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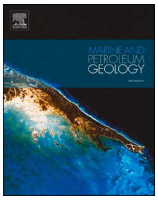

Research paper

Significance of Upper Triassic to Lower Jurassic salt in the identification of palaeo-seaways in the North Atlantic

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ABSTRACT

This work uses high-quality reprocessed 2D data, tied to borehole information, to address the development of North Atlantic Jurassic seaways on the continental margin of West Iberia. The seismic data reveal the full thickness of Mesozoic syn-rift strata filling deep-offshore basins in this latter region. Tectonic subsidence resulted in the separation of the seaway into distal and proximal sectors. As a result, backstripped curves for West Iberia document important tectonic subsidence during the Late Triassic-earliest Jurassic. The Lusitanian and Peniche basins were part of the same seaway during the early stages of rifting, with important rift-shoulder exhumation occurring between the seaway and the distal margin from Late Jurassic onwards. We estimate 5 km subsidence in the deep-offshore Peniche Basin during the Late Triassic-Early Jurassic when compared to the ~1.1 km recorded in the proximal Lusitanian Basin. Critically, borehole stratigraphy shows that early Mesozoic basins in West Iberia, Newfoundland, and the North Sea show a tripartite depositional evolution of stacked continental, evaporitic, and marine strata. The similar Early Triassic-Jurassic seismic and stratigraphic records of the Lusitanian and Peniche basins suggest a co-genetic evolution with other early Mesozoic basins along the North Atlantic margin.

Credit author statement

Walker Olivia A, Paper Writing, Seismic Interpretation, Modelling. Tiago. M. Alves, Paper Writing, Supervision, Methodology, Editing. Stephen P. Hesselbo, Editing. Tim Pharaoh, Funding acquisition, Editing. M. Nuzzo, Editing, Supervision. Nathalia H. Mattos, Editing.

1. Introduction

Extensive seaways can form during continental rifting, providing a marine passage between two pre-existing oceans (Korte et al., 2015). They also establish conduits of marine heat along newly developed continental margins, influencing regional climate, and are repeatedly documented in the geological record (Berggren, 1982; Lear et al., 2003; Smith and Pickering, 2003; Sijp et al., 2014). As one of the examples best documented in the literature, the Equatorial Atlantic Gateway developed first in the late Early Cretaceous to form a connection between the Central and South domains of the Atlantic Ocean (Bengtson et al., 2007). The Hispanic Corridor is another such seaway developed in the Early Jurassic, and provided a connection between the Palaeo-Pacific and the western Tethys Ocean. This corridor was likely established between North America, South America and Africa as early as the Hettangian based on the analysis of mixed bivalve fossil populations occurring in these three continents (Sha, 2002). It is one of the few Jurassic seaways described in the literature that is clearly associated with the breakup of the supercontinent Pangea. Younger seaways include: 1) the Red Sea, which has provided a connection between the Indian and the Atlantic Ocean via the Mediterranean Sea since the Late Paleogene (Gerges, 2002), and 2) the Arctic Gateway, which forms a connection between the Pacific and the Arctic Ocean since, at least, the Late Miocene (Marincovich and Gladenkov, 1999; Woodgate and Aagaard, 2005).

During the Early Jurassic, Northwest Europe and the North Atlantic as a whole recorded the development of a series of ocean seaways between the Western Tethyan realm in the south and the Boreal realm in

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the north (Ziegler, 1975). The Laurasian Seaway is the collective term to describe the interconnected seaways and straits that existed in the North Sea and North Atlantic area during the Early Jurassic (Bjerrum et al., 2001). The same system is alternatively referred to as the European Epicontinental Seaway in some publications (e.g. Harazim et al., 2013). The Viking Corridor, one marine connection identified largely from palaeobiogeographic research, was established in the Early Jurassic between Greenland, Norway, and the Northern part of the North Sea (Callomon, 2003; Korte et al., 2015). It provided the final connection to the Arctic domain from a northwards propagating rift system, with marine water spilling in from the Faroe-Shetland, Møre, and Vøring basins (Doré, 1991; Brikiatis, 2016). However, further south into what are now Iberia and the Bay of Biscay, relatively little is known about the palaeogeographic and palaeobathymetric history of the Laurasian Seaway.

The improved resolution of reprocessed 2D seismic data provided by TGS allowed us, for the first time, to interpret the base of uppermost Triassic – lowest Jurassic salt units in West Iberia to reveal a large offshore salt unit (Fig. 1). Detailed interpretation of syn-rift strata and tectonic subsidence curves for the Lusitanian, Porto and Peniche basins, is therefore used in this work to understand the palaeo-position and width of this latest Triassic-Early Jurassic seaway (Fig. 1a and b). In summary, this paper aims to address the following research questions:

1) What was the geometry and subsidence history of early rift basins in a segment of the North Atlantic as revealed by borehole and seismic-stratigraphic data?
2) What is the extent and the geometry of the south Laurasian Seaway offshore West Iberia?
3) Is there a common stacking pattern for the sedimentary deposits in the seaway, and is this similar to other seaways in Northwest Europe?

It is important to stress that the earliest Jurassic evaporite successions in West Iberia relate to an episode of crustal stretching during continental rifting. *Syn-stretching* salt is one division of the classification of passive margin salt basins defined by Rowan (2014); this salt is commonly deposited during active continental rifting. Early deposition of this type means that the salt deposit is restricted to proximal portions of the conjugate margin pair (Rowan, 2014). *Syn-stretching* salt is deposited directly over active half-grabens to mark the first incursion of marine water into the basins.

2. Data and methods

The interpreted seismic survey covers an area of 30,158 km^2 over the West Iberian Margin (Fig. 1b). This dataset comprises 2D lines acquired by TGS in 1998, later reprocessed in TWTT to image the full extent of syn-rift basins offshore West Iberia. The interpreted seismic grid includes 2D multichannel two-way time domain data, acquired using 6000 m long streamers to a total of 66 navigation lines. The seismic data are stacked at a 4 ms sampling rate and displayed in zero-phase European SEG convention such that an increase in acoustic impedance with depth results in a red reflectivity peak, while a negative trough will be displayed in black. In this work, interpretation was completed to 9.0 s TWTT, compared to the ~7.0 s TWTT of older data (Figs. 2 and 3) using Schlumberger's Petrel®. The new 2D data were also tied to exploration wells and DSDP/ODP data on Schlumberger's Petrel®.

Schlumberger's PetroMod® was used in this study to compute tectonic subsidence using 1-D Airy backstripping techniques (Watts and Ryan; Steckler and Watts, 1978). The software was used to investigate and contrast the burial history of strata in proximal and distal basins, and to generate subsidence curves to determine the timing of critical events. We analysed backstripping results for three (3) industry wells on the continental shelf and upper continental slope and built three (3) pseudo-wells in the continental slope basins (Fig. 1b). Well and pseudo-well locations along the West Iberian margin were selected based on their relative location on the margin and the reliability of seismic-

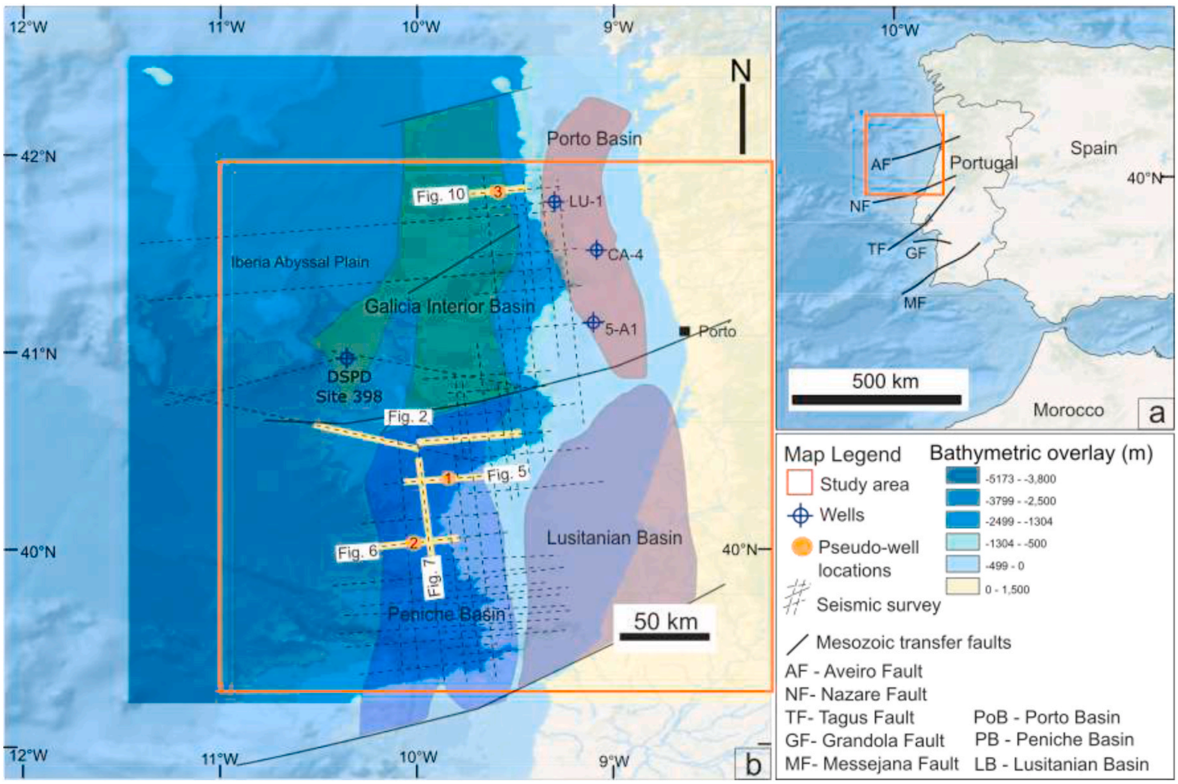

Fig. 1. a) Map of West Iberian margin showing its geographical location, major transfer faults, and the study area in this work, b) Bathymetric map of study area depicting the interpreted seismic grid with location of offshore industry and DSDP wells (Esri GEBCO, 2019).

