this time into the Advanced Rifting and Transition to Seafloor Spreading stages (Figure 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 (Figures 7d and 8). Where faults dip to the east, upper Jurassic strata appear planar (Figure 8).

[33] 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 (Figure 4). On the road from Grândola to Sines, the Oxfordian-Kimmeridgian breccia-conglomerates are polymictic (Figure 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 (Figure 5f). Toward the top of this unit, early Kimmeridgian marine limestones with ammonites mark the increased marine influence of the proximal margin (Figure 4).

[34] 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 (Figure 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 (Figure 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 (Figures 8 and 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].

4.2. Mesozoic Post-Rift Megasequences

[35] Megasequence 4 (Berriasian to mid Aptian) comprises retrograding shallow-marine siliciclastics overlain by limestones (Figure 6). On seismic data Megasequence 4 shows marked progradation, with main depocenters located on the outer proximal and distal margins (Figure 10). This suggests sediment bypass from hinterland sources, accompanied by widespread uplift of the inner proximal margin.

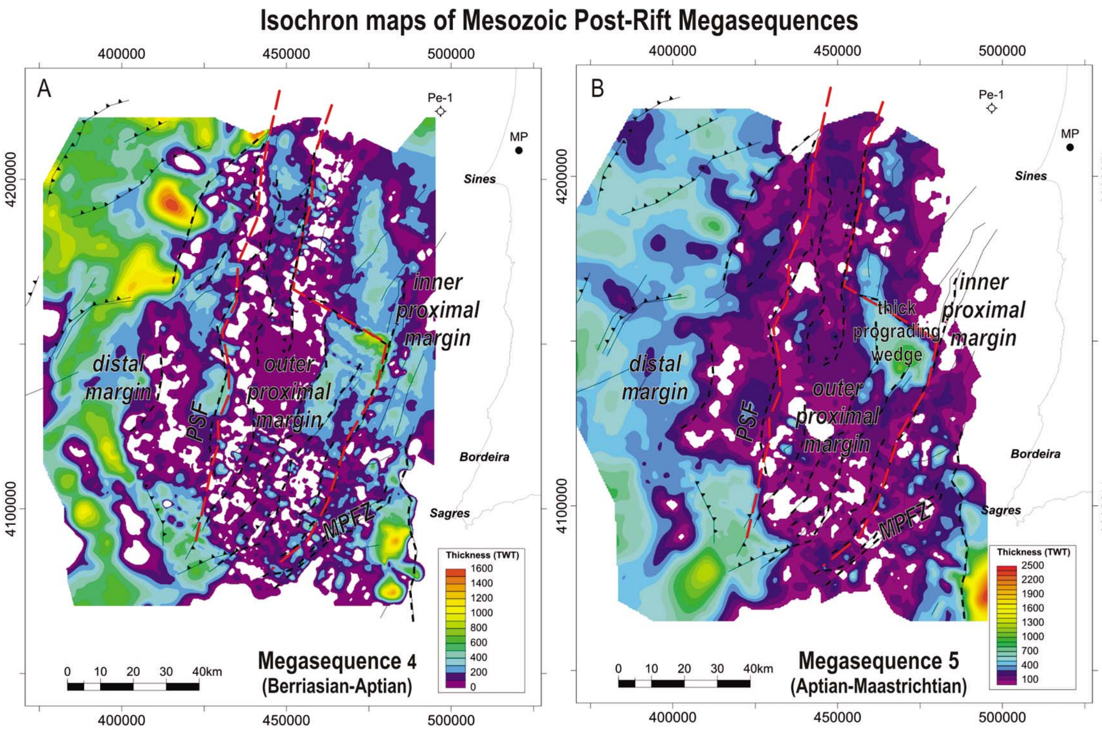

Figure 10. Isochron (TWT) maps of the principal Mesozoic post-rift depocenters, largely controlled by inherited the syn-rift physiography. (a) Megasequence 4 (Berriasian-Aptian) shows that favored depocenters are located on the inner proximal and distal margin. (b) Megasequence 5 (Aptian-Maastrichtian?), shows favored deposition on the distal margin and a prograding wedge on the outer proximal margin.

