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PETROLEUM SYSTEMS OF THE WEST IBERIAN MARGIN: A REVIEW OF THE LUSITANIAN BASIN AND THE DEEP OFFSHORE PENICHE BASIN

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The relatively well-studied Lusitanian Basin in coastal west-central Portugal can be used as an analogue for the less well-known Peniche Basin in the deep offshore. In this paper the Lusitanian Basin is reviewed in terms of stratigraphy, sedimentology, evolution and petroleum systems. Data comes from published papers and technical reports as well as original research and field observations. The integration and interpretation of these data is used to build up an updated petroleum systems analysis of the basin. Petroleum systems elements include Palaeozoic and Mesozoic source rocks, siliciclastic and carbonate reservoir rocks, and Mesozoic and Tertiary seals. Traps are in general controlled by diapiric movement of Hettangian clays and evaporites during the Late Jurassic, Late Cretaceous and Late Miocene. Organic matter maturation, mainly due to Late Jurassic rift-related subsidence and burial, is described together with hydrocarbon migration and trapping. Three main petroleum systems may be defined, sourced respectively by Palaeozoic shales, Early Jurassic marly shales and Late Jurassic marls. These elements and systems can tentatively be extrapolated offshore into the deep-water Peniche Basin, where no exploration wells have so far been drilled. There are both similarities and differences between the Lusitanian and Peniche Basins, the differences being mainly related to the more distal position of the Peniche Basin and the later onset of the main rift phase which was accompanied by Early Cretaceous subsidence and burial. The main exploration risks are related to overburden and maturation timing versus trap formation associated both with diapiric movement of Hettangian salt and Cenozoic inversion.

INTRODUCTION

The West Iberian margin is one of the least explored of the North Atlantic margins. A number of on- and offshore basins are present in West Iberia including the mainly onshore Lusitanian Basin and the deep offshore Peniche Basin (Fig. 1). Counterparts in the conjugate margin of eastern Canada are the Jeanne d'Arc and Whale Basins (cf. Wilson *et al.*, 1989; Pinheiro *et al.*, 1996; Peron-Pinvidic and Manatschal, 2009) where major oil and gas fields include Hibernia (1016 MM brls) and Terra Nova (170 MM brls) in Newfoundland, and Sable (2.7 TCF) and Deep Panuke (659 BCF) in Nova Scotia (CNSOPB, 2013). However no comparable discoveries have so far been made in the West Iberian margin.

Exploration of the West Iberian margin began in the 1930s. Seismic data was acquired over the next

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Fig. 1. Location map of the West Iberian margin of Portugal with the mainly onshore Lusitanian Basin and deeper-water offshore basins including the Peniche Basin. Bb, Berlengas Block. Red lines show the conjugate NNW-SSE and NE-SW fault system. Inset shows the Palaeozoic Iberian basement zones (Ribeiro *et al.*, 1990). Boxes mark the areas of Figs 2 and 3.

40 years and 78 wells were drilled with oil shows and sub-commercial discoveries recorded (UPEP, 2016). Increased seismic acquisition took place in the 1970s with the drilling of 22 offshore wells (Fig. 2). The margin was further explored between 1978 and 2004 (particularly the Porto Basin: Fig. 1), and an additional 28 wells were drilled with a few oil shows (Fig. 2). The deeper offshore has been covered by a seismic campaign (TGS-NOPEC 99-02; UPEP, 2016) (Fig. 2), and concessions in 2007 included three blocks in the Alentejo Basin (ENI (operator) and GALP) and four blocks in the Peniche Basin (Repsol (operator), Kosmos, GALP and Partex). Meanwhile, the Lusitanian Basin (onshore and shallow offshore) was explored by Mohave Oil & Gas from 1998 to 2014, with 2D and 3D seismic acquisition, nine wells and significant oil and gas shows recorded.

Recent exploration activity in the West Iberian margin has focused on the deep offshore with new 2D and 3D seismic campaigns, as well as aerial gravimetric surveys of both onshore and offshore areas (UPEP, 2016). Little direct information about the sedimentary infill of the deep offshore basins is available due to the absence of wells in water depths greater than 200m

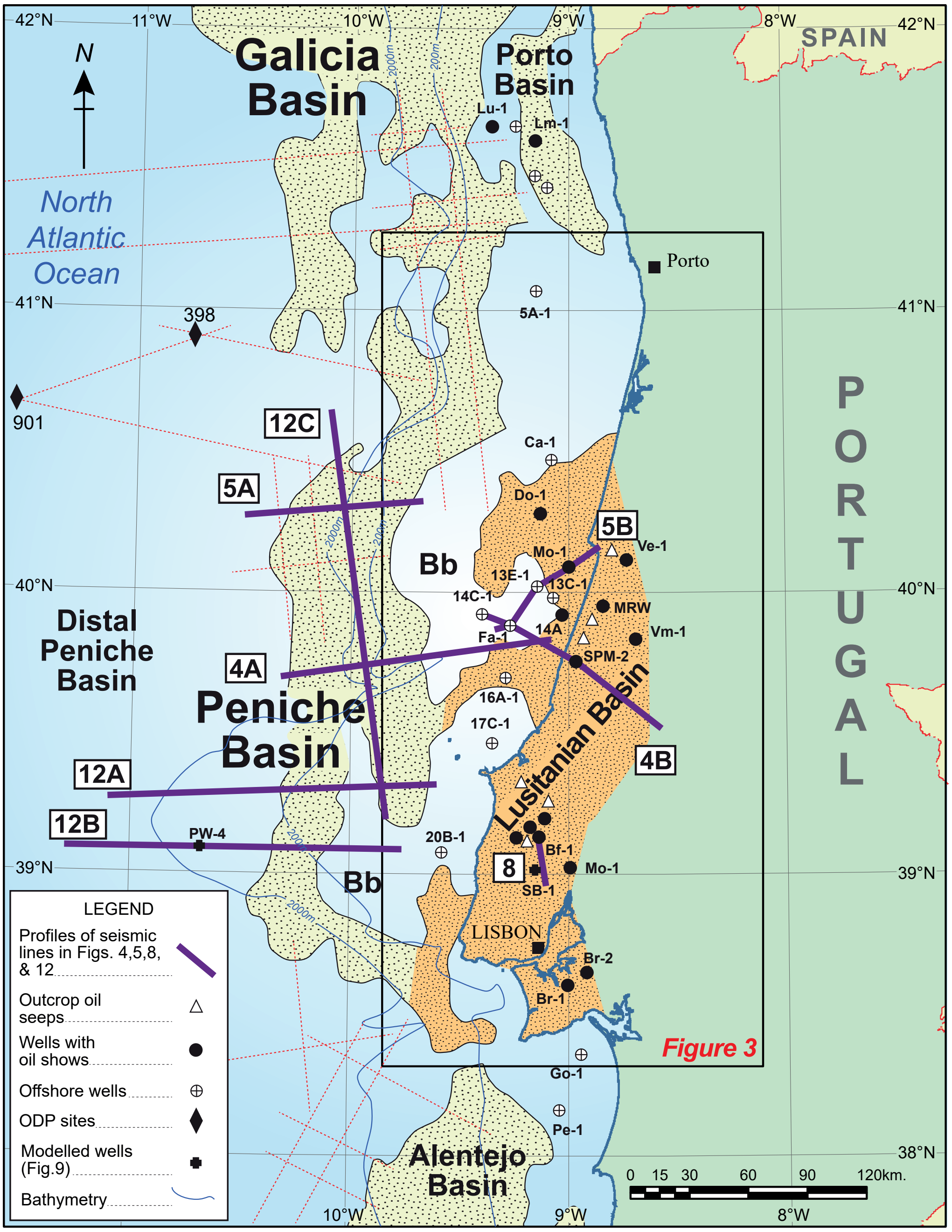

Fig. 2. Regional map of the Portuguese margin showing the location of the main TGS-NOPEC seismic lines (red), offshore wells, wells with oil shows, and locations of oil seeps (after UPEP, 2016). Purple lines show the profiles of seismic sections reproduced in Figs 4, 5, 8 and 12. Crosses mark the locations of modelled wells SB-1 and PW-4 (Fig. 9). Box marks the area of Fig. 3.

(Fig. 2). However the sedimentary fill in the deep offshore may be extrapolated from the outcrop geology of the onshore areas which has been well documented (e.g. Alves *et al.*, 2003, 2006, 2009; Pereira *et al.*, 2011, 2012; Pena dos Reis *et al.*, 2011).

In this paper we present an overview of the Lusitanian Basin and of the related petroleum systems and elements, and discuss possible correlations with the deep offshore Peniche Basin. The paper integrates outcrop and subsurface data from the onshore with recently-acquired seismic data from the offshore.

Available data

Overviews of the geology and evolution of the Lusitanian Basin include Witt (1977), Ribeiro *et al.* (1979), Wilson (1988), Wilson *et al.* (1989), Rasmussen *et al.* (1998), Azerêdo *et al.* (2003), Dinis *et al.* (2008), Pena dos Reis *et al.*(2000, 2011) and Kullberg *et al.* (2013). To complement this published information, the fill of the Lusitanian Basin was studied at 38 outcrop locations in terms of stratigraphy, sedimentology and lithofacies variations (Atlantis, 2010). In addition to these outcrop studies, more than 50 well reports were studied for different stratigraphic intervals.

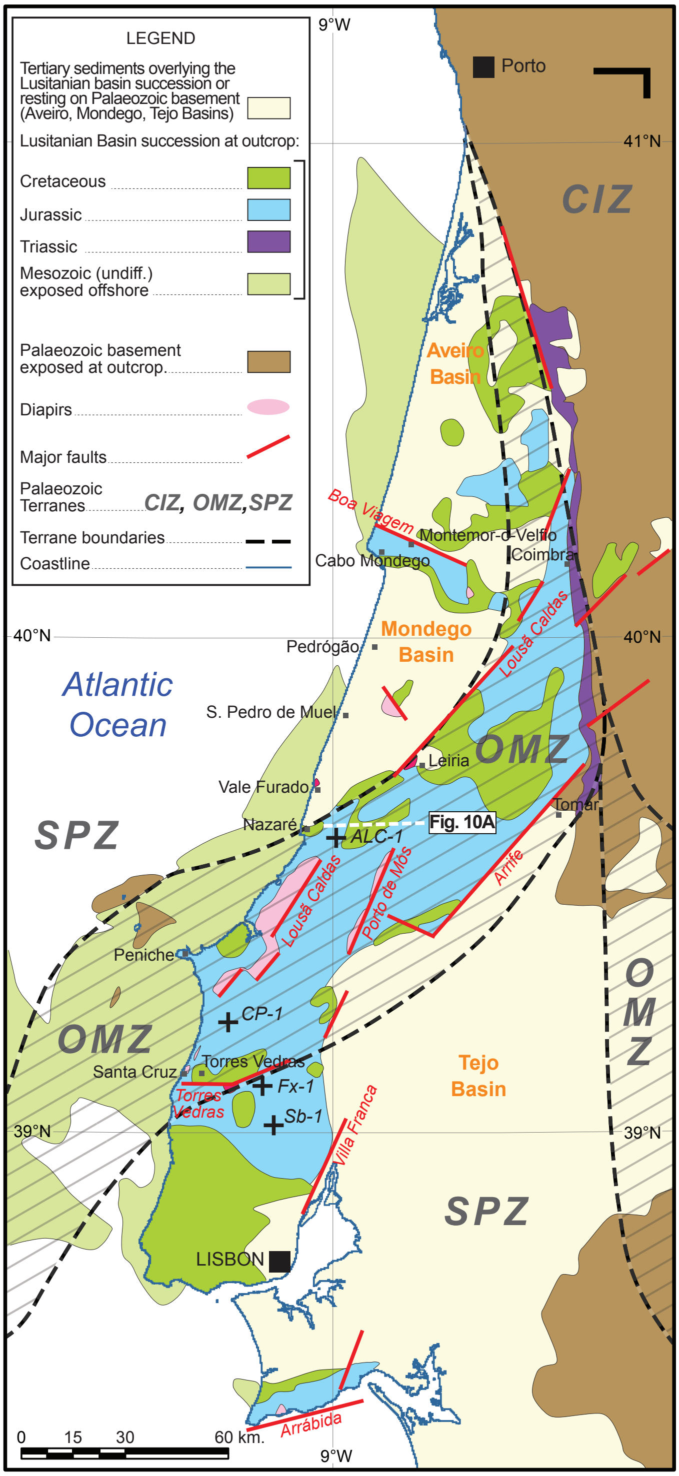

Fig. 3. Map showing structural and tectonic elements of the Lusitanian Basin, west-central Portugal. Mesozoic geology based on LNEG, 2010; Palaeozoic basement based on Pena dos Reis *et al.* (2012). Palaeozoic terranes: CIZ – Central Iberian Zone; SPZ – Southern Portuguese Zone; OMZ – Ossa Morena Zone. Outcropping diapirs with Hettangian evaporites are marked by pink polygons. White dashed line shows the profile line of the seismic section in Fig. 10a.

Finally, published regional and local 2D seismic lines (vd. Rasmussen *et al.,* 1998; Kullberg, 2000) and a comprehensive seismic interpretation report (Lomholt *et al.*, 1996) were used to investigate basin structure and tectono-sedimentary evolution. Based on these studies, petroleum systems and elements in the Lusitanian Basin were reviewed. Previous petroleum systems studies include that produced by the National Oil Agency (GPEP, 1986), and the reviews prepared by Pena dos Reis and Pimentel (2010a, 2010b) and Spigolon *et al.* (2011) which are updated in this paper.