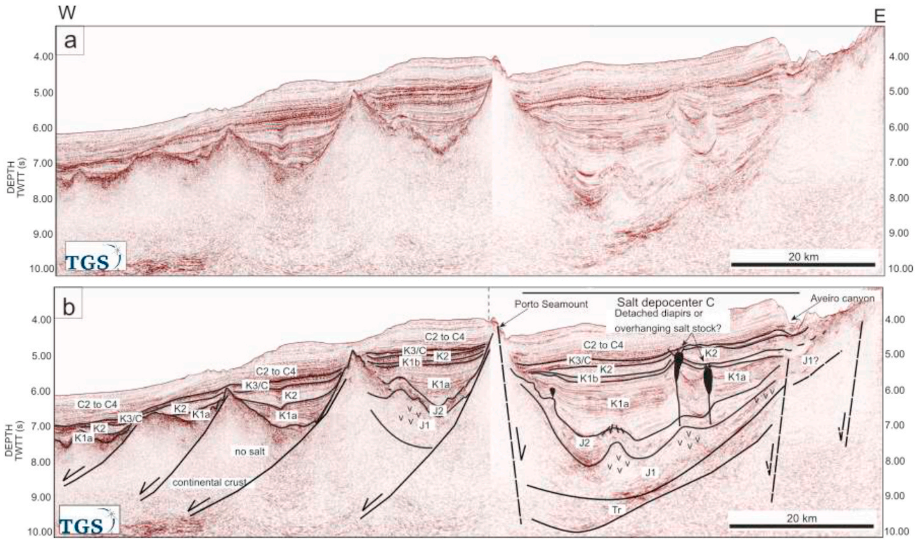

Fig. 2. Interpreted seismic profile of composite line (location shown above). Note structure of Peniche Basin and adjacent deep margin area. Upper Cretaceous Unit K1 is widespread along the margin. Note the disappearance of salt west into the deep margin area. TWTT = Two-way travel time.

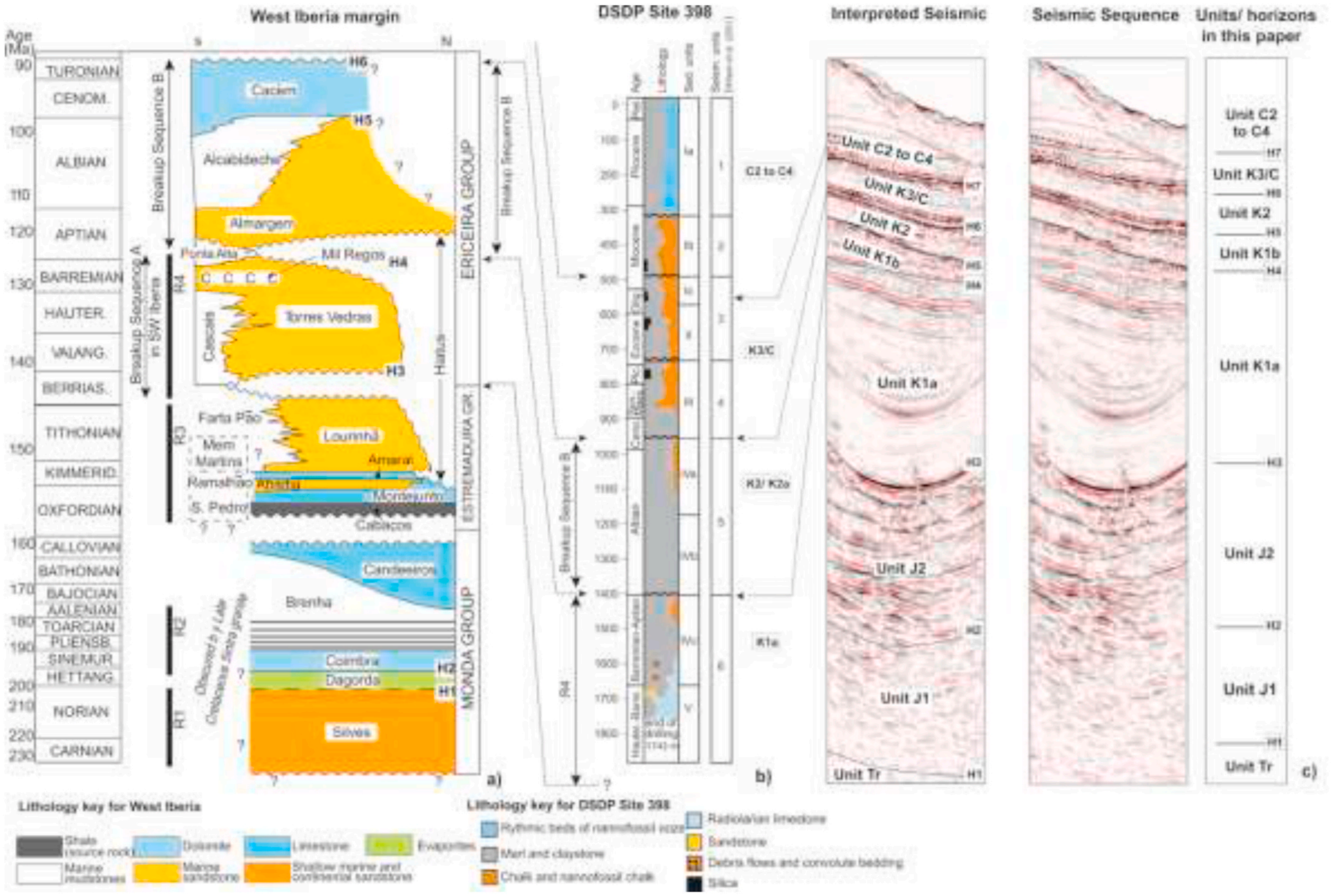

Fig. 3. Correlation panel between interpreted seismic stratigraphic units and well data from the West Iberian Margin (Alves and Cunha, 2018) and DSDP Site 398 (Groupe Galice, 1979; Rehault and Mauffret, 1979). See Fig. 5 and 1b for detailed location of seismic section and DSDP Site 398. Interpreted seismic horizons (Hn) are overlain on the assumed West Iberian margin equivalents.

stratigraphic interpretations, in the case of the pseudo-wells (Figs. 2 and 3).

Well Lu-1 was a wildcat drilled by Pecten in 1985 on the upper part of the continental slope off Porto (Fig. 1b). Well Lu-1 targeted a faulted anticline with an Upper-Middle Jurassic carbonate build-up reservoir at its crest. The well has a total depth of 4040 m (TD) and penetrates strata ranging from the Late Triassic (Silves Formation) to the Lower Cretaceous (Cacém Formation) (Fig. 4).

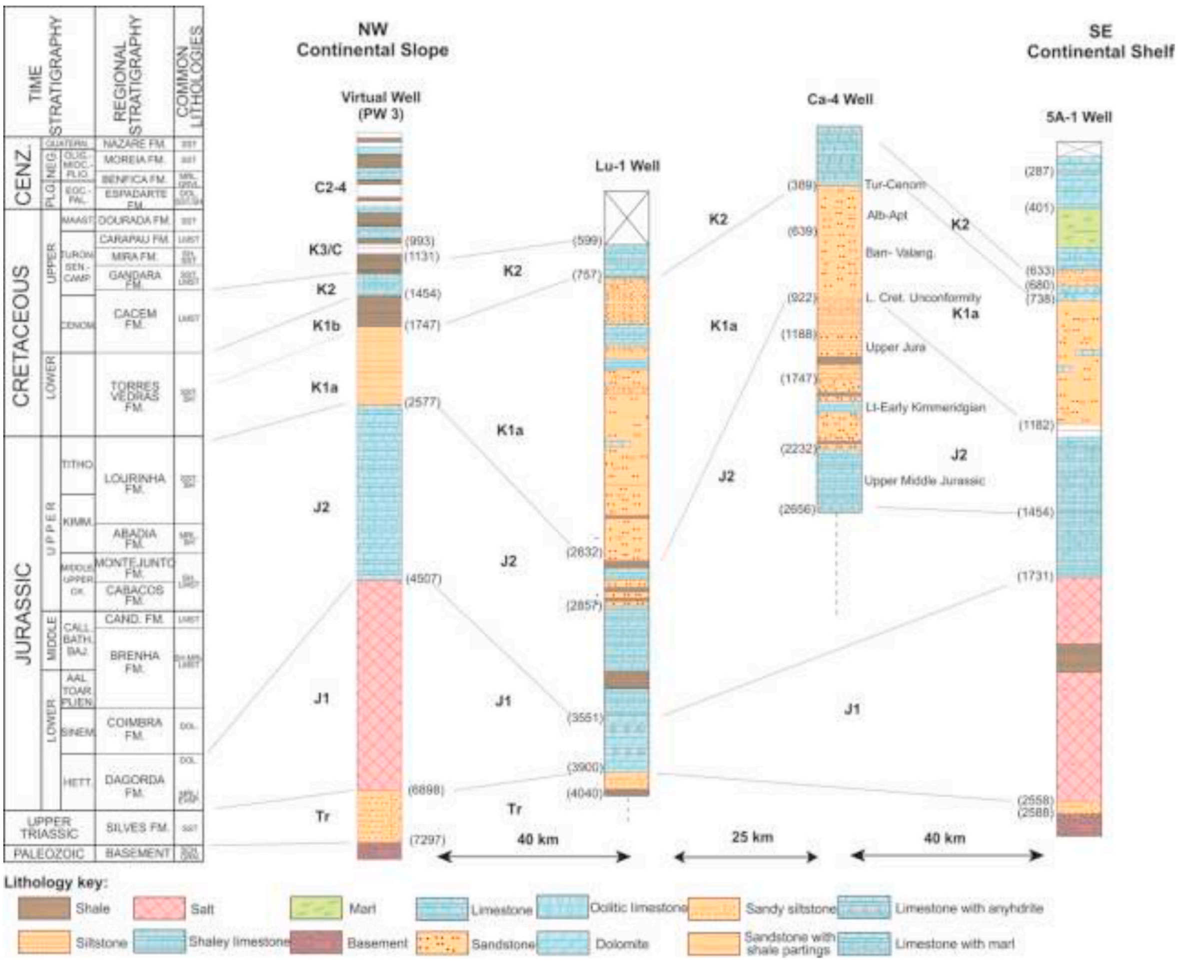

Fig. 4. Lithological logs of individual wells within the Porto and Peniche Basin areas. Note the presence of Triassic continental deposits, Upper Triassic-Lower Jurassic evaporites and finally marine Jurassic strata to comprise a tripartite stacking pattern of facies, as discussed later in this work.

Well 5A-1 was the fifth well drilled in 1975 by Shell Prospex Portuguesa on the continental shelf off West Iberia, to the SW of the city of Porto (Fig. 1b). Well 5A-1 was drilled on an anticline draped over a block faulted basement. The well has a total depth of 2626 m (TD) and drilled the entire sedimentary sequence down to metamorphic basement (Fig. 4).

Well Ca-4 was drilled by Texaco approximately 60 km northwest of Porto (Fig. 1b). Well Ca-4 aimed to drill a large anticlinal closure offset by a series of NNW trending normal faults generated in Upper Jurassic – Lower Cretaceous strata. The well has a total depth of 2749 m (TD) and penetrates Upper Cretaceous strata down to Upper-Middle Jurassic sequences (Fig. 4).

The well models were built using data from completion reports and geophysical logs (e.g. neutron porosity, sonic and density logs). Palaeoenvironmental data indicate that throughout the Mesozoic and Cenozoic the proximal wells experienced neritic (shelf) depositional environments (<200 m) except for Lu-1 located on the continental slope (Fig. 4). See Cunha (2008) and supplementary table 1 for details on data utilised and associated uncertainties).