[36] Megasequence 5 (Mid Aptian to Maastrichtian-Paleocene) is often absent on borehole data and outcrops (Figures 4, 6, and 10). However, on the outer proximal margin a prograding wedge up to 2500 m thick was deposited on a paleo-platform break (Figure 10). Seismic reflections are mostly chaotic within the Megasequence, becoming increasingly sub-parallel toward the outer proximal margin (Figure 9). This character suggests Megasequence 5 to comprise a deltaic wedge or prograding slope deposits.

5. Burial History in the Proximal Margin

5.1. Objectives and Boundary Conditions

[37] 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 modeled for its burial history (Figure 11). Burial history models on the distal margin are not included in the present work, although the superimposed growth strata (Megasequences 1, 2 and 3) points to prolonged tectonic subsidence of this domain of the southwest Iberian margin (Figure 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 paper. Such simplification of the burial history has a significant impact on model results as they conceal the effective subsidence rates subsequent to uplift periods. Our burial history model includes a suite of input parameters and boundary conditions, presented in Table 2.

[38] Thickness values for major lithological units were obtained from the completion well report and re-interpreted in this work (Figure 6).

[39] The age of erosive (and uplift) events were estimated on the basis of regional context of the Lusitanian and the Alentejo Basins (See references in Geological Setting section). 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 2).

[40] 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.

5.2. Analysis of Results

[41] As in the analysis of *Cunha et al.* [2009] a first pulse of extension on the inner proximal margin is characterized 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 (Figures 8 and 9). Our model also reveals that during the Sinemurian to Pliensbachian

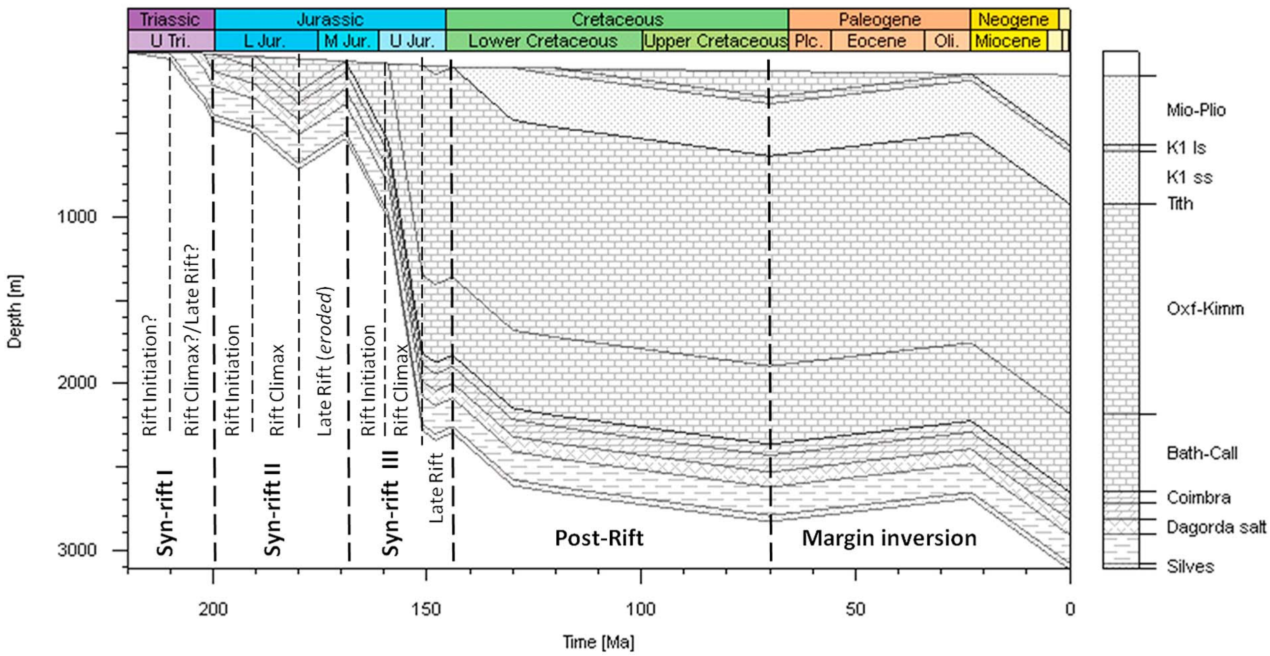

Figure 11. Burial history model of Pe-1 evidencing the distinct pulses within each rift phase (I, II and III). Subsequent to the final rift phase (Late Jurassic–earliest Cretaceous), the margin reveals limited subsidence and from the Late Cretaceous onwards, uplifting is estimated. Modeling made with Petromod freeware license.