For the Peniche Basin, no direct data are available except for some recent piston-core studies of the seabed, so the basin is known mainly from seismic data (e.g. Alves *et al.*, 2003, 2006, 2009). The correlation between the Lusitanian and Peniche Basins is based on the identification of similar unconformities and sedimentary infill packages, although differences are due to the basins' differing palaeo-geographical locations during the opening of the Northeast Atlantic. In addition to the published data, a group of 28 seismic profiles (courtesy of Petrobras) were analysed, and

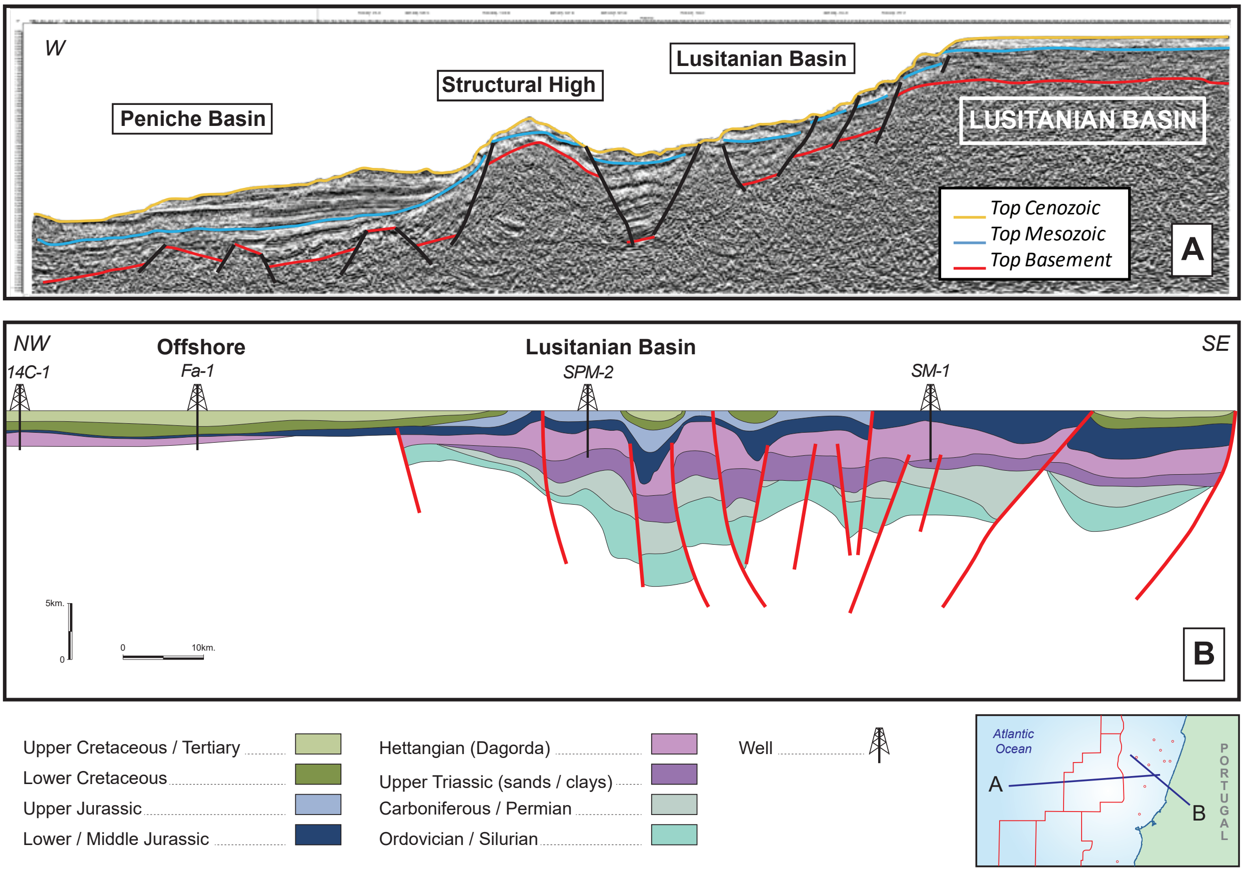

Fig 4. Schematic geological cross-sections based on interpreted seismic lines. (A) Composite east-west section across the Lusitanian and Peniche Basins based on the interpretation of two offshore lines (courtesy of Petrobras). (B) Adapted from an interpreted NW-SE section across the Lusitanian basin and adjacent offshore published by Uphoff *et al.* (1997). Section profiles are marked on the inset map and in Fig. 2.

based on these studies 14 pseudo-wells were modelled to investigate the basin's subsidence and thermal history (Sagres, 2013; Cardoso *et al.*, 2014).

REGIONAL FRAMEWORK

The evolution of the West Iberian margin is dominated by the episodes of Mesozoic rifting which accompanied opening of the North Atlantic. Rifting was accompanied by the development of a number of sedimentary basins, some of which continued to evolve during the Cenozoic while others underwent inversion due to Alpine deformation (Ribeiro *et al.*, 1980; Wilson *et al.*, 1989). The Mesozoic-Cenozoic Lusitanian Basin extends for about 250 km north-south in west-central Portugal and 100 km east-west (Figs 1, 2). The Algarve Basin to the south measures about 130 km east-west and 30 km north-south, and the Alentejo Basin in the SW covers a smaller area (20 x 20 km). These three onshore basins represent the proximal elements of a much larger Mesozoic-Cenozoic basin system which extends offshore into the Porto and Galicia Basins to the north, the Gulf of Cadiz Basin to the south and the Peniche Basin to the west (Fig. 1). The Peniche Basin has a more proximal segment, originally named and defined by Alves *et al.* (2006), and a more distal one, extending westwards for several hundred km into the Iberia Abyssal Plain (Wilson *et al.*, 2001; Alves *et al.*, 2006) referred to here as the "distal Peniche Basin" (Figs 1 and 2; *see below and Fig. 12*).

The stratigraphy of the Lusitanian Basin ranges from Upper Triassic to Cenozoic and is up to 5 km thick, most of it Upper Jurassic. Along the eastern margin of the basin, the basin fill is overthrusted by Palaeozoic basement rocks which are exposed in central and eastern Portugal (Fig. 3). The western margin is likewise characterised by a tectonic contact, and the Palaeozoic Berlengas Block (Bb, Figs 1, 2) separates the Lusitanian and Peniche Basins. The NW-SE elongated Berlengas Block measures a few hundred km long by tens of km wide (Alves *et al.*, 2006) and is exposed in islands located about 10 km off the town of Peniche (Fig. 3). The block was the source of sediments transported into the Lusitanian Basin during rifting in the Early Jurassic (Wright and Wilson, 1984), Late Jurassic (Pena dos Reis *et al.*, 2000) and Early Cretaceous (Dinis *et al.*, 2008). Coeval sediment input into the Peniche Basin to the west may also have occurred, although there is no direct evidence for it. The Berlengas Block was covered by

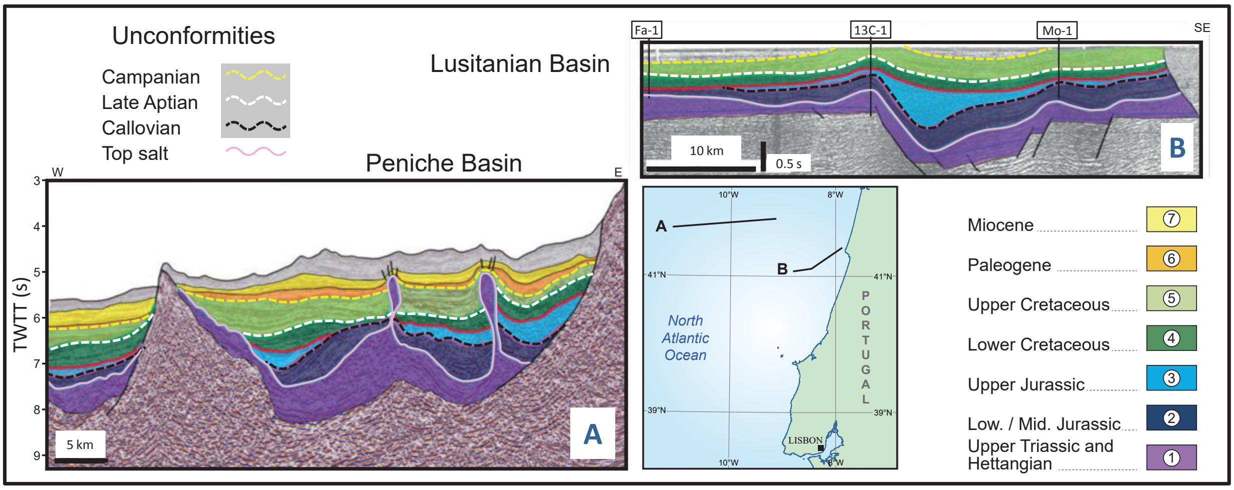

Fig. 5. Interpreted seismic lines from the offshore Lusitanian and Peniche Basins, showing the main unconformities recognized in both basins. (A) Seismic line across the offshore Lusitanian Basin, courtesy of Petrobras (authors' interpretation: the line was also interpreted by Alves *et al.*, 2006). (B) Seismic line S84-23 across the Peniche Basin interpreted by Rasmussen *et al.* (1998). Section profiles are marked on the inset map and Fig. 2. Numbers 1-7 refer to seismic-stratigraphic units discussed in the text.

a Late Cretaceous marine transgression and subsided throughout the Tertiary, allowing an open-marine connection between the Lusitanian and Peniche Basins to become established (Alves *et al.*, 2006).

Interpretations of seismic profiles across the Lusitanian and Peniche Basins (Figs 4, 5) show the presence of similar seismic-stratigraphic surfaces within the Mesozoic succession. Prominent unconformities in both basins are interpreted to correspond to erosional episodes in the Callovian and Late Aptian (Fig. 5) which resulted in the progradation of thick clastic wedges. Also, asymmetric rift-phase infills and overlying sag-phase successions can tentatively be correlated in both basins (Fig. 5).

However, the seismic stratigraphy of the Peniche Basin cannot be directly tied to any wells. The closest well with a well-studied Mesozoic succession (DSDP well Site 398) is located more than 70 km NW of the basin (Fig. 2), at the distal margin, giving a relatively poor stratigraphic control (Réhault and Mauffret, 1979; Groupe Galice, 1979). Therefore, the seismo-stratigraphic interpretation of the Upper Triassic to Upper Cretaceous infill of the Peniche Basin is based on correlations with the Lusitanian Basin (Alves *et al.*, 2006; Sagres, 2013; Cardoso *et al.*, 2014).

STRATIGRAPHY OF THE LUSITANIAN BASIN

As a result of late-stage Alpine inversion and uplift of the Lusitanian Basin, the stratigraphic successions deposited during pre-rift, rift and drift phases can be studied at outcrop and include a variety of lithofacies ranging from continental proximal deposits to distal deep-marine facies. In addition, the structural style and the importance of basement and diapiric structures can readily be investigated in surface exposures.

Palaeozoic basement

The Lusitanian Basin formed as a result of initial extension of Pangean continental crust in Late Triassic times, followed by two phases of rifting in the Jurassic and later seafloor spreading and opening of the North Atlantic in the Early Cretaceous (Wilson, 1988).

The basin is located on Palaeozoic basement which resulted from the amalgamation of various pre-existing terranes (Central Iberian Zone, CIZ; Ossa Morena Zone, OMZ; and Southern Portuguese Zone, SPZ; Figs 1 and 3) (Ribeiro *et al.*, 1979, 1990, 2007; Matte, 1991). Metamorphism and deformation of basement rocks occurred during the Late Palaeozoic Variscan orogeny and resulted in moderate to intense thermal maturation of organic-rich intervals.

In the Central Iberian Zone, the Palaeozoic succession contains a number of fine-grained organic matter-rich units up to several hundred metres thick. Gas shows in pre-salt reservoirs (Upper Triassic) in Central Portugal are considered to have been sourced by Early Palaeozoic black shales (Uphoff, 2005). The Ossa Morena Zone includes organic-rich intervals with good source-rock potential, and outcropping Silurian graptolitic black shales show variable $R_o\%_{eq}$ values ranging from late oil window to gas window, probably controlled by the proximity to major fault zones (Uphoff, 2005; Machado *et al.*, 2011). The Southern Portuguese Zone includes Carboniferous black shales with source-rock potential in the Baixo Alentejo Flysch Group (Oliveira, 1983) (Fig. 6a), with maturities up to the gas window (McCormack *et al.*, 2007; Fernandes *et al.*, 2012; Barberes, 2013) or above.

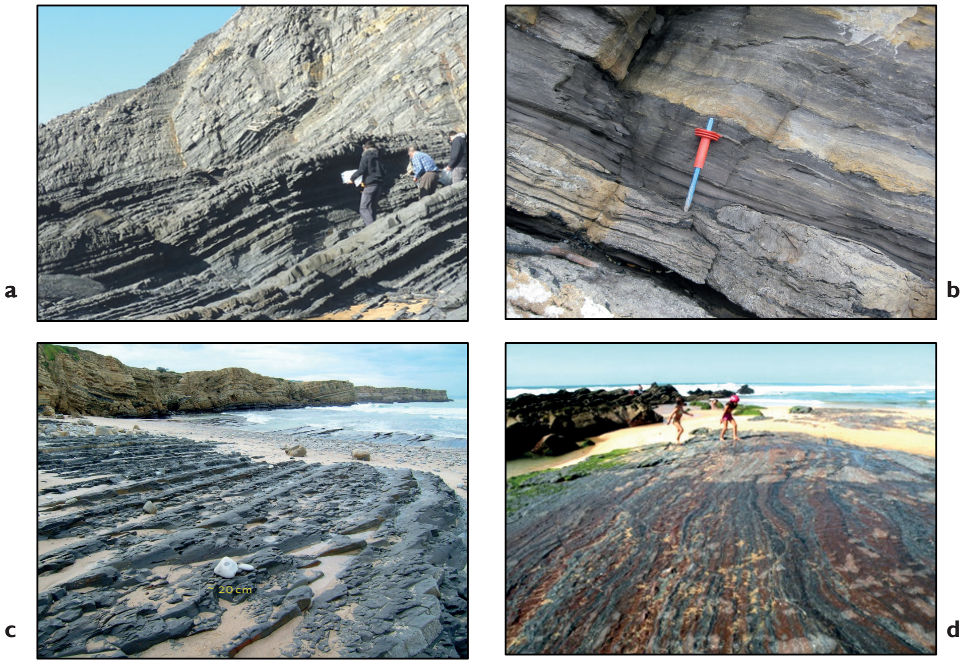

Fig. 6. Field photographs from the Lusitanian Basin. See text for discussion.
(a) Upper Carboniferous organic-rich turbidites in SW Portugal (Amoreira beach at Aljezur, 150 km south of Lisbon); similar lithologies may occur as basement in the Lusitanian and Peniche Basins.
(b) Upper Sinemurian organic-rich thin-bedded black shales and marls in the Água de Madeiros Formation (Polvoeira Member; Duarte and Soares, 2002). Polvoeira, 1.5 km south of São Pedro de Muel (location in Fig. 3).
(c) Lower Pliensbachian deep-marine marls and limestones in the Vale das Fontes Formation (Duarte and Soares, 2002) at Peniche (location in Fig. 3). Organic-rich intervals may have source rock potential with TOCs of up to 15% (Oliveira *et al.*, 2006).
(d) Deformed Hettangian evaporites and clays at the Santa Cruz diapiric structure.

Following the Variscan orogeny (Late Carboniferous – Permian), gradual uplift and erosion brought basement rocks to the surface. Associated brittle deformation referred to as late-Variscan faulting (Ribeiro *et al.*, 1990) resulted in the development of conjugate faults with NNE-SSW sinistral and NNW-SSE dextral orientations (Fig. 1) which controlled patterns of Mesozoic-Cenozoic sedimentation.