Three (3) pseudo-wells were compiled in areas with robust seismic stratigraphic markers following the interpretation in Alves et al. (2006, 2009) and Alves and Abreu Cunha, (2018). In essence, relative dates for seismic and stratigraphic units were based on known information from borehole and outcrop locations, and on published and unpublished information from the Lusitanian Basin (Wilson et al., 1989; Hiscott et al., 1990; Alves et al., 2003a, 2003b; Dinis et al., 2008; Turner et al., 2017), the Porto Basin to the north of this latter (Moita et al., 1996), the Iberia Abyssal Plain (Wilson et al., 1996, 2001; Eddy et al., 2017), and proximal parts of NW Iberia (Groupe Galice, 1979; Boillot et al., 1989; Murillas et al., 1990; Tucholke and Sibuet, 2007). The average palaeobathymetry for the pseudo-well models was constrained by biostratigraphic and lithological data from Lu-1 (before Cretaceous) and DSDP Site 398 (Cretaceous–Cenozoic) (Figs. 3 and 4). DSDP Site 398 is located offshore NW Portugal, and comprises important biostratigraphic and stratigraphic information from Cretaceous–Cenozoic (Groupe Galice, 1979) (Fig. 3), and this has allowed reliable constraints to be drawn for pseudo-wells 1–3.

The pseudo-wells considered in this work extend to the acoustic basement, wich is inferred to be Late Triassic in age (Fig. 4). The backstripping calculations (interpreted palaeobathymetry for the pseudo-well models) are largely constrained by DSDP Site 398 down to the Barremian, below which level assumptions were made that Jurassic palaeo-water depths in the offshore locations were greater than those calculated from the Lu-1 (see Supplementary Table 1 for input parameters). A rapid increase of palaeowater depth during the Late Jurassic-Early Cretaceous was also accounted for as a result of advanced rifting leading to continental breakup (e.g. Alves and Cunha, 2018).

3. Geological setting

3.1. Physiography

The continental shelf between the city of Porto (~41°N) and the Nazaré Fault is associated with the Iberia Abyssal Plain (Fig. 1a). In this area, the shelf is narrow (~60 km wide), showing a steep bathymetric drop into basins created by a Slope Fault System separating relatively deeper continental-slope basins from the Lusitanian Basin Alves and Cunha, 2018). The central and northern areas of the West Iberian margin are dissected by first order transfer faults associated with modern submarine canyon systems that reach the abyssal plain (Fig. 1a). From north to south, the main basins of the entire West Iberian margin are the Galicia, Porto, Peniche, Lusitanian and Alentejo basins (Pinheiro et al., 1996). West Iberia has been described to contain more than 40 sub-basins in its deep-offshore areas (Alves et al., 2009).

The Lusitanian Basin comprises a Mesozoic rift basin extending 250 km in a roughly north-south direction, and 100 km east-west. The basin comprises the proximal part of West Iberia's continental margin (Fig. 1b). In contrast, the Peniche Basin is a 300 km long north-south trending deep-water trough divided into outer proximal and a distal segments, which extend westwards into the Iberia Abyssal Plain for several hundreds of kilometres (Alves et al., 2006). There is little direct stratigraphic information on the Peniche Basin due to absence of borehole data in the largest depocentres in this area. Information on the sedimentary infill derives from seismic stratigraphic analyses tied to more than 50 exploration wells on the shelf, DSDP/ODP Data, and correlations with outcrop analogues (Alves et al., 2006).

3.2. Syn-rift evolution and continental breakup

The Mesozoic evolution of West Iberia was dominated by four distinct rift episodes: Triassic (Rift 1), Sinemurian–early Pliensbachian (Rift 2), and late Oxfordian (Rift 3). Rift 4 occurred in the latest Jurassic–Early Cretaceous and is chiefly recorded in the Peniche and Porto basins (Wilson et al., 1989; Wilson et al., 2001; Alves et al., 2009) (Fig. 4).

The Triassic rift phase (Rift 1) is well recorded at outcrop in the Lusitanian Basin and in Southwest Iberia (Rasmussen et al., 1998). It was associated with the first Mesozoic extensional phases that affected the Eurasian-American domain from the Permian to the late Early Jurassic (Arthaud and Matte, 1977). In the Lusitanian Basin is documented by the deposition of Triassic red fluvial clastics (Silves Formation) and Hettangian evaporites (Dagorda Formation) in fault-bounded basins (Sibuet and Ryan, 1979; Alves et al., 2002). After the latest Triassic, regional subsidence prevailed in the Lusitanian Basin to promote the widespread deposition of evaporites (Rasmussen et al., 1998) (Fig. 4).

The Sinemurian to Pliensbachian Rift 2 was best developed south of the Nazaré Fault, where marine deposition first occurred (Stapel et al., 1996). After Rift 2, Lower and Middle Jurassic carbonate and mudstone reflects a northwest-dipping carbonate ramp developed in a regional setting dominated by slow, widespread subsidence well before continental breakup was achieved (Coimbra and Brenha formations; Toarcian–Late Callovian (Wilson et al., 1989; Pereira and Alves, 2012).

The late Oxfordian Rift 3 is associated with rifting and subsequent continental breakup of the region where Tagus Abyssal Plain is located (Alves et al., 2009). This phase manifested itself in the Lusitanian Basin where several sub-basins developed. Two distinct depositional episodes are recorded in this basin: a) a first episode dominated by widespread carbonate deposition from the Early to Late Oxfordian (Cabo Mondego and Montejunto formations), b) a second episode documenting a large influx of clastic material during the Kimmeridgian (Abadia formation; Wilson et al., 1989).

The fourth rift episode (Rift 4) occurred in the Early Cretaceous in association with the migration of the rift axis from the Tagus Abyssal Plain to the Iberian Abyssal Plain (Alves and Cunha, 2018). It was recorded in the continental slope basins west of the Lusitanian Basin, Porto Basin and in the zone of transitional crust drilled by ODP legs 149 and 173. This rifting episode generated a new rift trough and evidence exists that the Nazaré fault separated Berriasian–early Aptian seafloor spreading at the Tagus Abyssal Plain from a region still experiencing continental rifting northwards to the Charlie-Gibbs Fracture Zone, until the late Aptian-early Albian (Driscoll et al., 1995; Dean et al., 2015).

Continental breakup was diachronous across the North Atlantic (Pinheiro et al., 1996; Srivastava et al., 1990; Boillot et al., 1989; Stapel et al., 1996). A breakup sequence in the deep-water basins west of Peniche, defined by Soares et al. (2012), marks the period from the onset of continental breakup to the establishment of thermal relaxation on a fully rifted margin; it was dated as spanning the late Aptian to Turonian. In southwest Iberia, the breakup sequence developed from the Berriasian to the Barremian (Alves and Cunha, 2018). On the Newfoundland margin, several of these sequences are documented on the Atlantic Margin of Canada as continental breakup propagated northwards into the Labrador Sea (Alves and Cunha, 2018).

4. Seismic interpretation of the Jurassic seaway

Eight seismic units were interpreted in the study area. These units have their age, internal character, thickness and lithology summarised in Table 2.

4.1. Unit Tr (Late Triassic)

Unit Tr is the basal seismic stratigraphic unit in the study area (Fig. 4). Its top (Horizon H1) coincides with a high amplitude surface interpreted to be the top of the Triassic strata. Borehole data shows this unit to correlate with continental (and minor evaporitic) deposits of the Silves formation, outcropping in the Lusitanian Basin and drilled on the continental shelf. In the new seismic data used in this work, it is possible to distinguish the boundary between salt and older strata with some confidence (e.g. Fig. 5).

4.2. Unit J1 (?latest Triassic-Hettangian)

Unit J1 is the primary seismic unit addressed in this paper (Fig. 4). It is bounded at its base by Horizon H1. Chaotic to transparent packages predominate in Unit J1, although some high-amplitude internal reflections occur in places. Unit J1 has been interpreted to comprise ?latest Triassic–Hettangian evaporites (Alves et al., 2006; Rowan, 2014). Its thickness ranges from 750 to 2500 ms TWTT, reaching 3500 ms TWTT within the most developed salt diapirs (Fig. 7). Unit J1 relates to the first episode of rifting (Rift 1) between West Iberia and Canada (Alves et al., 2002).

Unit J1 is bounded at its top by Horizon H2, the internal character of this horizon is variable due to the effect of the deformed salt. Unit J1 correlates with the top of Unit T/J1 in Alves et al. (2006); however, its basal limit differs to that of the latter authors as it is interpreted with more confidence due to the improved resolution and penetration of the new reprocessed seismic data (Fig. 5).

4.3. Unit J2 (Sinemurian to Kimmeridgian)

Unit J2 is defined at its base by Horizon H2 (Fig. 2) and consists of high-amplitude reflections, with most internal reflections being relatively continuous but often tilted. Unit J2 shows growth onto fault bounding tilt blocks (Fig. 5). The unit forms a thick syn-rift package up to 1080 ms in thickness in discrete sub-basins. This increase in thickness is associated with a phase of more gentle, regional subsidence, as discussed further in this paper.

Unit J2 was first defined by Alves et al. (2006) and its geometry, stratigraphic position and internal character relate it to the J2 megasequence in the northern Lusitanian Basin (Alves et al., 2002). It comprises Middle to Upper Jurassic syn-rift strata. Unit J2 relates to the second episode of rifting in West Iberia (rift 2).