(sequence 2a), prior to Toarcian-Aalenian uplift, the inner proximal margin of southwest Iberia recorded subsidence usually in excess of 200 m (Figure 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 (Figure 11). 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.

[42] 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.

[43] Although far from conclusively explain all the uncertainties regarding the differential subsidence throughout southwest Iberia, our 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 (Figures 7 and 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.

[44] 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

Table 2. Input Parameters for the Burial History Modeling of Borehole Pe-1

	Top (m)	Base (m)	Thickness (m)	Eroded (m)	Deposition		Erosion	
					From (Ma)	To (Ma)	From (Ma)	To (Ma)
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		

Basin, burial history modeling 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. Discussion

6.1. Multiphased Tectonic Systems Tracts Offshore Southwest Iberia

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

[46] In order to better investigate depositional trends on borehole data, six additional wells from offshore Lusitanian Basin were re-interpreted (Figure 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.

6.1.1. Rift Initiation Systems Tract

[47] The Rift Initiation systems tract marks the first increment of subsidence occurred in response to the onset of extension (Figure 11). It is often accompanied by a basal unconformity, overlain by coarse-grained deposits representing a regression maximum (Figures 4 and 6).

[48] Seismic data shows that rift initiation sequence tracts are often characterized by an overall wedge-shaped geometry, showing limited vertical expression due to reduced tectonic-related subsidence (Figure 8). Internal reflections are subparallel to divergent, often downlapping a basal unconformity (Figure 9). *Prosser* [1993] indicated hummocky channelized 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 (Figures 8 and 9).

[49] Data from studied outcrops and from well-logs documenting Lower to Late Jurassic strata west of the Lusitanian Basin, reveal that the rift initiation systems tract is characterized by alternate aggradational to retrogradational pattern (Figures 4, 6, and 12).

[50] 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 (Figure 12).

[51] 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 (Figure 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) (Figures 4, 5e, and 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.

[52] A similar response on wireline data to that in this paper 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 (Figure 11).

6.1.2. Rift Climax Systems Tract

[53] 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 characterized by presenting wedge-shape geometry, with divergent reflectors denoting an increase in thickness toward basin-bounding faults. Prograding 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 (Figures 8 and 9).

[54] 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 (Figure 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 depocenters.

[55] On wireline data, maximum flooding surfaces are characterized by peaks of the gamma-ray profile showing a retrogradational trend at first, changing to a prograding trend after the maximum flooding surface (Figures 6 and 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 (Figures 6 and 12). Seismic data also images this change from retrogradational to progradational (Figure 8). The burial model for well Pe-1 reveals a significant increase in subsidence during the Sinemurian-Pliensbachian and Callovian(?) to early Kimmeridgian stages (Figure 11). In a regional context, we consider 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.

6.1.3. Late Rift Systems Tract

[56] The Late Rift systems tract marks the progressive cessation of fault-controlled subsidence. This systems tract predominantly sub-parallel continuous to gently divergent internal reflections (Figures 8 and 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 (Figure 12).

[57] The lowermost boundary of Late Rift systems tracts is often characterized by downlapping strata at the center of individual basins and by onlapping sequences at their