Late Triassic to Early Jurassic

Late Triassic to Early Jurassic evolution of the Lusitanian Basin is interpreted to result from intra-continental rifting related to intense crustal stretching (Wilson, 1988; Rasmussen *et al.*, 1998; Kullberg *et al.*, 2012). A series of NNE-SSW trending asymmetric grabens developed in West Iberia in the Late Triassic. They were rapidly filled by alluvial-fan deposits including coarse-grained red beds (Silves Group: Palain, 1975) including two fining-upward megasequences (Fig. 7) with a total thickness of up to 400 m. Upper Triassic red beds have reservoir potential (Uphoff, 2005) and a recent exploration well (Porto Energy/Galp Energia; ALC-1, 10 km SE of Nazaré, Fig. 3) produced non-commercial hydrocarbons from this succession.

The Late Triassic grabens gradually filled as sabkha-like conditions developed in the Hettangian, with the deposition of thick clays and evaporites in internal parts of the basin (Dagorda Formation), while fine-grained sands and dolomites accumulated in peripheral areas (Pereiros Formation) (Soares *et al.*, 1996). The Dagorda Formation evaporites and clays (Fig. 6d) were highly deformed during later tectonic phases and now form diapirs which reach the surface in many parts of the Lusitanian Basin (Figs 3 and 10). A regional structural control may be inferred from the location and geometry of the diapiric structures. Prominent diapirs are located along NNE-SSW faults such as the Lousã-Caldas and Porto de Mos faults (Fig. 3) which are related to Late Variscan fractures in the basement. Diapiric growth is considered to have taken place mainly in the Late Jurassic (Wilson, 1988; Leinfelder and Wilson, 1989). However, local sub-aerial extrusion is documented only since the Late Cretaceous (Pena dos Reis, 2000).

Early and Middle Jurassic

Sinemurian open-marine carbonates (Coimbra Formation: Soares *et al.*, 2007) (Fig. 7), around 200 m thick, contain the first ammonites recorded in the Lusitanian Basin (Soares *et al.*, 1996) and were deposited on a broad ramp which onlapped the basement to the east and deepened to the NW (Duarte *et al.*, 2010; Duarte *et al.*, 2013). Dolomitic limestones (São Miguel Formation) are present in the north and east of the basin, whereas marly limestones are present

Fig. 6. Field photographs from the Lusitanian Basin (*cont.*).
(e) Oxfordian lagoonal carbonates of the Cabaços Formation at Pedrogão (location in Fig. 3). Organic-rich layers may have TOC of 3-5% (Silva *et al.*, 2014); laminated microbial carbonates have good reservoir potential.
(f) Upper Jurassic incised canyon filled with conglomerates (potential reservoir) eroding into Kimmeridgian fine-grained turbidites with source rock potential (Abadia Formation). Santa Cruz beach (location in Fig. 3).
(g) Coarse-grained late Aptian fluvial sandstones (Figueira da Foz Formation) with reservoir potential. Praia d'El Rey, 10 km NE of Peniche.
(h) Seepage oil in Oxfordian carbonates of the Montejunto Formation at the Torres Vedras quarry (location in Fig. 3).
(i) Seepage oil in Cenomanian brecciated carbonates at the Vale Furado beach (location in Fig. 3).

in central and western areas (Água de Madeiros Formation) (Azerêdo *et al.*, 2003), and include thin intervals with high TOC contents (Polvoeira Member: Duarte *et al.*, 2004, 2010, 2012) (Fig. 6b).

In Pliensbachian times, deep-marine marly limestones were deposited on a homoclinal ramp which extended over most of the Lusitanian Basin (Brenha Group; Witt, 1977). Sediments include some 100 m of alternating cm-thick marls and limestones (Vale das Fontes Formation: Rocha *et al.*, 1996; Azerêdo *et al.*, 2003) with source rock potential in OM-rich intervals (Oliveira *et al.*, 2006; Silva *et al.*, 2007: Duarte *et al.*, 2010, 2013; Spigolon *et al.*, 2010, 2011) (Fig. 6c).

During the rest of the Early and Middle Jurassic, open-marine marls were gradually replaced by limestones to both north (Cabo Mondego Formation: Azerêdo *et al.*, 2003) and south (Candeeiros Group: Witt, 1977). Marine regression led to shallower-water sedimentation (Azerêdo *et al.*, 2014), then to sub-aerial emergence and a corresponding depositional hiatus on the eastern margin of the basin in the Callovian (Fig. 7) (Wilson, 1988; Pena dos Reis *et al.*, 2000).

Late Jurassic

Following Callovian regression and a brief phase of emergence, sedimentation resumed in mid-Oxfordian times (Azerêdo *et al.*, 2002) (Fig. 7), but with a re-organization of sedimentation in the basin. Thus the Early to Middle Jurassic carbonate ramps which deepened to the NW were replaced in the Late Jurassic by a NNE-SSW elongated depositional trough which deepened to the SSW. Basal-Oxfordian sediments correspond to laminated marly limestones a few hundred metres thick (Cabaços Formation: Azerêdo *et al.*, 2002) deposited in coastal to transitional environments (Fig. 6e). Organic-rich intervals have good source rock potential (Spigolon *et al.*, 2011; Duarte *et al.*, 2012; Silva *et al.*, 2013). The formation is overlain by a few hundred metres of grey, fully-marine marly limestones (Montejunto Formation; Atrops and Marques, 1988) deposited during a rapid marine transgression.

In the Kimmeridgian, marine carbonate sedimentation was interrupted by the input of coarse basement-derived siliciclastics throughout the basin, including fluvial siliciclastics derived from the north (Boa Viagem Formation), transitional sandy and marly limestones (Alcobaça Formation) and marine turbidite sands and marls in the central southern sectors of the basin (Abadia Formation) (Fig. 6f).

The Abadia Formation is more than 2000 m thick and was deposited with very high sedimentation rates

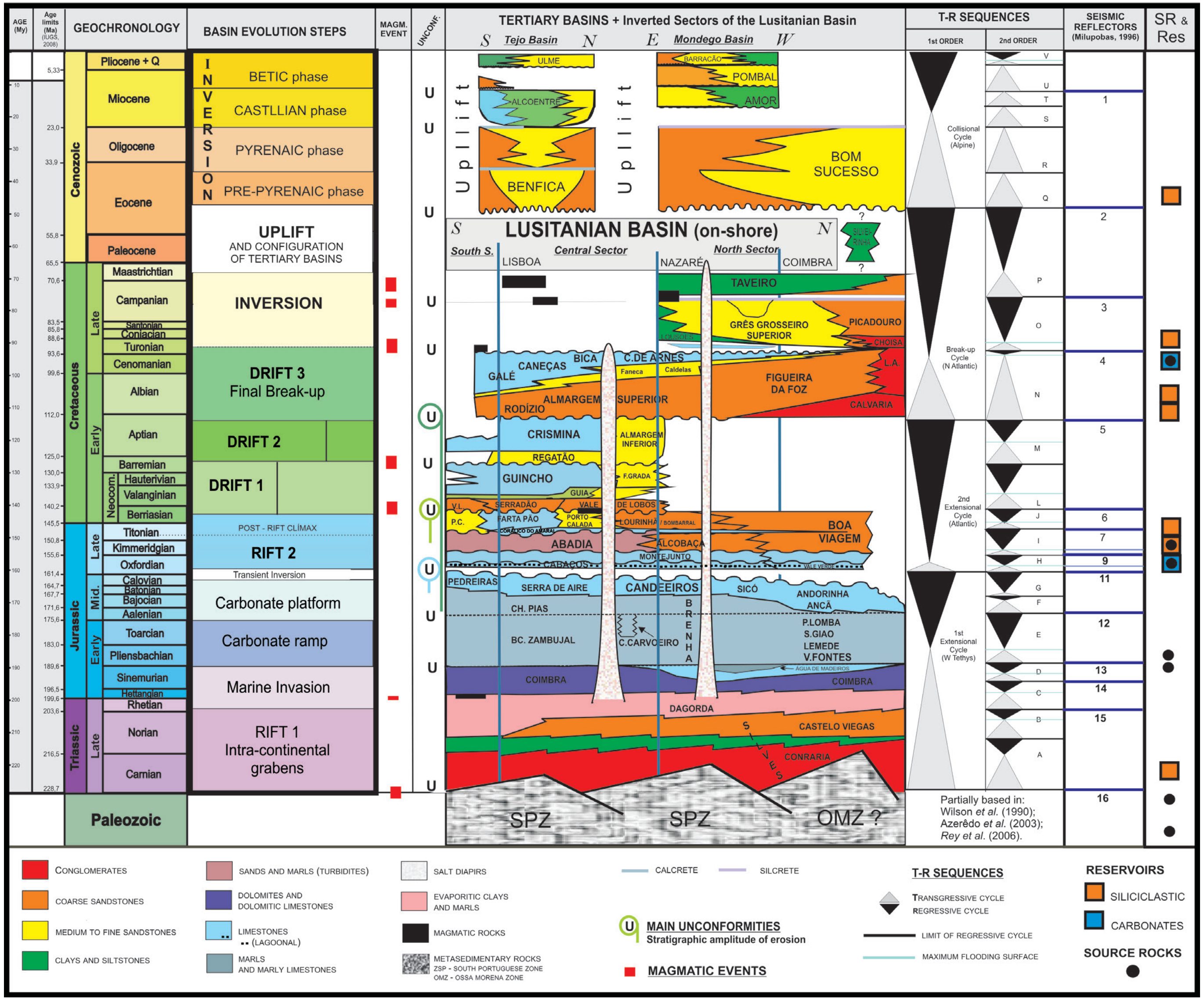

Fig. 7. Lithostratigraphic chart of the Lusitanian Basin including interpreted geodynamic events, cyclicity (T-R sequences, *sensu* Embry and Johannessen, 1992), seismic horizons (Lomholt et *al.*, 1996) and main petroleum systems elements (after Pena dos Reis et *al.*, 2011; partially based on Wilson, 1990; Azerêdo et *al.*, 2003; Rey et *al*,. *2006*).

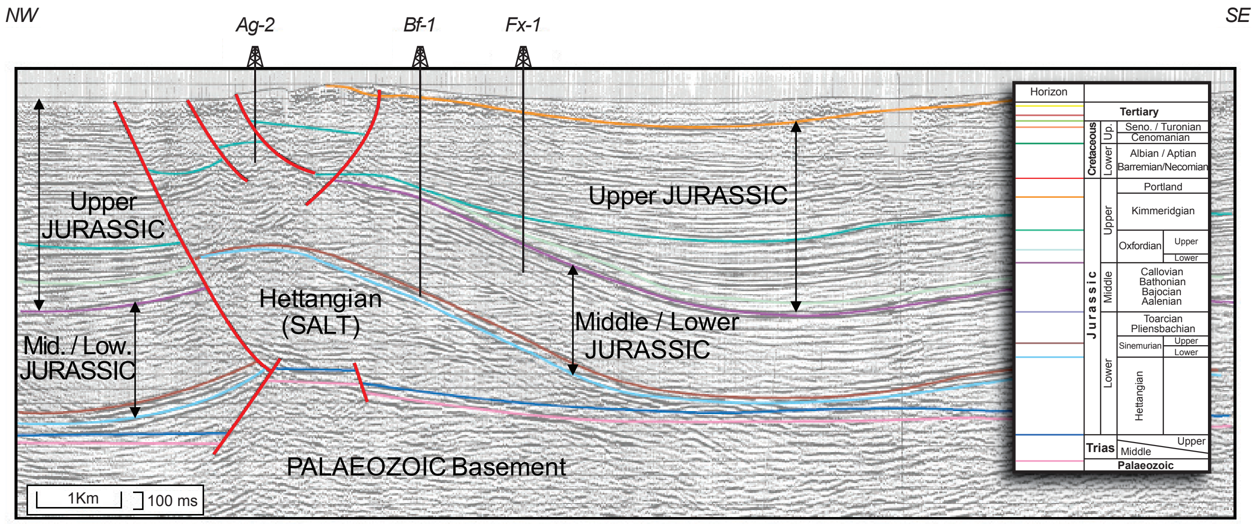

Fig. 8. Interpreted NW-SE seismic line from the central sector of the Lusitanian Basin (line AR9-80; interpretation and numbered horizons adapted from Rasmussen *et al.*, 1998). Profile location in Fig. 2.

(Pena dos Reis *et al.*, 2000), particularly in sub-basins around the Torres Vedras region (Leinfelder and Wilson, 1989) (Fig. 7). This formation has been a target for oil exploration in the Lusitanian Basin throughout the 20th century (UPEP, 2016). It is overlain by the late-rift carbonates of the Amaral Formation, around 100 m thick, which form an important seismic-stratigraphic marker both on- and offshore (Alves *et al.*, 2006) (Fig. 8).

Deposition of prograding continental siliciclastics continued during the Tithonian with the accumulation of almost 1 km of fluvio-deltaic sandstones and clays (Lourinhã Formation: Hill, 1988).

Early Cretaceous

The Cretaceous evolution of the Lusitanian Basin is closely related to the opening of the North Atlantic, which occurred in three stages clearly marked in the stratigraphic record by break-up unconformities (Dinis *et al.*, 2008). Lower Cretaceous sediments are known only from the southern and central parts of the basin, suggesting that the north was uplifted during the corresponding time interval (Fig. 7). The boundary between the sectors is marked by the Lousã-Caldas Fault Zone (Fig. 3) which is considered to represent a major transfer-fault system.

The Early Cretaceous sedimentary succession is composed of fluvial to coastal fine-grained siliciclastics and sandy limestones which can be grouped into two second-order cycles separated by break-up unconformities (Dinis *et al.*, 2008) (Fig. 7) associated with the opening of the Tagus segment of the Iberian-Newfoundland rift, and later with the Iberian segment (Dinis *et al.*, 2008; Alves *et al.*, 2009). An abrupt input of coarse siliciclastics (Figueira da Foz Group) marks an Aptian unconformity which is associated with the final opening of the North Atlantic and with seafloor spreading in the Galicia segment of the margin. The unit is present throughout the basin and is an excellent seismic-stratigraphic marker both on- and offshore (e.g. Alves *et al.*, 2006, 2009).

Late Cretaceous and Tertiary

Late Cretaceous evolution of the Lusitanian Basin corresponds to the development of a passive margin controlled both by uplift of adjoining continental areas and by eustatic sea-level variations. During the Albian and Cenomanian, a marine invasion occurred over most of the basin with the gradual development of a carbonate platform (Cacém Group) which persisted until the Turonian. This carbonate unit is present on both sides of (and may cover) the Palaeozoic Berlengas block, as there are no indications at outcrop of siliciclastics being transported subsequnetly into the Lusitanian Basin.