4.4. Unit K1a (Tithonian to early Aptian)

Unit K1a is defined at its base by Horizon H3, a high amplitude

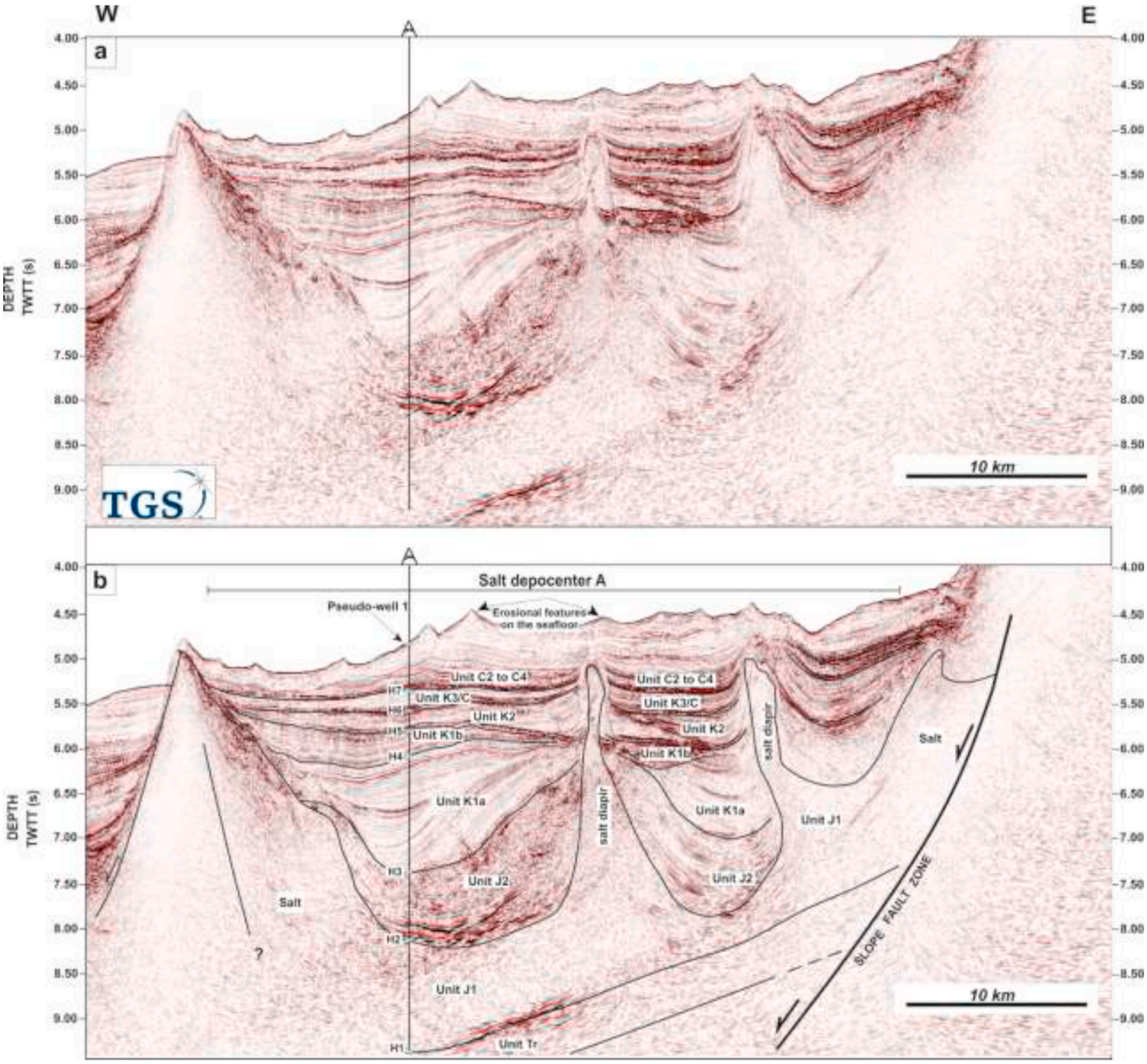

Fig. 5. a) Uninterpreted E-W section, and b) corresponding interpretation of a seismic profile acquired 50 km southwest of the Porto Seamount. Note the presence of developed salt diapirs, the clear base of salt in the seismic profile, and the apparent formation of bowl-shaped depocentres during the latest Jurassic-Early Cretaceous rift 4 (Unit K1a). See Fig. 1b for location. Location of pseudo-well 1 (PW1) shown in this figure.

negative reflection that likely indicates a regional flooding surface. Unit K1a is also bounded at its top by Horizon H4, another continuous and unconformable high-amplitude negative reflection (Fig. 4). Unit K1a shows a typical rift-related geometry as defined by Prosser (1993). Unit K1a is also bounded by H2 in areas with mature diapirs, where it was deposited into bowl-shaped depocentres between diapirs, indicating that halokinesis accompanied sedimentation. Unit K1a is largely made up of transparent reflections interpreted to be fine-grained strata, with minor high-amplitude continuous reflections interpreted to be coarse-grained units. This unit is interpreted to comprise marine strata, mainly muddy to sandy turbidites as drilled at DSDP Site 398 (Groupe Galice, 1979).

Unit K1a was first defined by Alves et al. (2006), who suggested it to comprise upper Berriasian-Aptian strata based on stratigraphic correlation with a pelagic-sediment-rich seismo-stratigraphic unit at DSDP Site 398 (Group Galice, 1979), and a Valanginian syn-rift turbidite unit at ODP Leg 103. In this work, we extend the base of this unit to syn-rift strata associated with the last continental rifting event in the Jeanne d'Arc Basin in Newfoundland, which started in the Tithonian (Sinclair, 1995). Unit K1a is also associated with the last rifting episode affecting West Iberia (Rift 4).

4.5. *Unit K1b (Aptian)*

Unit K1b is bounded at its base by Horizon H4, interpreted to be a Mid-Aptian Unconformity. Strata onlap onto this surface (Fig. 5). In contrast with the interpretation of Alves et al. (2006), which assumed this unit as part of K1 (from Alves et al., 2006), it appears that this unit does not contain growth strata and presents a clear facies change from unit K1a below. It represents the basal package of the *breakup sequence,* and is markedly regressive in nature (de Graciansky and Chenet, 1979; Réhault et al., 1979; Alves and Cunha, 2018). Internal reflections are transparent and in places chaotic, but appear to be relative flat when compared with Unit K1a. Unit K1b is bounded at its top by Horizon H5 (Figs. 5 and 6).

4.6. *Unit K2 (Albian to Cenomanian)*

Unit K2 is bounded at its base by Horizon H5, a high-amplitude surface marking the base of the Albian Black Shales as defined by de Graciansky and Chenet (1979) (Fig. 4). This horizon comprises a seismic reflection previous interpreted as a break-up unconformity by Groupe Galice (1979) and Réhault et al. (1979). This unconformity is now redefined as being at the base of Unit K1b, i.e. is relatively older that

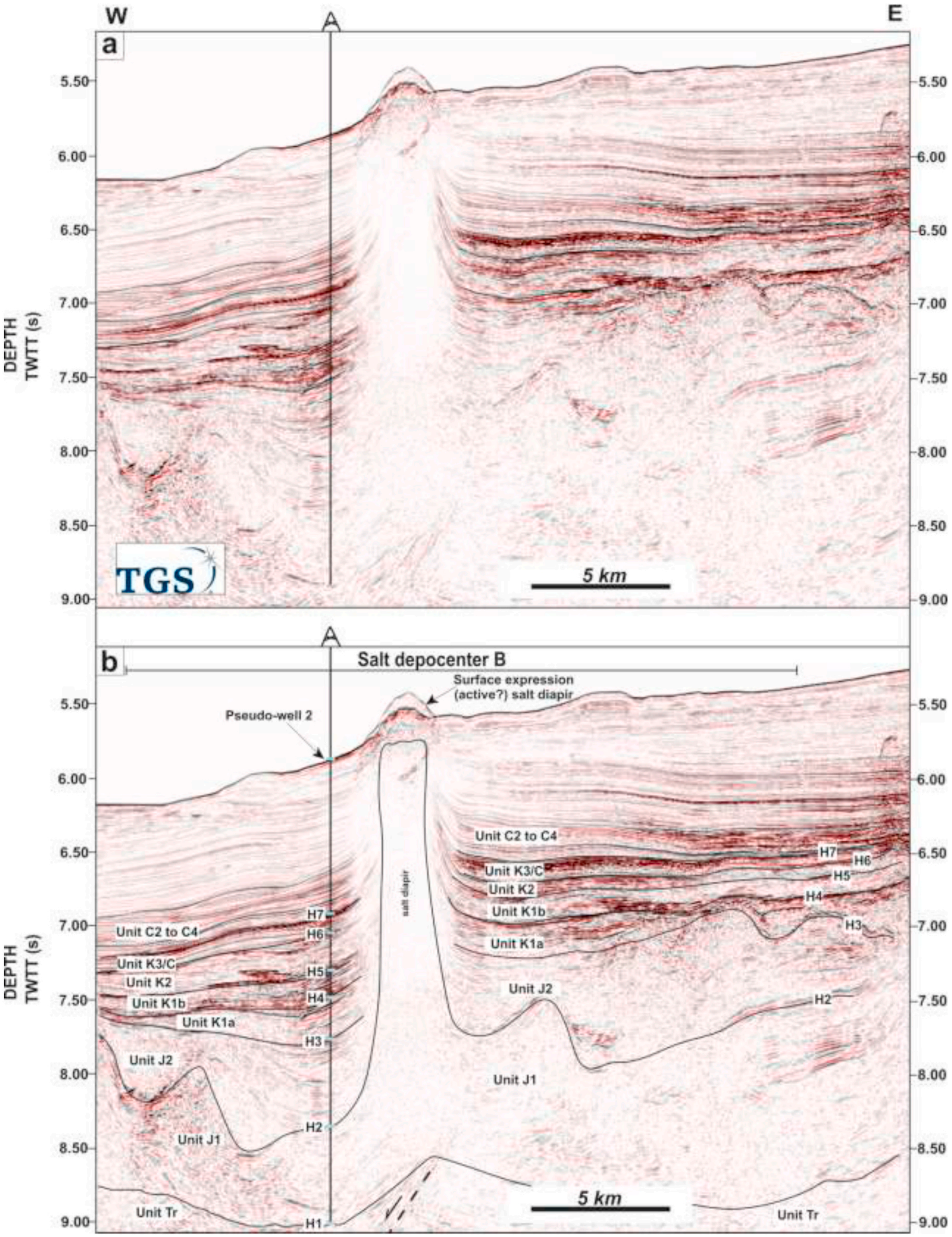

Fig. 6. a) Uninterpreted E-W section, and b) corresponding interpretation of a E-W seismic profile located to the west of the Porto Basin. See Fig. 1b for location. Note the surface expression of a developed salt diapir. The location of pseudo-well 2 (PW2) is also shown.

previously assumed.

Unit K2 is bounded at its top by Horizon H6, a high amplitude reflection that coincides with the top of carbonate-rich Cenomanian-Turonian strata. Unit K2 comprises a distinct basal seismic sequence of low-amplitude, progradational clinoforms and an upper sequence of high-amplitude continuous parallel reflections. Unit K2 truncates Units J2/3 and K1 in places (Fig. 5).