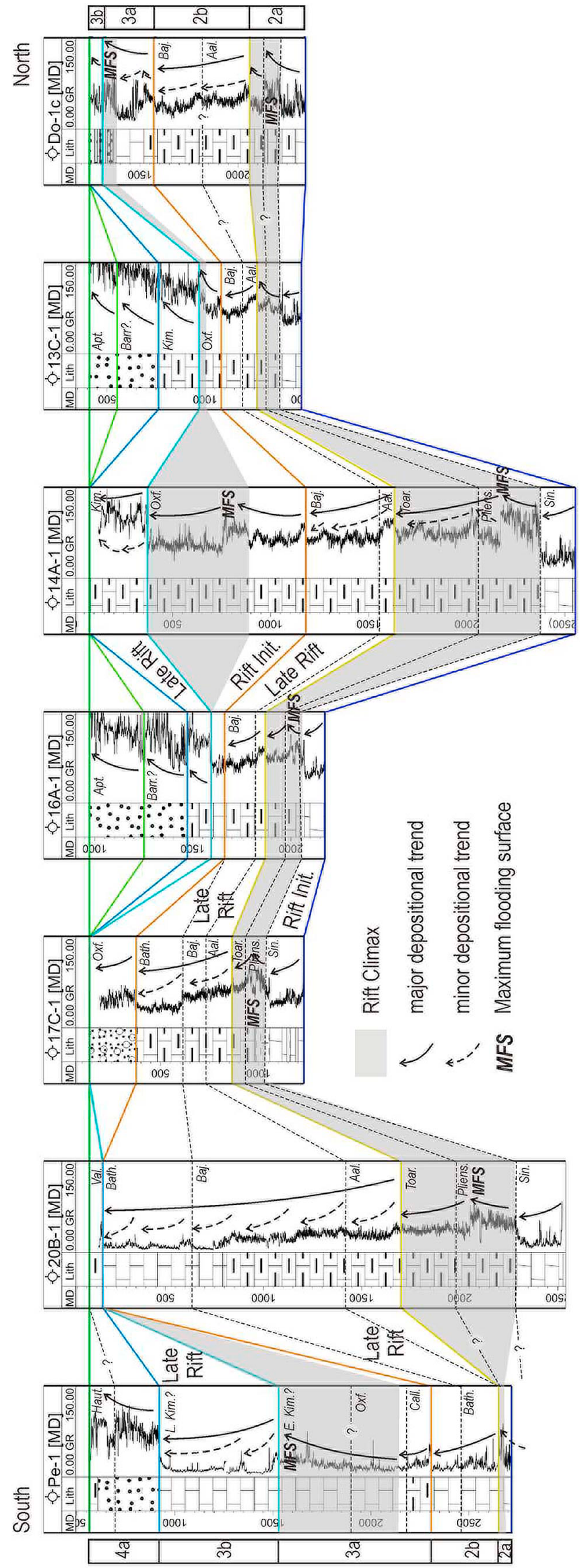

Figure 12. Cross section correlating well Pe-1 with selected exploration boreholes of the proximal margin of West Iberia. The correlation panel highlights the major Pliensbachian and Oxfordian-Kimmeridgian Rift Climax phases and the similar depositional trends within each pulse of the discrete rift phases. 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.