The passive margin underwent initial inversion in the Late Turonian (Fig. 7) and prograding siliciclastics were deposited in the north of the basin while the south was emergent. A series of magmatic intrusions of this age are known in the Lisbon area including a hypabyssal intrusion (Sintra Massif), dykes (Mafra Complex) and subaerial volcanics (Lisbon Volcanic Complex). This magmatic activity is interpreted to be related to crustal instability associated with the opening of the Bay of Biscay (Martins *et al.*, 2010).

During the Tertiary, the Lusitanian Basin underwent inversion along a NE-SW axis which was the axis of the Late Jurassic depocentre. Tertiary basins developed on either side of this uplifted axis: the Mondego Basin to the NW and the Tejo Basin to the SE (Fig. 3). Tertiary units may provide reservoir rocks and seals for Mesozoic-derived hydrocarbons.

PETROLEUM SYSTEMS OF THE LUSITANIAN BASIN

Source rocks

Potential Palaeozoic source rocks in the Lusitanian Basin include Silurian and Carboniferous units (Uphoff, 2005; Pena dos Reis and Pimentel, 2010a, 2010b). Silurian graptolitic black shales are present in the Ossa Morena Zone of central and northern Portugal (Fig. 3), and have TOC values up to 8% (BEICIP, 1996; Uphoff, 2005). Carboniferous turbidites are present in the Southern Portuguese Zone (Fig. 3) with TOC contents of up to 2% (Fernandes *et al.*, 2012; McCormack *et al.*, 2007; Barberes, 2013).

Lower Jurassic source rocks are composed of open-marine, marly black shales about 100 m thick within which two organic-rich intervals are recognised (e.g. Duarte and Soares, 2002; Duarte *et al.*, 2010, 2012; Silva *et al.*, 2010a, 2010b, 2011). TOC values are variable and kerogen is mainly Type II and III with some Type I (Duarte *et al.*, 2010; 2012; Spigolon *et al*, 2010). Organic contents are highest close to the maximum flooding surfaces of two second-order sequences (Duarte *et al.*, 2010, 2012; Silva *et al.*, 2010b, 2011; Poças Ribeiro *et al.*, 2013).The lower organic-rich unit is the upper Sinemurian to lower Pliensbachian Água de Madeiros Formation, around 40 m thick (Fig. 6b), with TOC values mostly over 5 % and up to 22.5 % (Duarte *et al.*, 2012). The upper organic-rich unit is the Pliensbachian Vale das Fontes Formation (Fig. 6c) whose upper member, around 30 m thick (Duarte *et al.*, 2010), has TOC values up to 15 % (Oliveira *et al.*, 2006). Organic-rich distal facies may occur in the NW of the basin (e.g. Pena dos Reis *et al.*, 2011; Duarte *et al.*, 2012; McWhorter *et al.*, 2014).

The main Upper Jurassic source rock is the mid-Oxfordian Cabaços Formation, composed of marly limestones deposited in lacustrine to lagoonal and coastal settings (Spigolon *et al.*, 2011; Silva *et al.* 2013). The unit is in general around 200 m thick and TOC values range from 2 to 5 % (up to 30%), with a dominance of Type III but also Types I and IV kerogen (Spigolon *et al.*, 2011). The formation rests on a regional Callovian unconformity corresponding to uplift and exposure of parts of the basin, a phase which was followed by gradual marine invasion during the Oxfordian. Organic matter accumulation and preservation took place in restricted settings, in coastal regions with continental input and ephemeral marine incursions (Fig. 6e). Regional variations point to an input of terrestrial higher-plant debris in northern parts of the basin, and to the development of widespread algal mats in the south (Spigolon *et al.*, 2011), but the heterogeneity of the deposits may ultimately suggest a more complex pattern (Silva *et al.*, 2014). Although the organic-richest layers are probably not contemporaneous, depending on local highs and lows which controlled marine incursions, this source rock in general extends throughout the basin (Silva *et al.*, 2014). Other Upper Jurassic source rocks identified in previous studies (BEICIP, 1996) include the Kimmeridgian Abadia Formation fine-grained turbidites which are up to 2 km thick (Pena dos Reis *et al.*, 2000) but have TOC values of ~1 % with mainly Types III-IV kerogen (BEICIP, 1996; Spigolon *et al.*, 2011).

Maturation

Both Lower and Upper Jurassic source rock units in the Lusitanian Basin have reached the hydrocarbon generation window, but maturities are variable as a result of regional variations in subsidence and overburden. These source rocks have been characterized as immature at a number of outcrop locations (e.g. Peniche and east of Torres Vedras; Oliveira *et al.*, 2006; Silva *et al.*, 2010b; Spigolon *et al.*, 2011; Duarte *et al.*, 2012). In nearby wells (e.g. SB-1, Pw-4, Fx-1 and CP-1; see Fig. 3 for locations), the presence of oil shows together with thermal modelling indicate oil-window maturities (Teixeira *et al.*, 2012) (Fig. 9).

In general, vitrinite reflectance data (BEICIP, 1996) and thermal modelling studies (Teixeira *et al.*, 2012) suggest that the Lower Jurassic source rocks are mature for oil in the north of the Lusitanian Basin and mature for gas in the centre; whereas Upper Jurassic source rocks are mostly mature in the centre but not in the north. This difference is due to the influence of the thick, Late Jurassic synrift siliciclastics in depocentres in the central part of the basin (Teixeira *et al.*, 2012). However, the Lower Jurassic source rocks may locally be mature in depocentres to the north, for example around São Pedro de Muel (McWhorter *et al.*, 2014). The Lower Jurassic source rock is modelled to have begun to generate oil around 150-140 Ma (Tithonian to Berriasian), and the Upper Jurassic around 130-120 Ma (Barremian to Aptian) (Teixeira *et al.*, 2012). In both cases, thermal maturation was associated with high rift-related heat flows during the Late Jurassic (Fig. 9).

The Lower and Upper Jurassic source rocks produce geochemically distinct types of hydrocarbons, as indicated by detailed organic geochemical studies including biomarkers and carbon stable isotope ratios (Spigolon *et al.*, 2010; Spigolon *et al.*, 2011). Oils at surface seeps can therefore be related to specific source rocks. Thus, seepage oils in Cretaceous sandstones near the Vale Furado and Caldas da Raínha salt diapirs (Fig. 10) are interpreted to be derived from Lower Jurassic source rocks; whereas the oils occurring in Upper Jurassic limestones and turbidites, such as at Torres Vedras (Fig. 6h) appear to be derived from Upper Jurassic source rocks (Spigolon *et al.*, 2010).

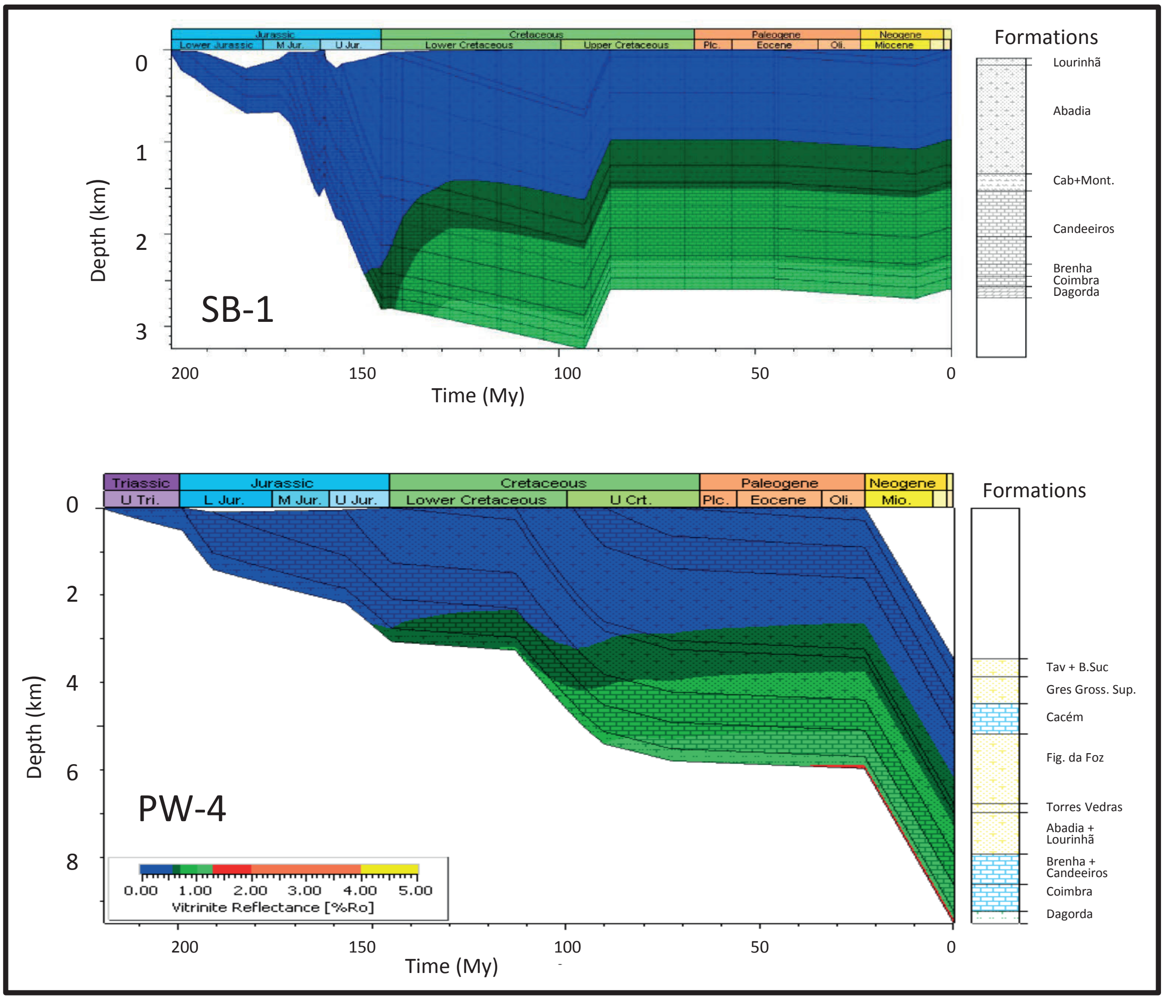

Fig. 9. Thermal and maturation modelling (with PetroMod) of Jurassic source rocks at the onshore well SB-1 and the deep offshore pseudo-well PW-4 (based on Teixeira *et al.*, 2012; Sagres, 2013) (see Fig. 2 and Fig. 12 for locations). Modelling of the SB-1 well shows significant Late Cretacous and Late Miocene upliift (700 m and 200 m, respectively); no uplift due to Alpine inversion was recorded at the PW-4 location.

Reservoir Rocks

Potential reservoir rocks in the Lusitanian Basin include a range of siliciclastic, carbonate and mixed deposits of ages varying from Late Triassic to Late Cetaceous (Pena dos Reis and Pimentel, 2010a, 2010b; UPEP, 2016).

Late Triassic alluvial fan deposits of the Silves Group have intergranular porosity partly filled by calcite cements and clays (Atlantis, 2010). Average porosities are around 16% and may reach 23%, locally with up to 70% saturation by hydrocarbons (Uphoff, 2005).

The Lower Jurassic includes thick dolomitized carbonates which are exposed near the eastern margins of the basin between Coimbra and Tomar (Fig. 3). The Hettangian Dagorda Formation (Fig. 7) includes dolomites with up to 20% primary porosity (Uphoff, 2005). In the Sinemurian Coimbra Formation open-marine carbonates, intercrystalline and vuggy porosity is related to early meteoric diagenesis, but no petrophysical data are available. The limestones and marls of the Early Jurassic Brenha Group have little reservoir potential although some fracture-related porosity may occur.

The Middle Jurassic Candeeiros Formation (Fig. 7) includes shallow-marine carbonates with high energy textures and some reefal build-ups with good reservoir potential (Uphoff *et al.*, 2010). These carbonates have inter-particle and vuggy porosity and may also be fractured.

Porosity in the Upper Jurassic limestones of the Montejunto Formation (Figs 6h, 7) (Uphoff *et al.*, 2010) may be improved by fracturing due to diapir-related deformation. The potential of the formation to serve as a reservoir is enhanced by its stratigraphic and geometric proximity to source rocks in the underlying basal-Oxfordian Cabaços Formation (Spigolon *et al.*, 2010; Pimentel and Pena dos Reis, 2011).

The overlying Oxfordian Abadia Formation includes fine- to coarse-grained turbidite sandstones with reservoir potential in coarser-grained facies (Fig. 6f), although intergranular pores may be occluded by caclcite cements (Garcia *et al.*, 2010). The formation is overlain by a prograding fluvio-deltaic sequence

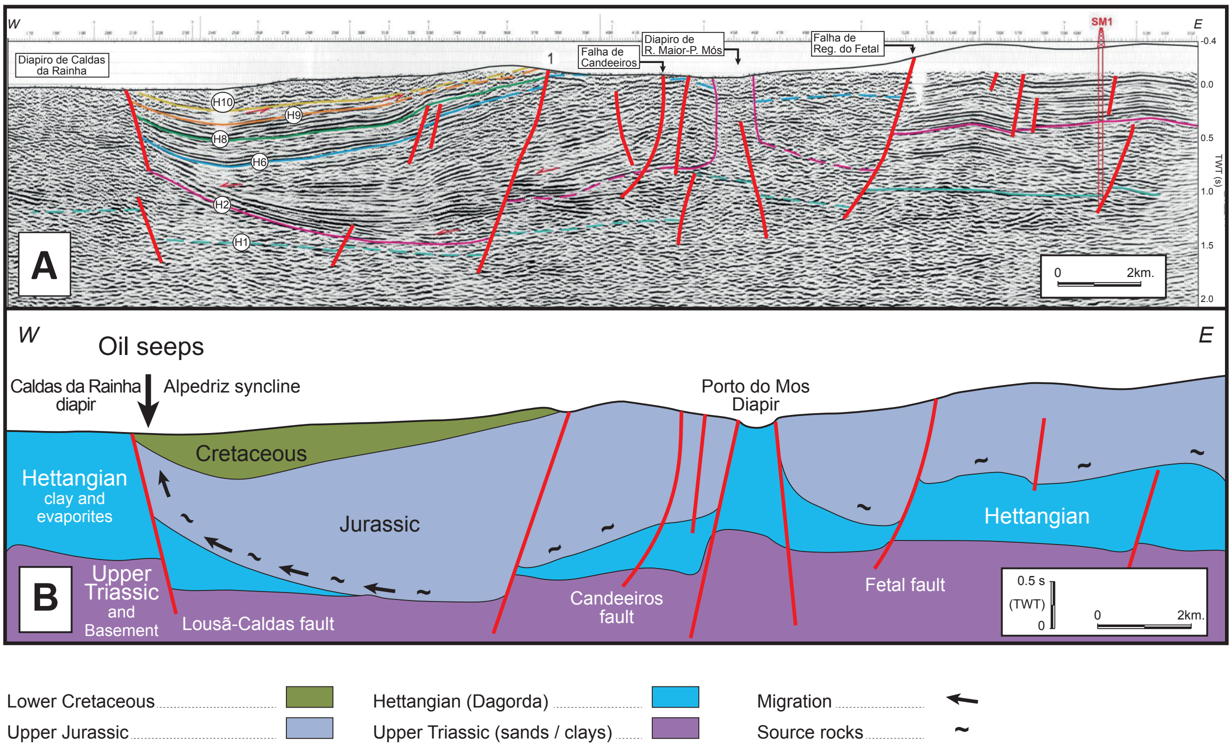

Fig. 10. (A) Interpreted west-east seismic line UTP 81-3, east of Nazaré (see Fig. 3 for location), from Carvalho (2013). (B) Schematic geological section based on line UTP 81-3, showing oil migration from Lower Jurassic source rocks to Lower Cretaceous reservoir rocks along the flanks of a diapir cored by Hettangian evaporites. This geometry is interpreted to occur at the Vale Furado coastal cliff, close to a piercing diapir, where seepage oils occur in Cretaceous sandstones (see Fig. 6i).