4.7. *Unit K3/C (Turonian-middle Eocene)*

Unit K3/C is bounded at its base by Horizon H6 and at its top by Horizon H7 (Fig. 5). It comprises transparent to low-amplitude internal reflections, and its average thickness is 100 ms. Stratigraphic information from DSDP Site 398 suggests this unit ranges in age from the Turonian up to the middle Eocene, including fine to coarse-grained

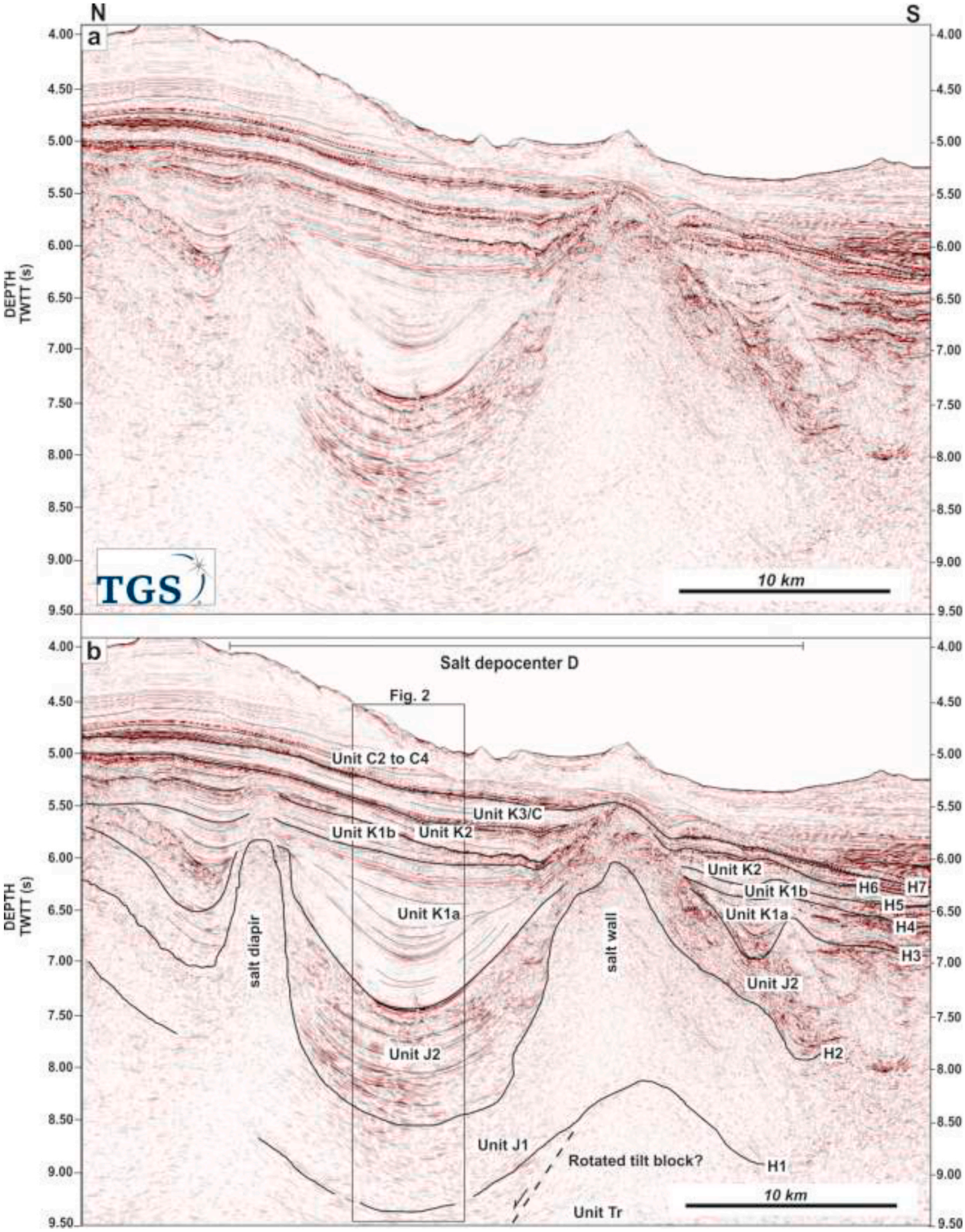

Fig. 7. a) Uninterpreted section, and b) corresponding interpretation of a N–S seismic profile to the west of the Lusitanian Basin, on the continental slope. see Fig. 1b for location. Note the presence of developed diapirs and the apparent formation of bowl-shaped depocentres during the latest Jurassic-Early Cretaceous rift 4 (Unit K1a).

turbidites and pelagites (Alves et al., 2006). This unit marks the oldest drift (or post-breakup) strata on the continental slope of West Iberia (Fig. 4).

4.8. *Unit C2–C4 (late Eocene-Holocene)*

In this paper Unit C2-4 comprises strata overlying Horizon H7, up to the sea floor (Fig. 5). It includes the Units C2 and C3/4 from Alves et al. (2006). Its base coincides with Horizon H7, which marks the base of the Cenozoic strata, in the study area (Fig. 4). Strata in this unit comprise of siliciclastic hemipelagites, turbidites, contourites and nannofossil oozes (Alves et al., 2006).

5. Salt distribution in continental-slope basins of West Iberia

The structural fabric of West Iberia follows the trend of Variscan basement faults according to seismic reflection and bathymetric data (Capdevila and Mougenot, 1988). Therefore, the Slope Fault System (SFS) of West Iberia comprises major N–S to ENE-WSW striking faults that bound the continental slope. Faults with similar strikes also control and separate Mesozoic tilt blocks on the continental slope and rise. In the study area, primary fault sets strike NE-SW and include large slope-bounding faults (SFS in Figs. 5 and 8) that cut through the continental slope to separate a shallow continental shelf from deeper continental slope basins. These faults can reach 150 km in length and divide the continental slope into westward tilting terraces at present (Alves et al., 2006). A secondary set of faults show NNW-SSW and N–S strikes (Fig. 8).

Fig. 8 shows how salt thickness in TWTT was mapped so as to document the distribution of salt across the study area. The average salt velocity calculated from wells in the area approaches 4.5 km/s, as estimated from Well Lu-1 (Fig. 3). In the study area, early Mesozoic salt has a thickness ranging from 750 to 2500 ms TWTT in distinct sub-basins, reaching 3500 ms TWTT within the most developed salt diapirs. Therefore, salt thickness away from diapirs, ranges from approximately 1.7 km–5.5 km, with mature diapirs comprising up to 7.5 km of salt in their interior (Fig. 8). The width of the salt reaches 40 km across salt-rich basins on the continental slope (Fig. 5). To the east, the early Mesozoic salt terminates against the Slope Fault System bordering the continental slope. Well Lu-1 located on the slope, primarily records dolomitic strata with minor salt, while well 5A-1 on the continental shelf, records the presence of 800 m of evaporites (Fig. 3). Further offshore, to the west of the study area, seismic data close to DSDP Site 398 do not reveal the presence of salt west of the continental slope basins defined by Alves et al. (2006) (Fig. 4). Such a salt distribution highlights a key feature; early Mesozoic salt in West Iberia follows a NE-SW trend that is confined by the structural lineaments and fault systems that segment the continental slope (Fig. 8).

Four main salt depocentres were identified in the region west of the Slope Fault System (Depocentres A-D). In these depocenters, halokinesis is related to regional extension and half-graben collapse relative to the SFS, conditioning the development of discrete salt structures. This type of salt tectonics is common in active rift basins, and on the outer shelf and upper slope of passive margins (Hudec and Jackson, 2007). Where precursor diapirs are absent, thickness of the evaporite deposit is the main control on structural style. Above thick salt, diapirs and adjacent withdrawal basins grow larger. Depocentre A is 25 km wide and mature diapirs form bowl-shaped depocentres for Jurassic and lower Cretaceous strata (Figs. 5 and 8). Here, diapirs reach 3500 ms TWTT, or 7.5 km. The two mature diapirs interpreted in depocentre A show growth that is limited to Cenozoic strata (C2–C4), narrowing at the head of the diapirs. Such a geometry reveals that abundant salt fed the diapir, which began to widen the deeper parts of the crest prior to widening the younger crest (Hudec and Jackson, 2007). Depocentre B comprises one large diapir with a clear surface expression; salt availability allowed this diapir to grow reactively near or up to the surface (Figs. 6 and 8). The much larger Depocentre C forms a 46 km wide salt basin filling a landward-dipping half-graben bounded to the east by the Slope Fault System (SFS) and to the west by the Porto Seamount (Figs. 2 and 8). Here, developed salt stocks are found in Cretaceous and Cenozoic strata, whereas salt pillows do not impinge on Cretaceous strata, forming Jurassic minibasins instead. Depocentre B and C are likely dextrally offset from Depocentre A from the west by the westward projection of the Aveiro Fault. Depocentre D is a 27 km wide diapir-bounded bowl-shaped depocentre mostly filled by Jurassic and Lower Cretaceous strata (Figs. 7 and 8).

6. Subsidence models: Deep offshore vs. continental shelf

6.1. *Continental shelf (exploration wells)*

All modelled exploration wells reveal important basement subsidence during Late Triassic-Early Jurassic rifting, followed by further deepening due to relative post-rift tectonic quiescence through the Middle Jurassic (Fig. 9a–c). Subsidence models for Well 5A-1, on the continental shelf, reveal a depositional hiatus and relative shallowing associated with exhumation of structural highs next to subsiding basins during Late Jurassic–Early Cretaceous rifting (Fig. 9a). In contrast, Well Lu-1 located on the upper continental slope records a marked increase in subsidence during that interval (Fig. 9b), likely due to rifting in the Late Jurassic to Early Cretaceous being focused west of the continental shelf. As a result, the relatively proximal wells (e.g. Well 5A-1) in the Lusitanian Basin record marked differences in their subsidence histories compared to the continental slope basins, including Well Lu-1 (Fig. 9b).

6.2. *Continental slope basins (pseudo-wells)*

All pseudo-wells reveal very marked syn-rift subsidence in an interval spanning the Late Triassic-to the Early Jurassic. Pseudo-wells 1–3 record more than 2000 m of subsidence during the Hettangian–Sinemurian (Fig. 9d–f), accompanying the deposition of thick salt, the deep-offshore equivalent of the Dagorda formation in the Lusitanian Basin. This latter character is robust evidence for the beginning of a developing seaway as early as the latest Triassic-Hettangian. The subsidence curves for continental slope basins reveal these to be considerably deeper than the more proximal continental-shelf basins during Late Triassic to Early Jurassic rifting, further highlighting the presence of a major structural feature separating both areas. Middle Jurassic to early Late Jurassic tectonic quiescence is also revealed by the subsidence models, followed by another episode of deepening associated with an increase in palaeowater depths during Latest Jurassic to Early Cretaceous rifting (Fig. 9d). Subsequent deepening into the Cretaceous is evidence for a seaway that continued to be present during subsequent rifting episodes (Rift 4) (Fig. 9d–f).

7. Tripartite stacking patterns in West Iberia

Exploration wells on the continental shelf of the West Iberian Margin record the significant change in deposition that occurred from the Triassic to the Early Jurassic as the seaway was developed, as one within a network, providing the gateway between the Boreal and Tethys Oceans. This tripartite stacked pattern of continental, evaporitic and marine strata records the transition from continental to marine deposition with salt deposition as the intermediary facies (Fig. 3).

Well 5A-1 penetrated the basement at its deepest and encountered 30 m of red micaceous mudstone (Triassic Silves Formation) followed by 814 m of an heterogeneous succession of salt interbedded with mudstone, anhydrite, limestone, mudstone and dolomite layers (Dagorda formation). Some 13 m of tight dolomite were encountered before a 277 m section of Middle to Lower Jurassic limestone, silty marlstone and stringers of anhydrite, clay and siltstone (Esturjão Formation; Fig. 3). This reveals the existence of marine incursions in this Early Jurassic seaway. Similarly, completion logs from Well Lu-1 show a minimum of 142 m of continental sandstone, conglomerate and red mudstone (Silves Formation) below a Sinemurian section of interbedded dolomite and anhydrite (Dagorda Formation). These latter evaporites are interpreted to have been deposited in a shallow sea created in the Hettangian. Interbedded limestone and shale were recorded above the Dagorda formation, followed by a 110 m section of black shale at the top of the succession, deposited as a result of continued subsidence during the Pliensbachian (Fig. 3).