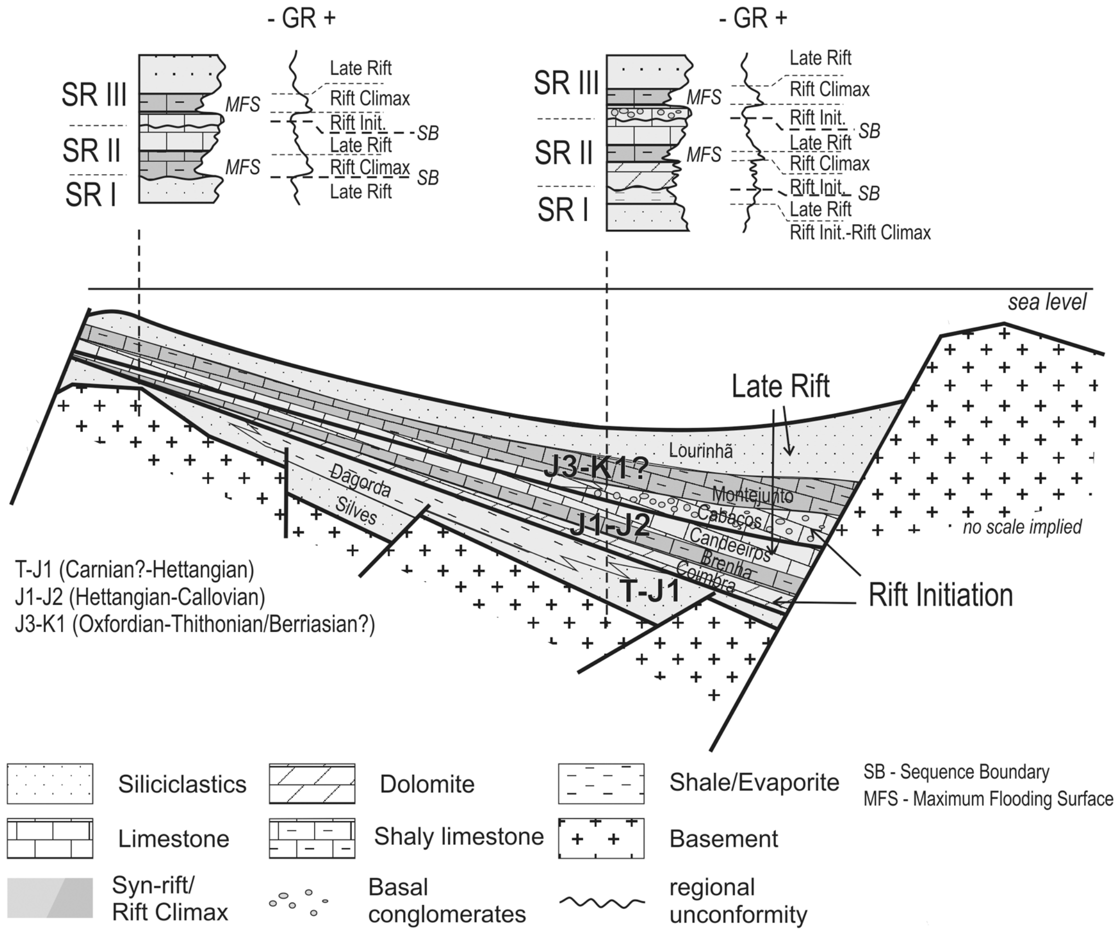

Figure 13. Schematic multiphased syn-rift deposition on a tilted block at southwest Iberia. At the uplifted footwall a hiatus occurs, which is synchronous with deposition of the Rift Initiation (or Rift Climax) depositional sequences on the subsiding hanging wall.

margins (Figures 8 and 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 (Figures 8 and 9).

[58] At outcrop and on wireline data, the Late Rift systems tract shows upward-coarsening strata predominantly showing progradation (Figures 4 and 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 (Figure 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 (Figure 11). Whether this mechanism is purely controlled by tectonic subsidence or eustatic variations is yet to be understood.

[59] Wireline data reveal an overall retrograding pattern in what are essentially shallow marine limestones (Figure 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.

6.2. Syn-Rift Tectono-Stratigraphy Across the SW Iberian Margin

[60] 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 (Figure 13). On the southwest Iberian margin, three major phases of extension resulted in the accumulation of second-order sequences (Megasequences in this paper) 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.

[61] The three Rift Climax events recognized 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 (Figure 13). In addition, our 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 (Figure 13).