(Lourinhã Formation) with inter- and intragranular primary porosity averaging 5% and up to 15% (Garcia *et al.*, 2010; Atlantis, 2010). Between the Abadia Formation turbidites and the Lourinhã Formation, a decametric-thick oolitic carbonate of regional extent (Amaral Formation; Leinfelder and Wilson, 1989) may contain significant depositional porosity although no petrophysical data is available.

Overlying Lower Cretaceous fluvial and transitional to coastal deposits have relatively high compositional and textural maturity. Primary porosity (average about 9 %) is reduced by the presence of infiltrated clays and irregular carbonate cements (Atlantis, 2010). Lower Cretaceous deposits include siliciclastics in proximal areas (Fig. 6g) and sandy to marly limestones in more distal areas. Nearshore high energy or biohermal carbonates may have significant primary porosity (Dinis *et al.*, 2008). Cenomanian shallow-marine and reefal carbonates may also have good reservoir properties (Dinis *et al.*, 2008).

Traps

Potential stratigraphic traps in the Lusitanian Basin include Upper Triassic sandstones overlain and sealed by Hettangian clays and evaporites, which may contain hydrocarbons derived both from Palaeozoic and Jurassic source rocks. Biohermal carbonate build-ups in the Middle Jurassic Montejunto Formation may also form stratigraphic traps for hydrocarbons; an example of such a build-up is recorded at the Pataias cement quarry, 10 km NE of Nazaré. The Upper Jurassic Amaral Formation together with Late Cretaceous (Cenomanian) successions may contain potential stratigraphic traps including oolitic and reefal carbonates, which are sealed by fine-grained siliciclastics. Maastrichtian clays of the Taveiro Formation unconformably cover and seal Late Cretaceous (Turonian-Campanian) sandstones in the Gres Grosseiro Superior Formation (Fig. 7), which may have reservoir potential (Cunha and Pena dos Reis, 1995; Pena dos Reis, 2000).

Structural traps in the Lusitanian Basin developed as a result of Mesozoic rifting and Alpine compression and inversion (Wilson, 1988; Ribeiro *et al.*, 1980). Diapiric structures related to Jurassic extension and subsidence are associated with oil shows (UPEP, 2016) and surface seeps (Spigolon et al, 2010, 2011; Pimentel *et al.*, 2011), such as the Caldas da Rainha diapir, east of Peniche (Fig. 10; location in Fig. 3). Here hydrocarbons may have migrated sub-vertically to the surface along diapir-related faults or along salt walls.

Alpine inversion led to the widespread development of compression features, such as anticlines and thrusts. However, coeval fracturing may have destroyed trap integrity and allowed leakage and loss of reservoired hydrocarbons.

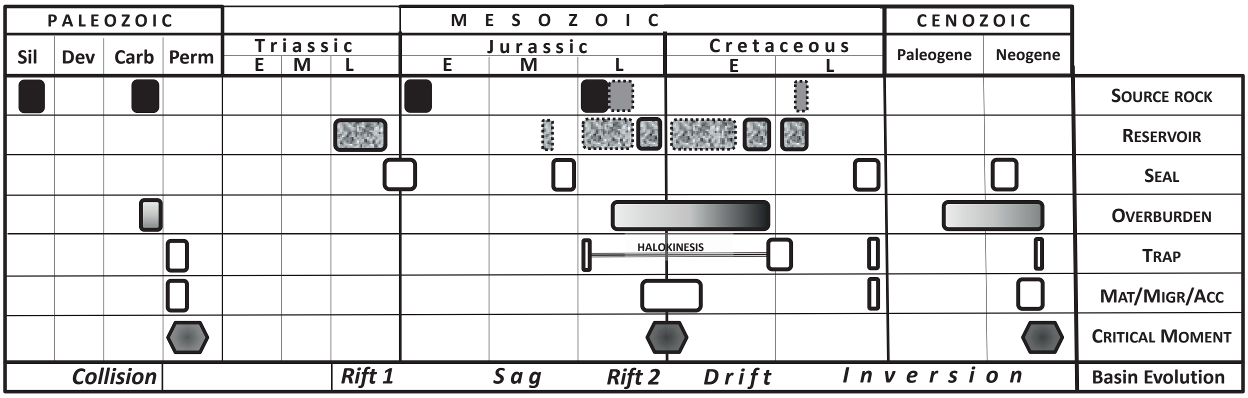

Fig. 11. Petroleum system events chart for the Lusitanian Basin (after Pena dos Reis and Pimentel, 2010b).

Seals

The Hettangian Dagorda Formation is a potential regional seal in the Lusitanian Basin, and comprises claystones with variable contents of gypsum and halite with thicknesses up to several hundreds of metres. Other shale-rich units e.g. in the Upper Jurassic and Lower Cretaceous may also act as seals, although their sealing capacity is reduced due to intercalation with sandstone intervals. Upper Cretaceous and Tertiary shale-rich units may act as important seals particularly in distal (western) parts of the basin. Carbonates in the Lower-Middle Jurassic and Upper Cretaceous successions have seal potential provided they have not been affected by brittle deformation, for example associated with diapiric structures. Clay-rich units which may act as regional seals include the Kimmeridgian Lourinhã Formation, Albian-Cenomanian distal estuarine deposits of the Figueira da Foz Formation, Maastrichtian fluvio-deltaic clays of the Taveiro Formation and Miocene estuarine clays of the Amor / Alcoentre Formations (Fig. 7).

Petroleum systems

Three possible petroleum systems have been identified in the Lusitanian Basin (Pena dos Reis and Pimentel, 2010a, 2010b) (Fig. 11): pre-salt; Lower Jurassic; and Upper Jurassic.

A pre-salt petroleum system may be sourced by Silurian black shales supplying Upper Triassic Silves Group sandstones sealed by Hettangian evaporite-rich shales (Uphoff, 2005). The black shales reached the oil and gas window in the Late Palaeozoic before late-Variscan uplift, but may have preserved some potential for further gas expulsion during Mesozoic reburial (Uphoff, 2005). This play has recently been targeted at the ALC-1 well which recorded non-commercial volumes of gas in Upper Triassic red-beds derived from Palaeozoic source rocks and sealed by Hettangian evaporites and clays. Other Palaeozoic units with source-rock potential include Carboniferous turbidites in the Southern Portuguese Zone (Fernandes *et al.*, 2012; McCormack *et al.*, 2007; Barberes, 2013). The main factor controlling this system seems to be the (over) maturation of the possible Lower and Upper Palaeozoic source rocks. Variable maturities have been reported from outcrops only a few metres apart (Uphoff, 2005; McCormack *et al.*, 2007) due to late-Variscan thrusting which has juxtaposed units from different depths and structural settings.

A second petroleum system is related to Sinemurian and Pliensbachian organic-rich marls in the Água de Madeiros and Vale das Fontes Formations. The marls' geochemical characteristics point to good oil generation potential (Duarte *et al.*, 2010, 2012; Spigolon *et al.*, 2011), and the succession has probably reached the oil window and locally even the gas window (Teixeira *et al.*, 2012; McWhorter *et al.*, 2014). These Lower Jurassic source rocks may have generated hydrocarbons which have migrated laterally and vertically to Jurassic and Cretaceous siliciclastics and carbonates, and also to Upper Triassic siliciclastics (Fig. 10A). Vertical migration has taken place along fault planes and diapir walls, for example at the Vale Furado surface seep (Fig. 10B) (Atlantis, 2010).

A third petroleum system involves oil generation by the transitional to shallow-marine marls of the Callovian Cabaços Formation, which are buried under a thick Oxfordian and Kimmeridgian rift-related siliciclastic succession (Abadia and Lourinhã Formations). Source rocks are modelled to have entered the oil window in the Early Cretaceous (Teixeira *et al.*, 2012). Oil may have migrated over short distances to the overlying Montejunto Formation limestones and the Abadia Formation turbidites (Spigolon *et al.*, 2010; Uphoff *et al.*, 2010; Pena dos Reis and Pimentel, 2011). A seal may be provided by Cretaceous and/or Tertiary clays and siltstones.

A speculative fourth petroleum system is related to the Tertiary cover of the Lusitanian Basin, which may contain various different reservoirs and seals for Mesozoic hydrocarbons. The Tertiary cover in the onshore Lusitanian Basin is relatively thin as a result of basin-scale inversion, with a maximum thickness of 800 m south of Lisbon (Ribeiro *et al.*, 1979).

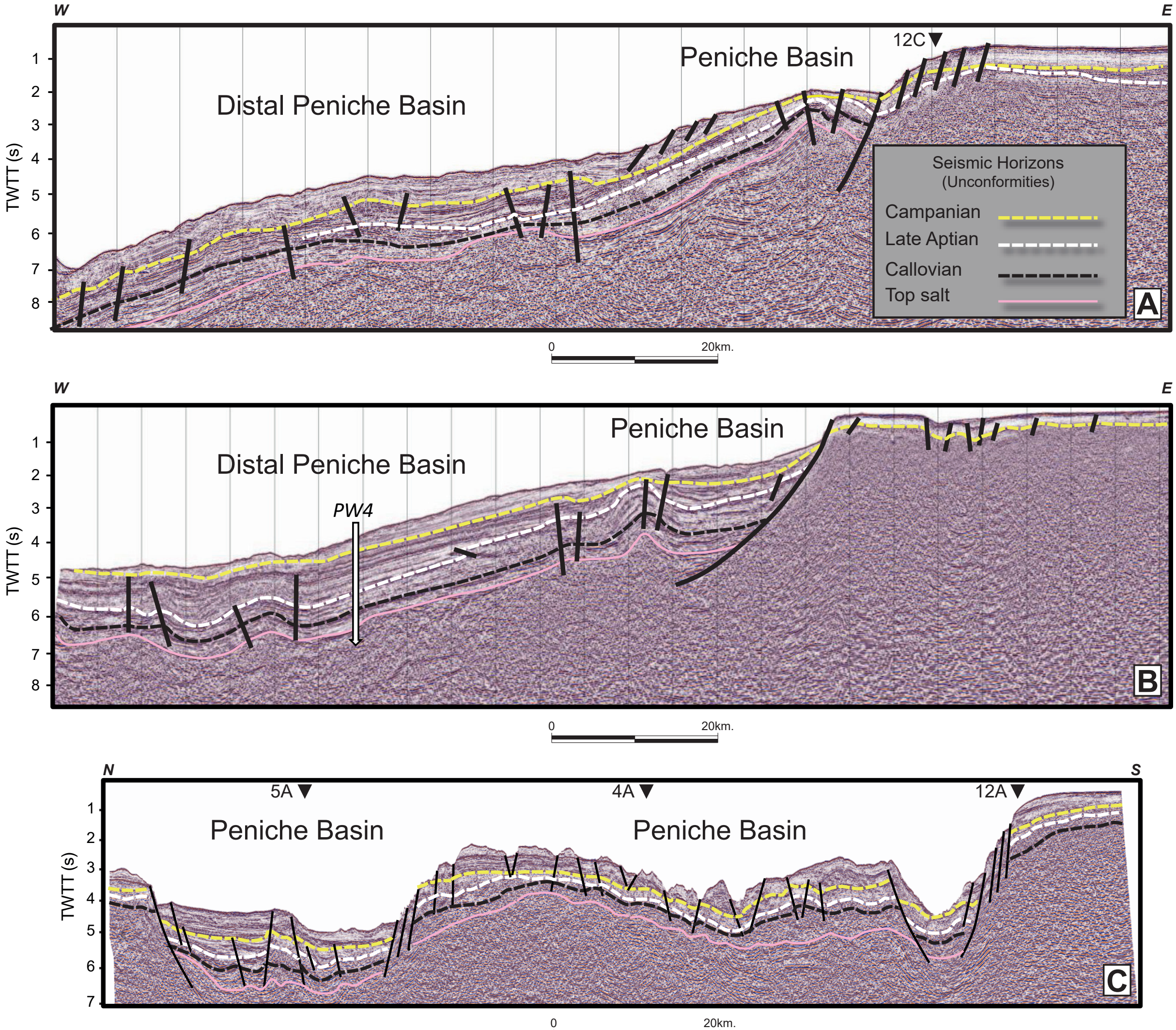

Fig. 12. West-east (a,b) and north-south (c) seismic lines across the Peniche Basin, courtesy of Petrobras (see Fig. 2 for locations), showing the seismo-stratigraphic fill and the main regional unconformities (see also Fig. 5). The line intersections are marked with black arrows.

However, this potential system may be more important in offshore areas, where prograding Tertiary units reach greater thicknesses.

THE PENICHE BASIN

As noted above, understanding of the Peniche Basin is necessarily limited due to a lack of direct data and is therefore restricted to the interpretation of seismic lines. Seven seismic-stratigraphic units have been identified (Alves *et al.*, 2006, 2009) (Fig. 5A) based both on intrinsic characteristics (including reflection patterns and internal surfaces, on- and offlaps) and on correlation with coeval units in onshore seismic lines (Fig. 5B) and with outcrops in the Lusitanian Basin (Sagres, 2013; Cardoso *et al.*, 2014).