Corroborating our seismic interpretation, the stratigraphy of the continental shelf basins, from south to north, records continental

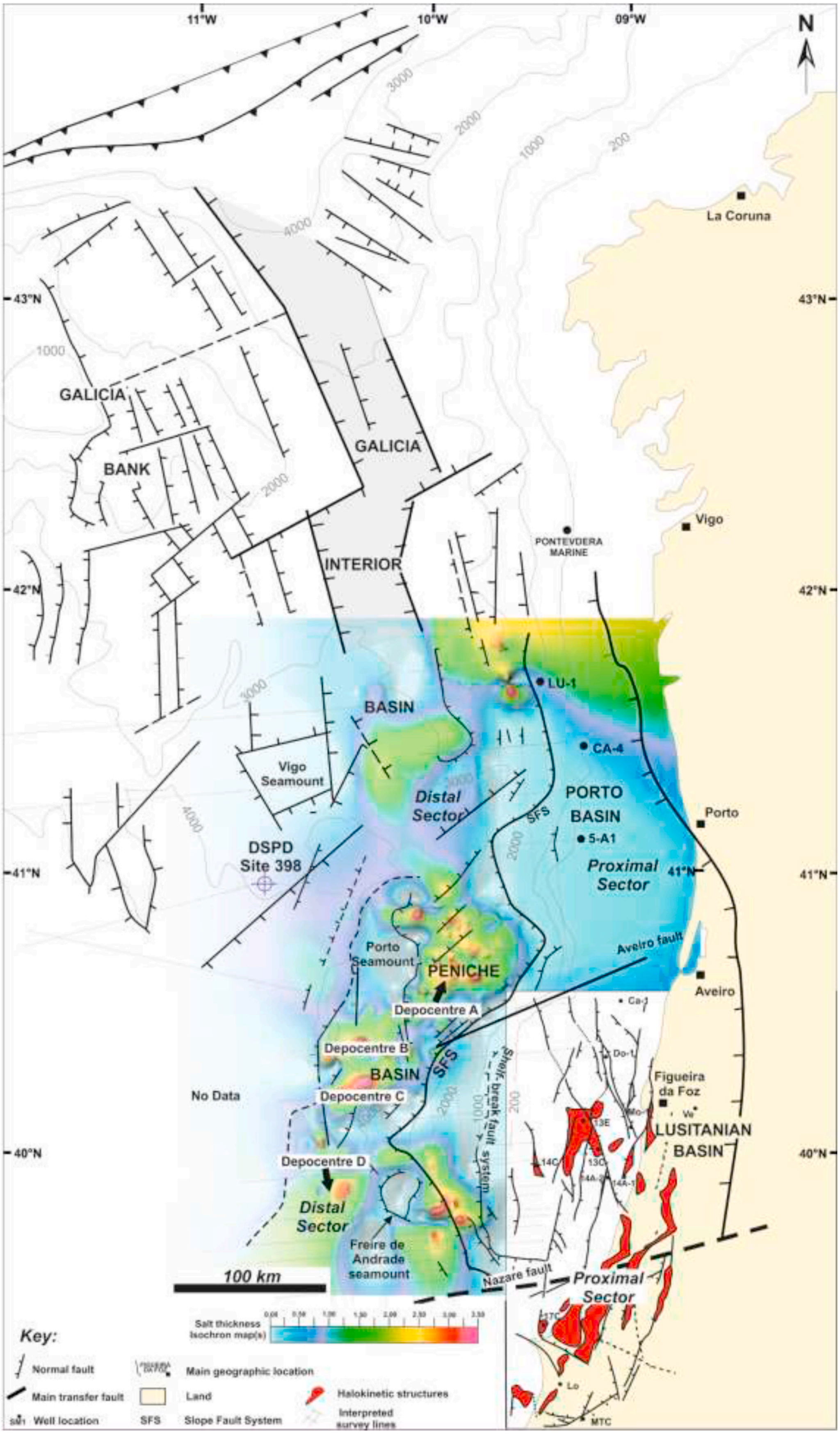

Fig. 8. Salt thickness map in TWTT, from Horizons H1 to H2, overlain by structural elements from Alves et al. (2006) and Murillas et al. (1990). Also shown is the interpreted seismic grid. Inset map is taken from Alves (2002) highlighting halokinetic structures mapped east of the study area, in the Lusitanian Basin.

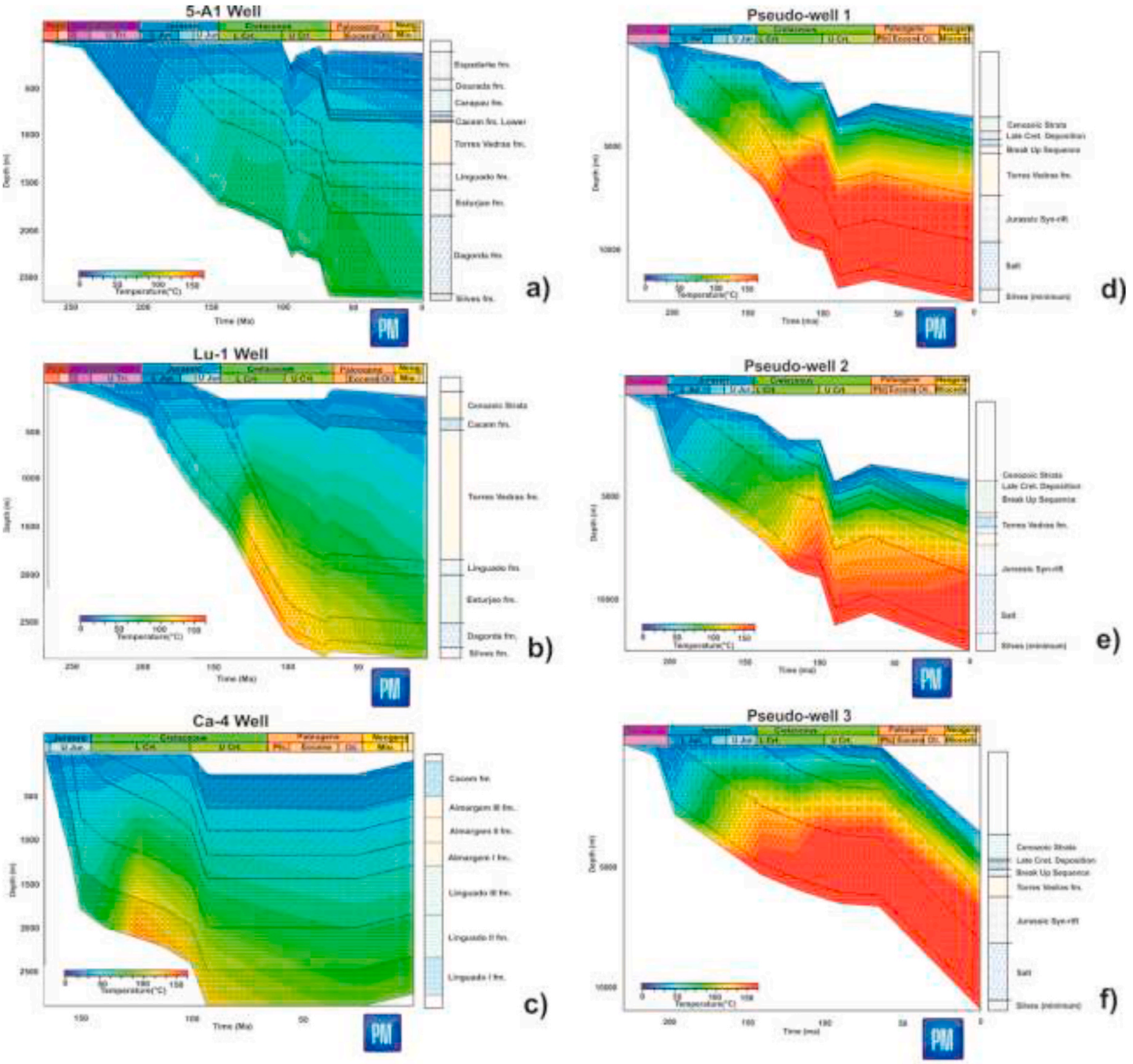

Fig. 9. a) Thermal subsidence curve for well 5A-1. b) Thermal subsidence curve for well Lu-1. c) Thermal subsidence curve for well Ca-4. All wells located on the continental shelf. d) Thermal subsidence curve for pseudo-well 1, e) Thermal subsidence curve for pseudo-well 2, f) Thermal subsidence curve for pseudo-well 3. Pseudo-wells are located in continental-slope basins to the west of the Lusitanian and Porto Basins. (Locations of pseudo-wells are shown in Figs. 1b and 8.

deposition in the Triassic (Silves Formation) followed by Hettangian evaporite deposition (Dagorda Formation), and subsequently by marine carbonates and muds deposition in the Sinemurian (Coimbra Formation) and Pliesbachian–Toarcian (Brenha Formation) (Alves and Cunha, 2018; Sêco et al., 2019) (Fig. 4).

8. Discussion

8.1. Seaway models for the Triassic–Early Jurassic of West Iberia

Detailed seismic interpretation reveals, for the first time the presence of an extensive Early Jurassic seaway in this region; the South Laurasian Seaway. Seismic interpretation shows that the thickest salt is confined by four (4) salt depocentres in the distal part of the margin that are bounded to the east by a Slope Fault System and to the west by several seamounts and syn-rift structural highs (Figs. 5 and 8). In this sector of the West Iberian Margin, salt thickness in Early Jurassic depocentres can reach 2500 ms and mature diapirs are observed (Fig. 8). Lower-Middle Jurassic strata (Unit J2) form syn-rift packages in salt depocentres that are 2.3 km thick in some places (Fig. 5). According to subsidence models in pseudo-wells 1, 2 and 3 more than 2.5 km of subsidence were recorded west of the Slope Fault System (Fig. 9d, e, f). It is proposed here that this enhanced subsidence was related to a strong phase of Late Triassic to Early Jurassic extension, as shown by the deposition of thick salt followed by the accumulation of Lower-Middle Jurassic strata partly influenced by the main phase of halokinesis, as well as continued extension related to rifting (Figs. 5 and 8 d, e, f).

Seismic interpretation at DSDP Site 398 has revealed a distinct lack of salt structures (Fig. 2). It is plausible to consider that salt disappears roughly west of the Porto Seamount where, at this location, only a small amount of salt is present (Fig. 2). Seismic interpretation also revealed that the continental Slope Fault System delimits the area of thick salt deposits on the continental slope from the shallower Lusitanian Basin (Fig. 8). However, analysis of industry wells on the continental shelf has revealed that Upper Triassic to Lower Jurassic salt is also present here, albeit with thicknesses that are significantly less than those to the west of the Slope Fault System (Fig. 3). According to our subsidence models (Fig. 9a, b, c) a similar pattern of subsidence to the continental shelf occurred in continental-slope basins, but the former show total subsidence values that are three times smaller (850 m) when compared to the latter (2500 m). Hence, a key finding in this work is that subsidence models reveal that the seaway of interest to this study was divided into two sectors (distal and proximal) by the Slope Fault System as early as the Late Triassic-earliest Jurassic; their different subsidence histories prove the existence of such a division. Such a character is also typically recorded in basins where syn-stretching salt is deposited, as defined by Rowan (2014), where evaporites are found in varying thicknesses and extent over the margin due to its early deposition during rifting.