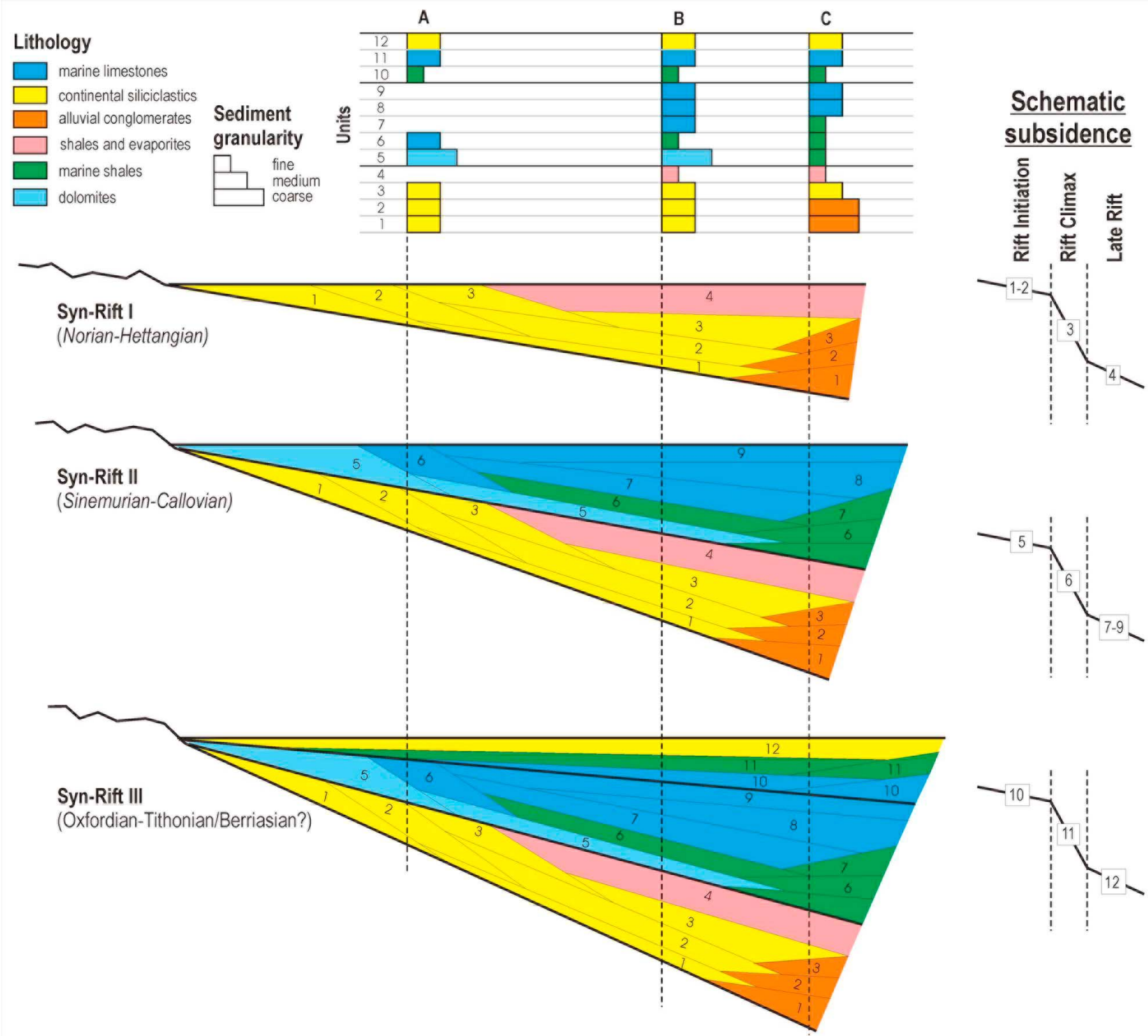

Figure 14. Schematic evolution of the proximal southwest Iberian margin during the multiphased rifting showing associated depositional sequences. Pseudo-wells are located at (a) the basin uplifted footwall, (b) the basin center, and (c) the hanging wall. Subsidence curves depict the evolution of the sub-basin through the discrete Syn-Rift phases and their tectonic pulses.

[62] Figure 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).

[63] 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. Rift Climax systems tracts (layers 3, 6, 7 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 depocenter(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.

[64] 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 depocenter(s) (locations B and C), the continued interplay between subsidence and deposition is often marked by disconformities or paraconformities.

[65] 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 (Figure 2). 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 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.

[66] 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 (Figure 2).

[67] 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 (Figure 12).

[68] 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 paper 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 favor the accumulation of correlative depositional tectonic systems tracts throughout continental margins. Results from this work can therefore be used to compare adjacent sectors of rifted continental margins such as West Iberia, Newfoundland or the North Sea [*Chang et al.*, 1992; *Gawthorpe et al.*, 1994; *Sinclair*, 1995; *Ravnås et al.*, 1997; *Leinfelder and Wilson*, 1998; *Ravnås and Steel*, 1998; *Gawthorpe and Leeder*, 2000; *Ravnås et al.*, 2000; *McLeod et al.*, 2002; *Alves et al.*, 2003b].

7. Conclusions

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

[70] 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 paper as meaningful tectonic system tracts [e.g., *Prosser*, 1993].

[71] 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.

[72] 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 characterized by overall aggradation/retrogradation overlying a basal regional unconformity.

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

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

[75] The modeling 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.

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