An initial rift phase in the Peniche Basin is recognised with rotated fault blocks and an asymmetric siliciclastic infill covered by evaporitic units which form the cores of diapiric structures (Unit 1, Fig. 5A). Top-salt is a clear marker (Figs 5A, 12), and is followed by a sag infill probably corresponding to a Late Triassic to Middle Jurassic sequence up to 4 km thick (Alves *et al.*, 2006) (Unit 2, Fig. 5A) which is overlain by the Callovian unconformity (Fig. 12). This is followed by a section up to 3 km thick probably consisting of Late Jurassic to Early Cretaceous carbonates and siliciclastics (Alves *et al.*, 2006) (Unit 3, Fig. 5A), topped by the Late Aptian unconformity (Fig. 12). The overlying seismic packages up to 3 km thick probably consist of alternating coarse and fine-grained siliciclastics, considered to be related to Lower Cretaceous rift to post-rift successions (Alves *et al.*, 2006) (Unit 4, Fig. 5A), and overlain by a Campanian unconformity (Fig. 12). Overlying units show blanket-like geometries with a thickness of up to 3 km and include deep-water sediments corresponding to the prograding Late Cretaceous drift succession (Unit 5,

Fig. 5A) and Tertiary inversion-related units (Alves *et al.*, 2006) (Units 6 and 7, Fig. 5A).

In this context, potential source rocks, reservoirs and seals are speculative and may only be confirmed by drilling which is expected to take place in the near future.

Basement

The Peniche Basin is located on stretched continental crust on the westernmost sector of the Iberian margin, with significant block rotations and thinning close to the ocean-continent transition (Peron-Pinvidic and Manatschal, 2009). The nature of the Palaeozoic basement here remains uncertain, but probably corresponds to the basement terranes which are known onshore (e.g. Capdevilla and Mougenot, 1988) (Fig. 3). Geodynamic reconstructions based on gravimetric and well data (Pena dos Reis *et al.,* 2012) from the Lusitanian Basin suggest that both Silurian and Carboniferous source rocks may be present at depth in the Peniche Basin, and may be mature for hydrocarbon generation in local kitchens.

In the Lusitanian Basin, late Variscan faults controlled the location and evolution of depocentres (Pena dos Reis *et al.*, 2011), and basement faults may have had a similar influence on potential Mesozoic kitchens in offshore areas. Basement-rooted Mesozoic extensional faults are frequently observed both onshore (Kullberg, 2000) and offshore (Pereira *et al.*, 2012), and are inverted into compressional thrust-faults and folds forming anticlinal traps and seismic-scale closures. However, this tectonism may have generated fractures in potential seals.

Basement structures also controlled the location of diapirs and salt-walls. Onshore in the Lusitanian Basin, diapirs cored by Hettangian evaporites and clays are related to long-lived reactivation of NNE-SSW basement fractures (Rasmussen *et al.*, 1998; Kullberg, 2000). Surface oil shows related to these structures occur at a number of locations (*see above*) and similar diapir-associated traps may also be present in the Peniche Basin.

Source rocks

Two main source rocks have been reported in the Lusitanian Basin: Lower Jurassic marls, and Upper Jurassic marly limestones (*see above*). Cenomanian-Turonian black shales may also have source rock potential.

Palaeogeographic reconstructions of the Lusitanian Basin for the Early Jurassic indicate the presence of an open-marine ramp deepening to the NW (Duarte *et al.*, 2010; Pena dos Reis *et al.*, 2011). The Early Jurassic palaeogeographic configuration of the Peniche Basin is speculative, but symmetrical infill geometries and thickening towards rotated blocks and rift shoulders suggest the possibility of deeper-water conditions towards the east, and the source-rock potential of the Lower Jurassic succession therefore probably increases in this direction.

Palaeogeographic reconstructions for the Late Jurassic (Pena dos Reis *et al.*, 2011) indicate shallow-water coastal and transitional environments in the Lusitanian Basin, in which organic matter accumulation occurred in lagoonal settings (Spigolon *et al.*, 2010). Similar conditions may have occurred in the Peniche Basin with possibly similar source-rock distribution. The main risk in this case would be based on local TOC and thickness variations.

A widespread carbonate platform developed in the Lusitanian Basin during the Cenomanian-Turonian and includes shallow-marine facies including reefs and bioherms (Cacém Group) deepening westwards with a possible connection to the Peniche Basin (Alves e*t al.*, 2006). Open-marine facies may therefore occur in the Peniche Basin including carbonates deposited during the Turonian highstand and anoxic event (cf. Jarvis *et al.*, 2011). Offshore DSDP well 398 (Fig. 2) records the presence of chalks and organic-rich shales which may have some source rock potential (Réhault and Mauffret, 1979). However, seismic data from the Peniche Basin (Alves *et al.*, 2006) and maturation modelling in both the proximal and distal parts of the basin (Sagres, 2013) suggest that this unit has barely reached the early oil window. This is due both to the insufficient post-Turonian overburden which does not exceed 2 km (Alves *et al.*, 2006), and to the low heat-flow values related with the drift phase. Therefore maturation will have been sufficient to generate hydrocarbons only where the source rock is very deeply buried.

Maturation and Migration

In the Lusitanian Basin, preliminary modelling studies show that the Lower Jurassic source rocks are mature for oil in the north of the basin and mature for gas in the centre; and that Upper Jurassic source rocks are mature in the centre (*see above*).

In the Peniche Basin, preliminary modelling studies of 14 pseudo-wells in both the proximal Peniche Basin (*sensu* Alves *et al.*, 2006) and the distal Peniche Basin (as defined in this paper) suggests that Lower Jurassic source rocks are mature for oil generation throughout the basin, and that the Upper Jurassic is mature for oil generation over about one-half of the basin area (Fig. 13) (Sagres, 2013; Cardoso *et al.*, 2014). The potential Lower and Upper Jurassic source rocks probably entered the oil window around 140 Ma (Valanginian) and 100 Ma (Cenomanian), respectively. Considering the modelled maturation ages for the Lusitanian Basin (around 150-140 and 130-120 Ma, respectively), maturation in the Peniche Basin is likely to be more recent (Table 1). This difference in age could be explained by the Early Cretaceous rifting in the Peniche

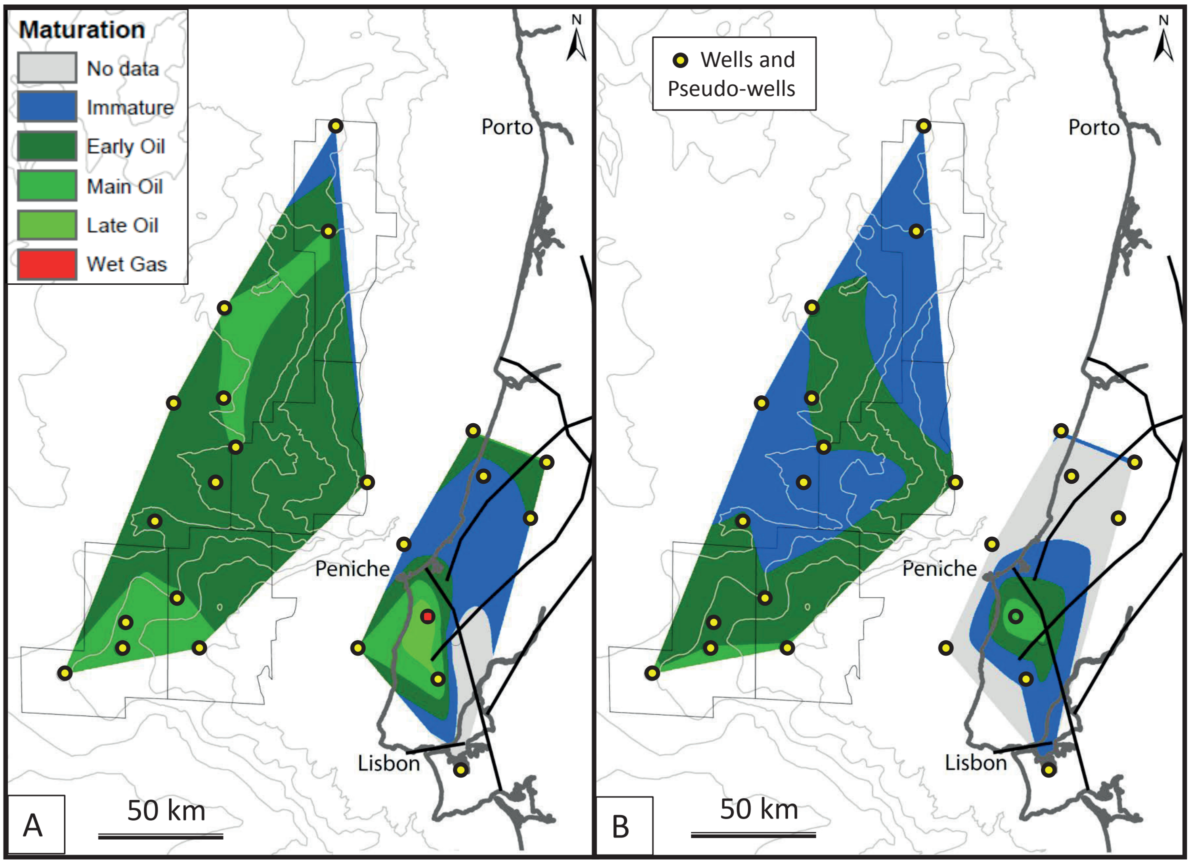

Fig. 13. Present-day maturities of Lower and Upper Jurassic source rocks based on thermal history modelling (with PetroMod) of 14 pseudo-wells in the Peniche Basin and nine wells in the Lusitanian Basin (from Sagres, 2013; and Cardoso *et al.*, 2014). (A) Lower Jurassic source rocks; (B) Upper Jurassic source rocks. The four irregular polygons mark the present-day offshore concession blocks (UPEP, 2016)

Basin (Alves *et al.*, 2006, 2009) which provided the necessary overburden for maturation of the Upper Jurassic source rock.

Tertiary subsidence and siliciclastic input was also important in the Peniche Basin, where sediments are over 2 km thick (Alves *et al.*, 2006) (Fig. 12). Jurassic potential source rocks were already mature by the beginning of the Tertiary. In some areas, the Lower Jurassic source rock may even have reached the gas window during the Neogene (Sagres, 2013; Cardoso *et al.*, 2014).

However the Tertiary overburden seems to have been insufficient for potential Late Cretaceous source rocks to have entered the oil window (Sagres, 2013; Cardoso *et al.*, 2014). As in the Lusitanian Basin (Fig. 10), Lower Jurassic –sourced oil may have migrated into Lower Cretaceous sandstones deformed by diapiric structures. Migration may have begun at the beginning of the Early Cretaceous when diapir development and upward growth was taking place, deforming the Jurassic succession, and probably increased with Late Cretaceous and Cenozoic inversion. Upper Jurassic –sourced oil, generated since the Cenomanian, may likewise charge inversion-related structures. The seal intgergrity of these structures is crucial for trap efficiency in the Peniche Basin.

Reservoir Rocks

Reservoir rocks in the Lusitanian Basin include Upper Triassic red-beds, Lower Jurassic limestones, Upper Jurassic turbidites and Lower Cretaceous sandstones (UPEP, 2016). However the relationship between these units and their offshore equivalents is uncertain. Palaeogeographic connections between the two basins are not well constrained, and the basins were probably separate until the Cenomanian although some by-pass corridors may periodically have been present. After the Cenomanian, inversion probably maintained some uplifted blocks, whereas by-pass corridors in other areas allowed the input of Tertiary siliciclastics.

In the Peniche Basin, uncertainties about Upper Triassic red-beds are related in general to the configuration of the half-grabens and to drainage patterns, as well as to the influence of diagenesis and cementation on porosity and net-to-gross values. Upper Jurassic rift-related siliciclastics are probably not as important a reservoir as in the Lusitanian Basin (Abadia Formation turbidites) because the Late Jurassic was not a synrift phase in the Peniche Basin. However, in the Peniche Basin, Lower Cretaceous synrift turbidites (Réhault and Mauffret, 1979; Alves *et al.*, 2006) may have similar reservoir properties to the synrift Abadia Formation in onshore areas. In

Table 1. Comparison of petroleum systems elements and processes in the Lusitanian and Peniche Basins.

Petroleum System Elements and Processes	PENICHE BASIN	LUSITANIAN BASIN
SEALS	4. Interbedded Tertiary marine clays 3. Upper Cretaceous marine clays 2. Upper Jurassic distal turbidites 1. Hettangian evaporitic clays	3. Upper Cretaceous and Tertiary continental clays 2. Interbedded Lower Cretaceous marls 1. Hettangian evaporitic clays
MAIN RESERVOIRS	4. Tertiary marine siliciclastics 3. Lower Cretaceous syn-rift turbidites? 2. Upper Jurassic proximal turbidites ? 1. Upper Triassic redbeds	3. Lower Cretaceous fluvials 2. Upper Jurassic syn-rift turbidites 1. Upper Triassic redbeds
MIGRATION PATHS	Extensional faults Compressional faults Diapirs and Salt walls	Extensional faults Compressional faults Diapirs and Salt walls
MATURATION	C) Barremian-Aptian (130-120 My) B) Tithonian-Berriasian (150-140 My) A) Late Carboniferous (c. 300 My)	C) Cenomanian (100 My) B) Berriasian (140 My) A) Late Carboniferous (c. 300 My)
SOURCE ROCKS	C) Upper Jurassic: Cabaços equivalent ? B) Lower Jurassic: Vale das Fontes equivalent ? A) Paleozoic: Silurian black-shales (OMZ) and Carboniferous fine turbidites (SPZ)	C) Upper Jurassic: Cabaços Formation B) Lower Jurassic: Vale das Fontes Formation A) Paleozoic: Silurian black-shales (OMZ) and Carboniferous fine turbidites (SPZ)

addition, deep-sea fan geometries with channelized and overbank deposits together with contourites are likely be present and may have good reservoir potential (Alves *et al.*, 2006).

Although Late Cretaceous and Early Tertiary deposits onshore do not act as reservoir rocks due to lack of seal, they may be important reservoir units offshore provided an efficient seal is present (Table 1). Campanian incised channels identified onshore (Pena dos Reis, 2000) suggest the input of sand to the deep offshore where sandbodies may be sealed by Maastrichtian clays.

In terms of carbonate reservoir rocks, the poor quality of Lower and Middle Jurassic limestones, onshore and probably also offshore, make them unlikely to contain Lower Jurassic oil. However, in the Peniche Basin, Upper Jurassic oil accumulations may be present in Montejunto-equivalent limestones which may be fractured due to inversion tectonics. Oil may also be present in porous carbonate bioherms similar to those drilled onshore.

Seals

In the Lusitanian Basin, Hettangian evaporitic marls seal Upper Triassic red beds, Middle Jurassic limestones seal Bathonian carbonates (Uphoff *et al.*, 2010), and Tithonian marls seal Kimmeridgian turbidites (Reis *et al.*, 2000). The same reservoir-seal pairs may occur in the Peniche Basin, although lateral facies variations may introduce differences. In addition, Cretaceous and Tertiary shallow- to deep-marine carbonates and shales may have sealing capacity (Table 1). Effective seals may be provided by paralic to deep-marine Maastrichtian fine-grained sediments, which are observd to overlie salt-related structures in onshore outcrops and which are also recoded in offshore seismic lines.