Further east in the northern Lusitanian Basin, uppermost Triassic to Lower Jurassic salt is recorded in multiple exploration wells and at outcrop (Alves et al., 2002) (Fig. 8). Salt accumulations in the Lusitanian Basin are bounded to the east by the Porto-Tomar Fault (Pinheiro et al., 1996; Soto et al., 2012). It is proposed in this work that the Jurassic seaway included the Lusitanian Basin and, therefore, spanned from this latter basin to the vicinity of the Porto seamount, reaching a width of ~200 km (Fig. 8).

Exploration wells in the Porto Basin, seismic interpretation in the Peniche Basin, and outcrop observations in the Lusitanian Basin, have documented shared terrestrial, evaporite and marine depositional patterns. Similarly, north of the study area, in the Galicia Interior Basin, there is evidence of earliest Jurassic strata with shallow marine facies, as pointed out in Murillas et al. (1990) and proven by dredge samples from seamounts off Galicia and Portugal (Alves, 2002). The Galicia Interior Basin is itself considered as part of a Triassic rift system formed between Europe and Laurentian Pangaea, formed prior to the opening of the Central Atlantic around the Bathonian-Callovian (e.g. Klitgord and Schouten, 1986). Basins recording similar times for early syn-rift extension occur in Newfoundland, offshore eastern Canada, and along the continental shelf of Portugal, Spain and west of France. As also stated in Murillas et al. (1990), the transition between the Porto Basin and the Galicia Interior Basin has been poorly defined in old, vintage seismic data where bottom multiples obliterate nearly all the primary reflections at the depth of occurrence of Upper Triassic-Lower Jurassic strata. However, the data in the present work show the northernmost areas of

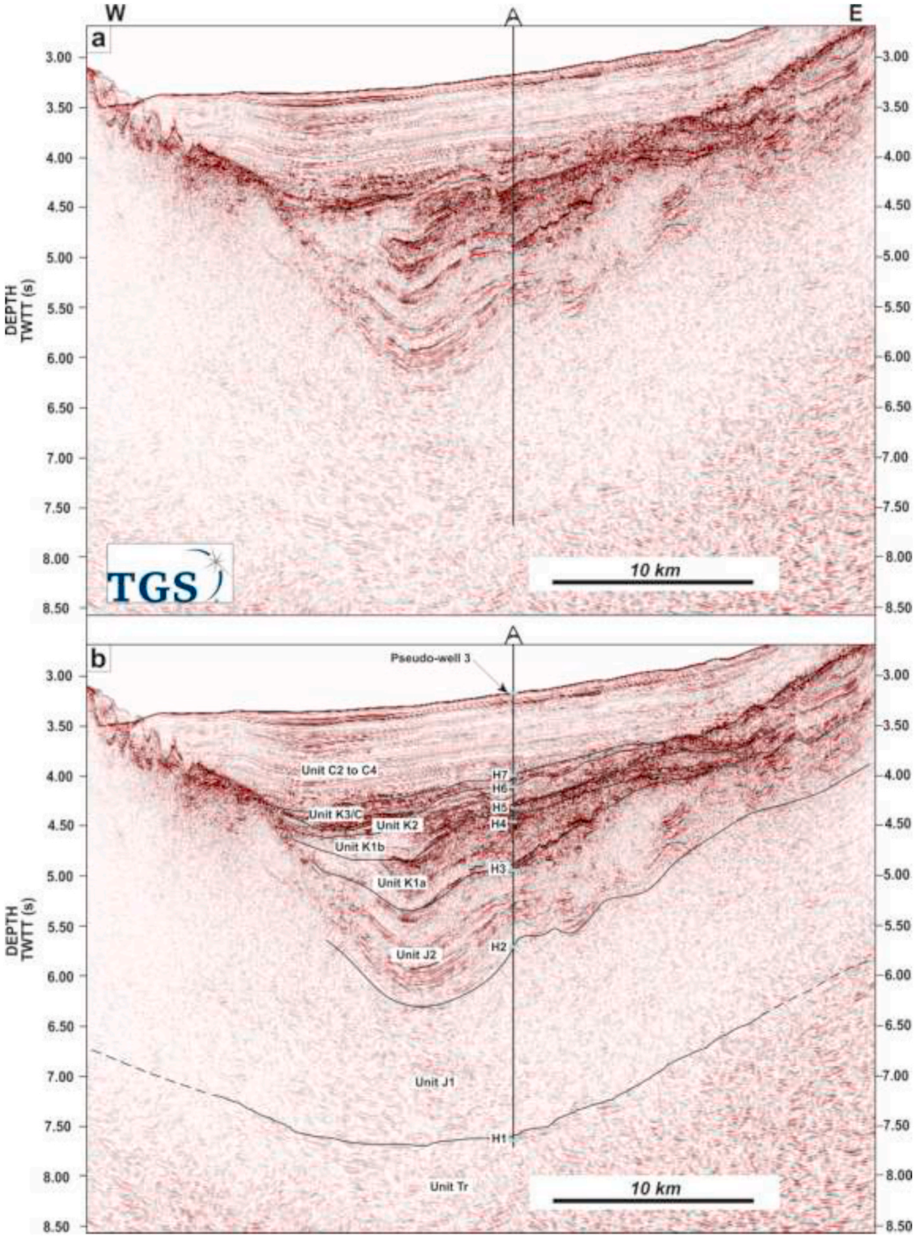

Fig. 10. a) Uninterpreted E-W section, and b) corresponding interpretation of a seismic profile close to the northernmost part of the study area, into the Galicia Interior Basin See Fig. 1b for location. Note the absence of salt structures in this location and interpreted presence of thick salt. Location of pseudo-well 3 is also shown in the figure.

the continental slope to comprise local depocentres with thick salt and Jurassic strata, justifying the continuation of the Early Jurassic seaway towards the NW of Iberia, into Spanish waters (Figs. 8 and 10). In fact, it is now understood that the Porto Basin and its prolongation towards the Galician Shelf, where the exploration wells referred to by Murillas et al. (1990) were drilled, comprises the proximal part of a larger, deeper axis of continental rifting that extends from the continental slope of Portugal towards the Galicia Interior Basin, both delimited by NE-SW and NW-SE faults (Figs. 5–8). The tectonic evolution of the Porto Basin and these latter continental-slope depocentres is similar, with syn-rift extension starting in the Early Mesozoic (Triassic to Early Jurassic), and recording their principal extensional episode during the latest Jurassic-Early Cretaceous (Alves et al., 2006; Alves and Cunha, 2018).

8.2. *Early Jurassic palaeogeography of the North Atlantic*

Palaeogeographic reconstructions for the North Atlantic Area indicate that from the Early Jurassic, and through the rest of the Mesozoic, a combination of marine basins and seaways connected the Tethys region and the Arctic via a North Atlantic rift system (Ziegler, 1982) (Fig. 11). The Jurassic palaeogeography for the North Atlantic and North Sea areas includes deep shelf, shallow shelf, carbonate platforms and landmasses as main regions. The present study shows that the Lusitanian, Porto and Peniche basins have similar Late Triassic-Jurassic tectono-sedimentary evolutions in the form of a common tripartite stacking patterns, i.e. shared facies associations comprising the deposition of continental strata in the Triassic, evaporite deposits in Hettangian, and fully marine deposits in the Jurassic (Fig. 3). Such facies associations suggest a co-genetic evolution for the three basins, favouring the interpretation that a seaway existed during the early stages of continental rifting spanning from the Lusitanian to the Peniche and Porto Basins. This seaway was compartmentalised as early as the Hettangian into a proximal and distal sector (Fig. 8).

The predominant depositional setting over the rifting North Atlantic area was one of transgressive pulses associated with rift propagation that started in the Permian (Ziegler, 1988). In the Zechstein Basin of NW Europe, a tripartite stacking pattern of continental-evaporite-marine facies is recorded up to the Central Norwegian Sea, though alluvial, lacustrine and other continental facies were once again prevalent in the Triassic due to uplift of the Fennoscandian Shield in the north, and the Anglo-Brabant and Variscan massifs to the south (Lervik, 2006; Kortekaas et al., 2018).

The Zechstein Sea spanned most of NW Europe but lacked Tethyan involvement. However, from the Late Triassic into the Early Jurassic, rifting propagated westwards from the Tethys Ocean (Ziegler, 1988) as part of a rift system largely controlled by Caledonide basement structures in the North Atlantic (Doré, 1992), and by a pervasive Variscan basement fabric in West Iberia (Pinheiro et al., 1996). Hence, the two-sector division of West Iberia documented in this work suggests a marked difference between the proximal parts of the seaway (Lusitanian Basin) and the distal, more developed depocentres that are now part of the Peniche Basin.

A decreasing trend in soluble minerals west of the western periphery of the Tethys Ocean (Jansa et al., 1980), is evidence for the westward propagation of the Tethyan rift and subsequent marine encroachment via inter-continental graben systems. In West Iberia, stratigraphic and compositional similarities exist between the Late Triassic to Hettangian evaporite deposits found in the Lusitanian Basin and Grand Banks in Canada (Wilson et al., 1989; Hiscott et al., 1990; Alves et al., 2003a, 2003b; Uphoff, 2005), signifying the two areas were linked at the time of deposition. By the Sinemurian-Pliensbachian, full marine deposition was established south of the Nazaré fault (Stapel et al., 1996). Furthermore, Mouterde et al. (1979, 2007) record mixed ammonite assemblages in the Lower Jurassic of the Lusitanian Basin, where Boreal and Tethyan assemblages were found to co-exist. This demonstrates the influence of both water masses from northern and southern ocean seaways at a time when marine conditions were undoubtedly established off West Iberia.