On the continental shelf, Tertiary deposits may be more than 1 km thick (decreasing northwards) and rest uncomfortably on the eroded Mesozoic succession (Alves *et al.*, 2003). This unconformity is related to Alpine inversion during the Campanian and Paleogene (Cunha and Pena dos Reis, 1995; Dinis *et al.*, 2008; Alves *et al.*, 2003), and is overlain by Neogene sandstones or, further west, by silts and clays with sealing capacity. In deeper-water areas west of the continental slope, thicknesses may be greater (Fig. 12) and facies finer-grained in overbank areas away from slope gullies and fan-lobes (Alves *et al.*, 2003).

However, Alpine inversion may have fractured both Mesozoic and Tertiary seals. The presence of a significant Plio-Quaternary cover, related to extensional collapse of the margin (Alves *et al.*, 2003), may lower but not eliminate this risk. Inversion structures and their geometries are therefore an important control on potential traps and seals in the Peniche Basin.

CONCLUSIONS

The main conclusions from this review of the Lusitanian Basin and the deep offshore Peniche Basin are as follows:

1. A number of plays identified in the Lusitanian Basin may also be valid for the Peniche Basin. These include:

(i) a pre-salt play sourced by Silurian and/or Carboniferous black shales supplying Upper Triassic red beds and sealed by Hettangian evaporites and clays; (ii) a diapir-related play sourced by Lower Jurassic deep-marine shales and marls, supplying Cretaceous fluvial sandstones and sealed by Upper Cretaceous marls; (iii) a turbidite play sourced by Upper Jurassic marls which in the Lusitanian Basin locally supply hydrocarbons to Upper Jurassic turbidite sandstones and fractured limestones; in the Peniche Basin, Upper Jurassic source rocks may supply equivalent rift-related deposits of Early Cretaceous age.

A fourth potential play, absent in onshore areas, may involve Jurassic source rocks supplying Late Cretaceous to Early Tertiary sandstones sealed by Neogene clays.

2. Basement terranes controlled the regional distribution of potential Palaeozoic source rocks and the location of possible pre-salt plays. Basement structures controlled the configuration of uplifted and subsiding blocks, influencing patterns of Mesozoic source- and reservoir-rock distribution and thickness, as well as overburden and thermal maturation heterogeneities.

3. Both Lower and Upper Jurassic source rocks have been identified in the Lusitanian Basin, but their areal distribution further to the west is difficult to predict because palaeogeographic reconstructions are currently incomplete at a regional scale. However, both source rocks may be present throughout most of the Peniche Basin and could be mature for oil generation.

4. Hydrocarbon migration seems mainly to be dependent on faulting, and related both to extension and compression. Considering the modelled late maturation timing (mostly Cretaceous), compressional structures were probably more important in defining migration pathways; many of them may correspond to the re-activation of pre-existing extensional structures.

5. Mesozoic traps are predominantly structural, associated with Late Cretaceous compression; stratigraphic traps are associated with local carbonate build-ups. Offshore, Tertiary stratigraphic traps are related to coarse-grained channel sandstones interfingering within finer-grained overbank deposits. Major unconformities may also act as traps, including those between deformed Mesozoic reservoir units and overlying Tertiary seals.

6. Alpine inversion is important and may explain some of the exploration failures in the Lusitanian Basin. Less significant inversion-related features have been also recognized at the Peniche Basin, resuling in folds and faults which may have had an important impact on seal integrity.

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REFERENCES

ALVES, T. M., GAWTHORPE, R. L., HUNT, D. H. and MONTEIRO, J. H., 2002. Jurassic tectono-sedimentary evolution of the northern Lusitanian basin (offshore Portugal). *Marine and Petroleum Geology* **19**, 727–754.

ALVES, T. M., GAWTHORPE, R.L., HUNT, D. W. and MONTEIRO, J. H., 2003. Cenozoic tectono-sedimentary evolution of the western Iberian margin. In: Kenyon, N.H., Woodside, J., Ivanov, M. and Suzyumov, A. (Eds), Sedimentary Processes and Hydrocarbon seepage on Deep European Continental Margins. *Marine Geology,* **195**, 75-108.

ALVES, T. M., MOITA, C., SANDNES, F., CUNHA, T., MONTEIRO, J. H. and PINHEIRO, L. M., 2006. Mesozoic – Cenozoic evolution of North Atlantic continental-slope basins: the Peniche basin, western Iberian margin. *AAPG Bulletin,* **90** (1), 31–60.

ALVES, T. M., MOITA, C., CUNHA, T., ULLNAESS, M., MYKLEBUST, R., MONTEIRO J.H. and MANUPPELLA, G., 2009. Diachronous evolution of Late Jurassic – Cretaceous continental rifting in the northeast Atlantic (west Iberian margin). *Tectonics*, **28**, TC4003, doi:10.1029/2008TC002337.

ATLANTIS, 2010. Modelo evolutivo para riftes marinhos no Jurássico da Bacia Lusitânica. In: Garcia, A., Pena dos Reis, R. and Pimentel, N. (Coord.), Unpubl. Final Report, PETROBRAS/CENPES/PROFEX, 48 pp, 11 Technical Vols.

ATROPS, F. and MARQUES, B., 1988. Précisions stratigraphiques sur les formation à ammonites du Jurassique supérieur dans le Massif de Montejunto (Nord du Tage, Portugal). In: ROCHA, R.B. and SOARES, A.F. (Eds.), *Proc. 2nd Int. Symp. Jur. Strat.*, Lisboa, **1**, 505-516.

AZERÊDO, A.C., CABRAL, M. C, RAMALHO, M. M., and PEREIRA, R., 2002. Overview of microfossil assemblages and paleoecological signatures in the Middle-Upper Jurassic transitional sucessions from the Lusitanian Basin, Portugal. *Com. Inst.Geol.Mineiro* **89**, 155-178.

AZERÊDO, A.C., DUARTE, L.V., HENRIQUES, M.H. and MANUPPELLA, G., 2003. Da dinâmica continental no Triássico aos mares do Jurássico inferior e médio. *Cad.Geol. Portugal*, Inst.Geol.Mineiro, Lisboa, 43 pp.

AZERÊDO, A.C., DUARTE, L.V. and SILVA, R., 2014. Sequential configuration in transgressive-regressive facies cycles (2nd order) of the Lusitanian Basin (Portugal) Lower and Middle Jurassic. *Comunicações Geológicas* **101**, Especial I, 383-386. LNEG, Lisboa, Portugal.

BARBERES, G., 2013. A utilização da Espectrometria de Raios gama na Exploração de Shale Gas, o Carbonífero da Zona Sul-Portuguesa. MSc Thesis (unpubl.), Coimbra University, 69 pp.

BEICIP-FRANLAB, 1996. Geochemical evaluation of the Lusitanian and Porto Basins. Gab. Pesq. Explor. Petróleo, Lisboa. *Unpubl. Report,* 9 Vols.

CAPDEVILLA, R. and MOUGENOT, D., 1988. Pre-Mesozoic basement of the Western Iberian Continental Margin and its place in the Variscan Belt. In: G. Boillot, E. L.Winterer *et al., Proceedings of the Ocean Drilling Program*, *Scientific Results,* **103**, 3-12.

CARDOSO, F., TEIXEIRA, B., PIMENTEL, N., PENA DOS REIS, R., and CORTESÃO, A., 2014. Evaluation of the thermal maturation of Jurassic potential source-rocks in the Western Iberian Margin, based on modelling of Lusitanian Basin's wells and Peniche Basin's pseudo-wells. *Comunicações Geológicas* **101,** Especial I, 397-400. LNEG, Lisboa.

CARVALHO, J., 2013. Tectónica e caraterização da fracturação do Maciço Calcário Estremenho, Bacia Lusitaniana. Contributo para a prospeção de rochas ornamentais e ordenamento da atividade extrativa. Ph.D Thesis, Lisbon University, 443 pp. http://repositorio.lneg.pt/handle/10400.9/2049

CNSOPB, 2011. Play Fairway Analysis, New Geoscience, New Opportunity. http://energy.novascotia.ca/sites/default/files/files/A01_Executive%20Summary.pdf

CUNHA, P. P. and PENA DOS REIS, R.P., 1995. Cretaceous sedimentary and tectonic evolution of the northern sector of the Lusitanian Basin (Portugal). *Cretaceous Research* **16**, 155-170.

DINIS, J. L., REY, J., CUNHA, P.P., CALLAPEZ, P.M. and PENA DOS REIS, R., 2008. Stratigraphy and allogenic controls on the western Portugal Cretaceous: an updated synthesis. *Cretaceous Research* **29**, 772-780.

DUARTE, L. V. and SOARES, A.F., 2002. Litostratigrafia das séries margo-calcárias do Jurássico Inferior da Bacia Lusitânica (Portugal). *Comun. Instituto Geológico e Mineiro*, **89**, 135–154.

DUARTE, L. V., PERILLI, N., DINO, R., RODRIGUES, R. and PAREDES, R., 2004. Lower to Middle Toarcian from the Coimbra region (Lusitanian Basin, Portugal): sequence stratigraphy, calcareous nannofossils and stable-isotope evolution. *Rivista Italiana Paleont. Strat., Milano*, **110** (1), pp. 115-127.

DUARTE L.V., SILVA R.L., OLIVEIRA L.C.V., COMAS-RENGIFO M.J. and SILVA F., 2010. Organic-rich facies in the Sinemurian and Pliensbachian of the Lusitanian Basin, Portugal: total organic carbon distribution and relation to transgressive-regressive facies cycles. *Geologica Acta* **8**, 325–340.

DUARTE, L.V., SILVA, R.L., MENDONÇA FILHO, J.G., POÇAS RIBEIRO, N. and CHAGAS R.B.A., 2012. High-resolution stratigraphy, palynofacies and source rock potential of the Água de Madeiros Formation (Upper Sinemurian) of the Lusitanian Basin, Portugal. *Journ. Petrol. Geol.* **35**, 105–126.

DUARTE, L.V., SILVA, R.L., MENDONÇA FILHO, J.G., AZER-EDO; A.C., CABRAL, M. C., COMAS-RENGIFO, M.J., CORREIA, G., FERREIRA, R., and LOURWIRO, I., 2013. Advances in the Stratigraphy and Geochemistry of the Organic-Rich Lower Jurassic Series of the Lusitanian Basin (Portugal). In: STRATI 2013, R.Rocha, J.Pais, J.C.Kullberg, S.Finney (Eds). Springer Verlag.

EMBRY, A.F. and JOHANNESSEN, E.P., 1992. T–R Sequence Stratigraphy, facies analysis and reservoir distribution in the uppermost Triassic- Lower Jurassic succession, western Sverdrup basin, Arctic Canada. In: Vorren, T.O., Bergsager, E., Dahl-Stamnes, O.A., Holter, E., Johansen, B., Lie, E., Lund, T.B. (Eds.), Arctic Geology and Petroleum Potential, vol. 2. Norwegian Petroleum Society (NPF), 121–146.

FERNANDES, P., MUSGRAVE, J. A., CLAYTON, G., PEREIRA, Z., OLIVEIRA, J.T., GOODHUE, R. and RODRIGUES. B., 2012. New evidence concerning the thermal history of Devonian and Carboniferous rocks in the South Portuguese Zone. *Journal of the Geological Society, London*, **169**, 647 –654.

FERREIRA, R.F., JÚNIOR, A.R.M. and CALHÔA, A.M., 2011. A Petrobras em Portugal. *Bol. Geociências Petrobras*, **19** (1/2), 9-22.

GARCIA, A. J. V., ARMELENTI, G., PENA DOS REIS, R., PIMENTEL, N. and ROCHA, L. M., 2010. Diagenetic Processes and Porosity Evolution Controls in Upper Jurassic Siliciclastic deposits of the Lusitanian Basin (Portugal). *Ext. Abstracts* II Central & North Atlantic Conjugate Margins Conference, Lisbon, vol. III, 121-124. http://metododirecto.pt/CM2010/index.php/vol/article/view/220/18.

GPEP, 1986. The Petroleum Potential of Portugal. Gabinete para a Pesquisa e Exploração de Petróleo, *Internal Report*, DGGE/DPEP, 62 pp.

GROUPE GALICE, 1979. The continental margin off Galicia and Portugal; acoustical stratigraphy, dredge stratigraphy and structural evolution. *DSDP Preliminary Reports,* **47** (2), 633-662.

JARVIS, I., LIGNUM, J.S., GRÖCKE, D.R., JENKYNS, H.C. and PEARCE, M. A., 2011. Black shale deposition, atmospheric CO_2 drawdown, and cooling during the Cenomanian-Turonian Oceanic Anoxic Event. *Paleo-oceanography*, **26**, PA3201.

KULLBERG, J. C., ROCHA, .B., SOARES, A.F., REY, J., TERRINHA, P., AZERÊDO, A.C., CALLAPEZ, P., DUARTE, L.V., KULLBERG, M.C., MARTINS, L., MIRANDA, R., ALVES, C., MATA, J., MADEIRA, J., MATEUS, O., MOREIRA, M. and NOGUEIRA, C., 2012. A Bacia Lusitaniana: Estratigrafia, Paleogeografia e Tectónica. In: Dias, R., Araújo, A., Terrinha, P. and Kullberg, J. C. (Eds). *Geologia de Portugal*, **II,** 195-347.

LEINFELDER, R.R. and WILSON, R.C.L., 1989. Seismic and sedimentologic features of Oxfordian-Kimmeridgian syn-rift sediments on the eastern margin of the Lusitanian Basin. *Geol. Rundschau* **78** (1), 81-104.

LNEG, 2010. Carta Geológica de Portugal, Escala 1:1.000000. Lab.Nac.Energia e Geologia (LNEG), Lisboa, Portugal.

LOMHOLT, S., RASMUSSEN, E.S., ANDERSEN, C., VEJBÆK, O.V., MADSEN, L. and STEINHARDT, H., 1996. Seismic interpretation and mapping of the Lusitanian Basin, Portugal. *Contribution to MILUPOBAS Project*, EC Contract JOU2-CT94-0348, Geological Survey of Denmark, 70 pp.

MACHADO, G., FRANCÚ, E., VAVRDOVA, M., FLORES, D., FONSECA, P.E., ROCHA, F., GAMA PEREIRA, L., GOMES, A., FONSECA, M. and CHAMINÉ, H., 2011. Stratigraphy, palynology and organic geochemistry of the Devonian-Mississipian metasedimentary Albergaria-a-velha unit (Porto-Tomar shear zone, W Portugal). *Geological Quarterly* **55** (2), 139-164.

MARTINS, L., MIRANDA, R., ALVES, C., MATA, J., MADEIRA, J., MUNHÁ, J., TERRINHA, P., YOUBI, N. and BENSALAH, K., 2010. Mesozoic magmatism at the West Iberian Margins: timing and geochemistry. Abstracts II Conj. Margins Conf., Lisbon, 172-175. http://metododirecto.pt/CM2010/index.php/vol/article/view/138/19

MATTE, P., 1991. Accretionary history and crustal evolution of the Variscan Belt in western Europe. *Tectonophysics*, **196**, 309-339.

McCORMACK, N., CLAYTON, G. and FERNANDES, P., 2007. The thermal history of the Upper Palaeozoic rocks of southern Portugal. *Marine and Petroleum Geology* **24**, 145-150.

McWHORTER, S., TORGUSON, W., and McWHORTER, R., 2014. Characterization of the Lias of the Lusitanian Basin, Portugal, as an Unconventional Resource Play. Ext. Abstract AAPG 2014 ACE, Houston, Texas. Search and Discovery Article #80376.

MOUGENOT, D., 1988. Géologie de la Marge Portugaise. Thèse de Doctorat, Univ. Pierre et Marie Curie, Paris, 155 pp.

OLIVEIRA, J.T., 1983. The marine Carboniferous of South Portugal: a stratigraphic and sedimentological approach. In: Lemos de Sousa, M. J. and Oliveira, J. T. (Eds), The Carboniferous of Portugal. *Mem. Serv. Geol. Portugal* **29**, 3-38.

OLIVEIRA, L.C.V., RODRIGUES, R., DUARTE, L.V. and LEMOS, V., 2006. Avaliação do potencial gerador de petróleo e interpretação paleoambiental com base em biomarcadores e isotopos estáveis do Carbono na seção Pliensbaquiano-Toarciano inferior (Jurássico inferior) da região de Peniche (Bacia Lusitânica, Portugal). *[Evaluation of the petroleum generative potential and paleoenvironmental interpretation based on biomarkers and carbon stable isotopes at the Pliensbachian-Early Toarcian (Early Jurassic) section of Peniche (Lusitanian Basin, Portugal).]Bol. Geociências Petrobras*, **14** (2), 207-234.

PALAIN, C., 1976. Une série détritique terrigène. Les "Grès de Silves": Trias et Lias inférieur du Portugal. *Mem.Serv.Geol. Portugal*, N.S. **25**, 377 pp.

PENA DOS REIS, R., 2000. Depositional systems and sequences in a geological setting displaying variable sedimentary geometries and controls: example of the Late Cretaceous Lusitanian basin (central Portugal). *Comun. Inst. Geol. Min*., **87**, 63-76.

PENA DOS REIS, R. and PIMENTEL, N., 2010a. A evolução da Bacia Lusitânica (Portugal) e dos sistemas petrolíferos associados. VII Congresso Nac. De Geologia, *e-Terra* 19 (4). metododirecto.pt/CNG2010/index.php/vol/article/download/70/345.

PENA DOS REIS, R. and PIMENTEL, N., 2010b. Sistemas petrolíferos no onshore da Bacia Lusitânica, uma visão geológica integradora. In: Noronha, F. and Ribeiro, A., (Eds), *Ciências Geológicas, Ensino, Investigação e sua História*, *Assoc. Port.Geólogos*, **2,** 143-156.

PENA DOS REIS, R. and PIMENTEL, N., 2011. Sedimentation, Source-rocks and Reservoirs in Upper Jurassic sin-rift deposits of the Lusitanian Basin (Portugal). *Abstracts* 28th IAS Meeting of Sedimentology, Zaragoza. http://meg.ipn.pt/wordpress/wp-content/uploads/2013/05/Zaragoza_IAS.pdf

PENA DOS REIS, R., CUNHA, P., DINIS, J. and TRINCÃO, P., 2000. Geological evolution of the Lusitanian Basin (Portugal) during the Late Jurassic. *GeoResearch Forum*, **6**, 345-356.

PENA DOS REIS, R., PIMENTEL, N., and CALHÔA, M., 2012. Influences of the Avalonia-Gondwana collision structures in the evolution of North Atlantic Basins – the example of the West Iberian Basin. *Abstracts* III Atlantic Conj. Margins Conf., Trinity College, 168-169. http://meg.ipn.pt/wordpress/wp-content/uploads/2013/05/BasementPoster.pdf.

PENA DOS REIS, R., PIMENTEL, N.L. and GARCIA, A.J.V., 2011. A Bacia Lusitânica (Portugal): análise estratigráfica e evolução geodinâmica. *[The Lusitanian Basin (Portugal): stratigraphic analysis and geodynamic evolution.] Bol. Geociencias da Petrobras*, **19** (1/2), 23-52.

PEREIRA, R., ALVES. T. M. and CARTWRIGHT, J., 2012. Post-rift compression on the SW Iberian margin (eastern North Atlantic): a case for prolonged inversion in the ocean–continent transition zone. *Journal of the Geological Society, London*, **168**, 1249–1263.

PEREIRA, R., SILVA, C., MACIEL, C. and LEONARDO, P. 2011. Exploration insights of the deep offshore West Iberian Margin in the context of the central and North Atlantic rifting. *Abstracts* 2nd AAPG-MAPG Conference, Marrakesh, AAPG Search&Discovery Article #90137.

PERON-PINVIDIC, G. and MANATSCHAL, G., 2009. The final rifting evolution at deep magma-poor passive margins from Iberia-Newfoundland: A new point of view. *International Journal of Earth Sciences*, **98**(7), 1581-1597.

PIMENTEL, N. L., PENA DOS REIS, R. and BUENO, G.V., 2011. Guia de Campo da Bacia Lusitânica, Portugal. [*Field trip guide of the Lusitânica Basin, Portugal.] Bol. Geociencias Petrobras* **19**(1), 251-275.

PINHEIRO L.M., WILSON R.C.L., PENA DOS REIS R., WHITMARSH R.B. and RIBEIRO A., 1996. The Western Iberia Margin: a geophysical and geological overview. In: Whitmarsh, R.B., Sawyer, D.S., Klaus, A. and Masson, D., (Eds), *Proceedings of the Ocean Drilling Program*, *Scientific Results* **149**, 3–23.

POÇAS RIBEIRO, N., MENDONÇA FILHO, J.G., DUARTE, L.V. SILVA, R.L., MENDONÇA, J.O. and SILVA, T.F., 2013. Palynofacies and organic geochemistry of the Sinemurian carbonate deposits in the western Lusitanian Basin (Portugal): Coimbra and Água de Madeiros formations. *International Journal of Coal Geology* **111**, 37-54.

RASMUSSEN, E.S., LOMHOLT, S., ANDERSEN, C and VEJBAEK, O.V., 1998. Aspects of the structural evolution of the Lusitanian basin in Portugal and the shelf and slope area offshore Portugal. *Tectonophysics* **300** (1-4), 199-255.

RÉHAULT, J.P. and MAUFFRET, A. 1979. Relations between tectonics and sedimentation around the northwestern Iberian margin. In: *Initial Reports of the DSDP*, **47** (2), 663-681.

RIBEIRO, A. ANTUNES, M.T., FERREIRA, M.P., ROCHA, R.B., SOARES, A.F., ZBYZSEWSLY, G., MOITINHIO DE ALMEIDA, F., CARVALHO, D. and MONTEIRO, J.H., 1979. Introduction a la géologie génerale du Portugal. Serv.Geol. Portugal, Lisboa, 114 pp.

RIBEIRO, A., KULLBERG, M.C.., KULLBERG, J.C., MANUPPELLA, G. and PHIPPS, S., 1980. A review of Alpine tectonics in Portugal: foreland detachment in basement and cover rocks. *Tectonophysics* **184**, 357-366.

RIBEIRO, A., MUNHÁ, J.M., DIAS, R., MATEUS, A., PEREIRA, E., RIBEIRO, M.L., FONSECA, P., ARAÚJO, A, OLIVEIRA, J.T., ROMÃO, J., CHAMINÉ, H., COKE, C. and PEDRO, J.C., 2007. Geodynamic Evolution of the SW Europe Variscides. *Tectonics*, **26**, Art. TC6009.

RIBEIRO, A., QUESADA, C. and DALLMEYER, R., 1990. Geodynamic Evolution of the Iberian Massif. In: Dallmeyer, R. D. and Martinez-Garcia, E. (Eds), Pre-Mesozoic Geology of Iberia, Springer-Verlag, 397-410.

ROCHA, R.B., MARQUES, B.L., KULLBERG, J.C., CAETANO, P.C., LOPES, C., SOARES, A.F., DUARTE, L.V., MARQUES, J.F. and GOMES, C.R., 1996. The 1st and 2nd rifting phases of the Lusitanian Basin: stratigraphy, sequence analysis and sedimentary evolution. *Milupobas Final Report*, 4 vols., Lisboa.

SAGRES, 2013. Registo Tectono-sedimentar e Evolução Geodinâmica da Bacia Lusitânica e da Margem Oeste Ibérica. In: Pena dos Reis, R. and Pimentel, N. (Coord.), *Final Report* (unpublished), Petrobras/CENPES.

SANTOS, O.F, RUSSO, J., MENDES, M., PIMENTEL, N. and PENA DOS REIS, R., 2010. Modelling of Cretaceous uplift and erosion events in the Lusitanian Basin (Portugal*). Ext.Abstr.* II Central & North Atlantic Conjugate Margins Conference, Lisbon, III, 249-252. http://metododirecto.pt/CM2010/index.php/vol/article/view/231/25

SILVA, F., DUARTE, L.V., OLIVEIRA, L.C., RODRIGUES, R. AND COMAS-RENGIFO, M.J., 2010a. Contribution to the knowledge of petroleum generative potential of Late Sinemurian – Pliensbachian of the Lusitanian basin - northern sector (Portugal). In: Pena dos Reis, R. and PimenteL, N. (Eds), *Extended Abstracts* II Central & North Atlantic Conjugate Margins Confer., III, 256–260.http://metododirecto.pt/CM2010/index.php/vol/article/view/173/26

SILVA, R.L., MENDONÇA FILHO, J.G., DUARTE, L.V., COMAS-RENGIFO, M.J., AZERÊDO, A.C. and FERREIRA, R., 2010b. Organic-rich facies of the top Ibex–Margaritatus zones (Pliensbachian) of the Lusitanian Basin (Portugal):TOC and biomarkers variation. *Geochimica et Cosmochimica Acta*, **74** (12-S1), A962.

SILVA, R.L., DUARTE, L.V., COMAS-RENGIFO, M.J., MENDONÇA-FILHO, J.G. and AZERÊDO, A.C., 2011. Update of the carbon and oxygen isotopic records of the Early–Late Pliensbachian (Early Jurassic, c.187 Ma): insights from the organic-rich hemipelagic series of the Lusitanian Basin (Portugal). *Chemical Geology* **283**, 177–184.

SILVA, R.L., MENDONÇA FILHO, J.G, AZERÊDO, A.C. and DUARTE, L.V., 2014. Palynofacies and TOC analysis of marine and non-marine sediments across the Middle–Upper

Jurassic boundary in the central-northern Lusitanian Basin (Portugal). *Facies,* **60** (1), 255-276.

SOARES, A.F., MARQUES, J.J. and SEQUEIRA, A.D., 2007. Notícia Explicativa da Carta Geológica de Portugal, Escala 1:50.000, Folha 19-D (Coimbra), INETI, 71 pp.

SPIGOLON, A.L.D., BUENO, G.V., PENA DOS REIS, R., PIMENTEL, N.L. and MATOS, V., 2010. The Upper Jurassic Petroleum System: evidence of secondary migration in carbonate fractures of Cabaços Formation, Lusitanian Basin (Portugal). *Ext. Abstr.* II Central & North Atlantic Conjugate Margins Conference, Lisbon, vol. III, 274-278. http://metododirecto.pt/CM2010/index.php/vol/article/view/181/29

SPIGOLON, A.L.D, PENA DOS REIS, R., PIMENTEL, N. and MATOS, V., 2011. Geoquímica organica de rochas potencialmente geradoras de petróleo no contexto evolutivo da Bacia Lusitânica. *[Organic geochemistry of petroleum source rock potential in the evolutionary context of the Lusitanian Basin, Portugal.] Bol. Geociências da Petrobras*, **19** (1/2), 131-162.

STAPEL, G., CLOETINGH, S. and PRONK, B., 1996. Quantitative subsidence analysis of the Mesozoic evolution of the Lusitanian Basin (Western Iberia Margin). *Tectonophysics*, **266**, 493-507.

TEIXEIRA, B.A., PIMENTEL, N. and PENA DOS REIS, R., 2012. Regional variations in Source Rock maturation in the Lusitanian Basin (Portugal) – the role of rift events, subsidence, sedimentation rate, uplift and erosion. *Abstracts* III Atlantic Conjugate Margins Conf., 91-92. *http://meg.ipn.pt/wordpress/wp-content/uploads/2013/05/SRMaturationAbstract1.pdf*

UPEP, 2016. Exploration and Production of Petroleum Resources. http://www.enmc.pt/en-gb/activities/exploration-and-production-of-petroleum-resources.

UPHOFF, T. L., 2005. Subsalt (pre-Jurassic) exploration play in the northern Lusitanian basin of Portugal. *AAPG Bulletin,* **89** (6), 699-714.

UPPHOFF, T. L., ALLEN, G., STEARNS, M. and MONTELEONE, P., 1997. Exploratory well to start in Lusitanian basin, Portugal. *Oil & Gas Journal*, **95**, 49.

UPHOFF, T. L., STEMLER, D.P. and McWHORTER, R.J., 2010. Jurassic reef exploration play in the southern Lusitanian Basin, Portugal. Ext. Abstr. II Central & North Atlantic Conjugate Margins Conference, Lisbon, vol. III, 284-288. http://metododirecto.pt/CM2010/index.php/vol/article/view/129/30

WILSON, R.C.L., 1988. Mesozoic development of the Lusitanian Basin, Portugal. *Rev. Soc. Geol. España,* **1** (3-4), 393-407.

WILSON, R.C.L., HISCOTT, R. N., WILLIS, M. G. and GRADSTEIN, F. M., 1989. The Lusitanian basin of West-Central Portugal: Mesozoic and Tertiary tectonic, stratigraphy and subsidence history. In: Tankard, A.J and Balkwill, H. R, (Eds), Extensional tectonics and Stratigraphy of the North Atlantic Margins. *AAPG Memoir*, **46**, 341-361.

WITT, W.G., 1977. Stratigraphy of the Lusitanian Basin. Shell Prospex Portuguesa. Unpubl.Report, 61 pp.

WRIGHT, V.P. and WILSON, R.C.L., 1984. A carbonate submarine-fan sequence from the Jurassic of Portugal. *Journ. Sedim. Petrol.*, **54**, 394-412.