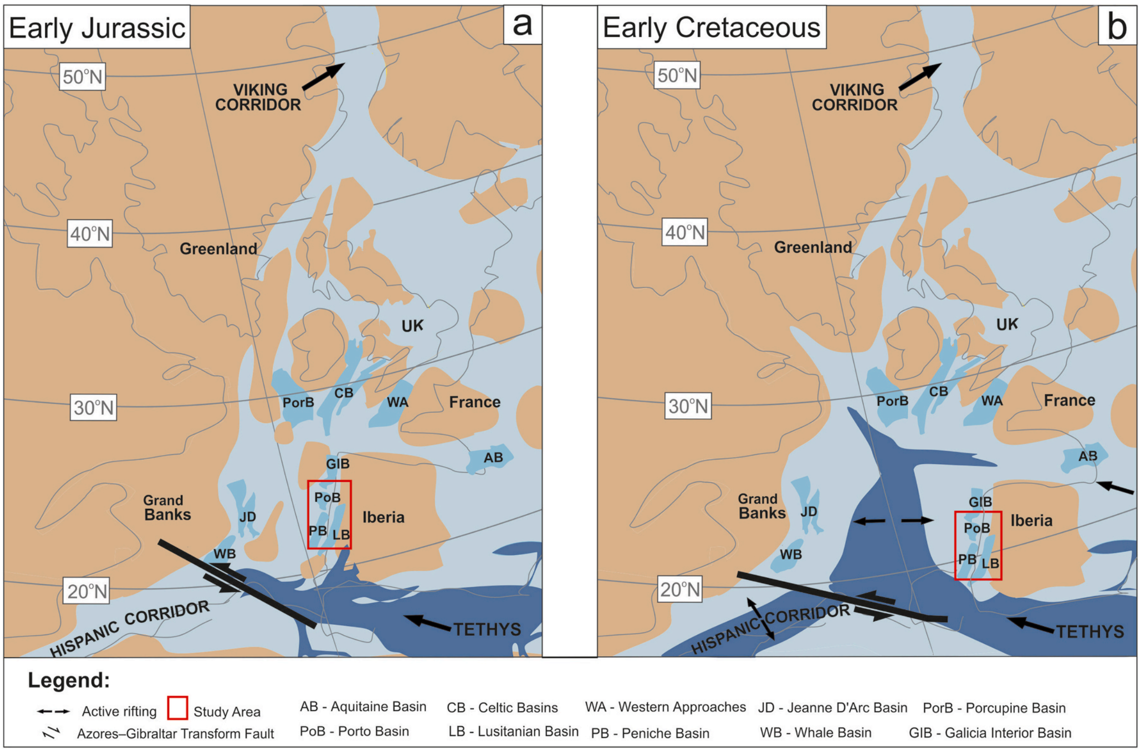

Fig. 11. Palaeogeographic maps for the North Atlantic Ocean. a) palaeogeography of the North Atlantic during the Early Jurassic highlighting the establishment of several ocean seaways; b) palaeogeography of the North Atlantic during the Late Jurassic/Early Cretaceous, when continental rifting broadened the older seaways and led to the rupture of continental crust between Iberia and Canada. Figure based on Van De Schootbrugge et al. (2019).

Further north, seawater incursions followed the axes of rifting from Northern Iberia into the Rockall Trough, Faroe-Shetland Basin, and into a part of a rift arm separating Greenland and Norway (Ziegler, 1982) (Fig. 11). This created a connection between the Tethys Ocean and the Boreal Sea through the Viking Corridor by, at the latest, Toarcian times (Brikiatis, 2016). With ammonite faunas placing the first connection earlier in the Pliensbachian (Dera et al., 2011), the same transgression resulted in marine deposition with sandy accumulations corresponding to the Dunlin Formation on the margins of basins, but forming the Cook and Johansen formations in Norway and Greenland. This phase brought full marine conditions to the NE Atlantic system as proven by its tide dominated sand deposits (Dore, 1992).

We conclude that the establishment of a continuous seaway between the Boreal and Tethyan oceans by the Toarcian culminated in the deposition of argillaceous strata across the North Atlantic region (Korte et al., 2015). Ammonite populations in the Sinemurian prove that the Viking Corridor provided a passage between realms where water exchanges occurred continuously, with the magnitudes of such exchanges being controlled by fluctuations in sea levels and currents (Dera et al., 2011). These patterns suggest that a late Pliensbachian sea-level lowstand temporarily segregated populations until full recovery in the Toarcian. A similar setting may have occurred in West Iberia, where outcrop data indicated the first appearance of ammonites in the late Sinemurian (Duarte et al., 2014). According to Skjerven et al. (1983), the likely reason behind the unsuccessful connection between realms in the Viking Corridor prior to the Toarcian was due to deposition keeping pace with the development of accommodation space and rising sea levels throughout the Triassic. We extend this interpretation to the lowermost Jurassic in the south Laurasian Seaway, stressing that episodic marine incursions in Unit J1, and the deposition of thick syn-stretching salt, constitute evidence for an early seaway. At the same time, we consider that the establishment of a permanent marine seaway between the Boreal and Tethyan oceans occurred later in the Pliensbachian-Toarcian, following evidence for a first Sinemurian stage of marine incursions in the Lusitanian Basin (Duarte et al., 2014), making our study area similar to the North Sea region (Hesselbo et al., 2007).

8.3. *Tripartite stacking patterns in strata during early North Atlantic rifting*

A tripartite stacking pattern appears in other basins associated with the opening of the North Atlantic in the early Mesozoic. One such places is the conjugate margin of West Iberia in Newfoundland, Canada, where the continental deposition of the Eurydice Formation is overlain by the evaporites of the Argo Formation and capped by the marine rocks of the Iroquois Formation (Sinclair, 1995) (Fig. 12).

The basins of the Irish continental margin also record similar sequences representing the opening of the North Atlantic. Rift-related subsidence occurred during the Triassic in the NE Rockall Basin, leading to the accumulation of extensive red (continental) beds overlain by marginal to marine evaporites and limestones in the Rhaetian, extending into the Early Jurassic (Jones and Underhill, 2011). Evaporite deposits are also recorded in the smaller Slyne, Erris and Donegal basins (Tate and Dobson, 1989). In the Porcupine Basin, contemporaneous facies show Triassic strata dominated by sandstones that were capped by evaporite deposits at the end of the Triassic. These are followed by Lower Jurassic marine carbonate and claystone (Jones and Underhill, 2011).

A similar stacking pattern was also recorded in a well drilled 290 km southwest of Lands' End on the UK continental shelf. The Britoil 72/10-1A well in the Western Approaches encountered undifferentiated coarse clastic sediments (sandstones and conglomerates) at its base that were correlated to Permian deposits in the southwest of England. These strata are overlain by Upper Triassic silty claystone and 600 m of evaporite deposits below claystone of Hettangian age (Bennet et al., 1985).

The Triassic-Early Jurassic rifting episode manifests further east, in the Aquitaine Basin, in the form of thick clastic and evaporite successions. The Aquitaine Basin records Rhaetian to Hettangian argillo-evaporitic sedimentation over the whole basin, expressed in the west by 800–900 m of evaporites with dolomite-anhydrite sequences at the edge and dolomite-anhydrite-halite sequences in the centre of the basin

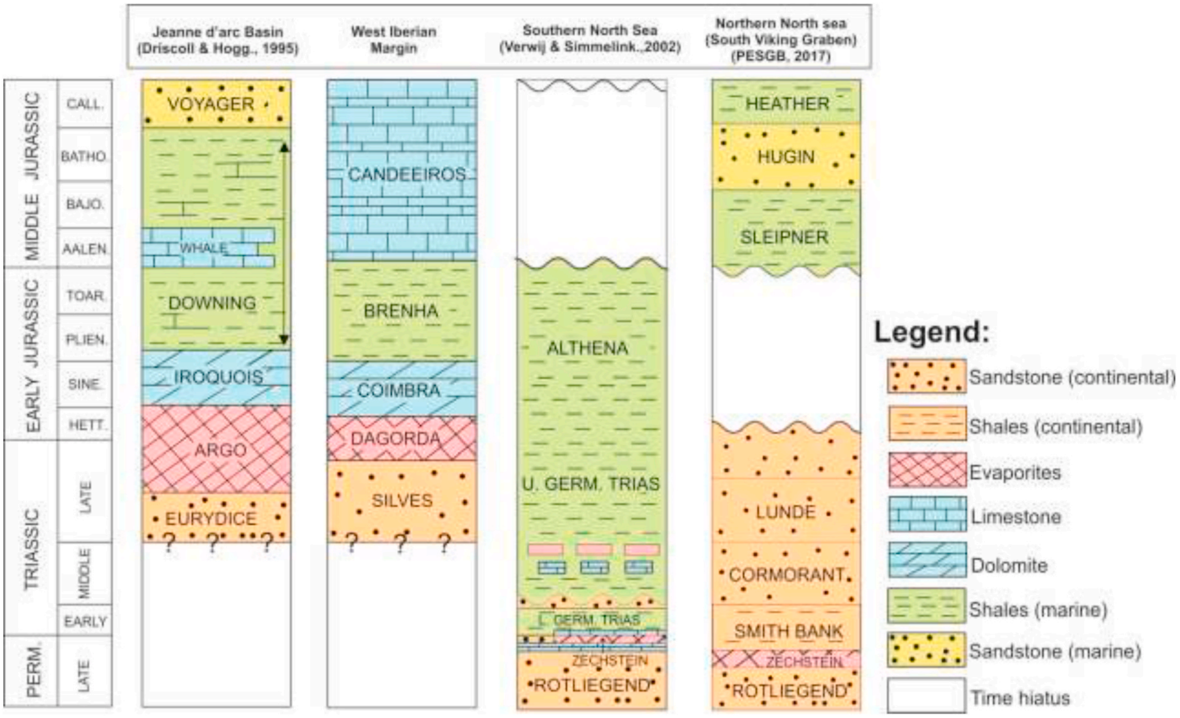

Fig. 12. Simplified stratigraphic column for the Jeanne d'Arc Basin, West Iberian Margin, Southern North Sea and Northern North Sea revealing similar tripartite stacking patterns during the early stages of continental rifting.

(Curnelle et al., 1982). From the Sinemurian onwards, through to the Early Cretaceous, shallow marine sedimentation persisted across the Aquitaine Basin (Curnelle et al., 1982). A similar, but older stacking pattern is also observed in the Zechstein basins of NW Europe. The Southern North Sea and part of the Northern North Sea record a succession of continental rocks (Rotliegend Group) overlain by Upper Permian Zechstein evaporites. These are further capped by a sequence of marine rocks. It is therefore proposed that the seaway considered in this work, in West Iberia, may have had a relationship with older seaways in Northern Europe that also led to the accumulation of tripartite continental-evaporite-marine facies (Fig. 12). It could be further proposed that the broad region of continental rifting shown in Fig. 11 was linked to the Early Jurassic Viking Corridor, further north, between Greenland and Norway (Fig. 11).

9. Conclusions

The data in this study reveals that Triassic–Early Jurassic continental rifting in the North Atlantic coincides with the establishment of a ~200 km wide seaway in West Iberia. New reprocessed data and tectonic subsidence curves for the Lusitanian, Porto and Peniche basins, West Iberia, reveal the palaeo-position and width of this Triassic-Early Jurassic seaway, which was divided in two distinct sectors. In conclusion, the major findings of this paper are as follows:

1) The thickness of the West Iberian salt was quantified for the first time, varying from 1.7 km to 2.5 km in the main depocentres of continental-slope basins. This, and an overlying thick succession of Lower-Middle Jurassic strata, indicate the presence of a South Laurasian seaway relatively wide and extending into what are, at present, continental-slope basins.
2) The marked Early Jurassic subsidence observed in the in the salt-rich depocentre reaches over 2000 m by the Hettangian and contrasts with the results from exploration wells drilled on the continental shelf. These more proximal wells recorded a maximum of 800 m of subsidence at this time, a character emphasising how partitioned this seaway was.
3) Continued tectonic subsidence through the Early Jurassic is estimated based on tectonic subsidence models, recording a maximum of 5 km in the offshore Peniche Basin. This value compares with the 1.1 km in the proximal Lusitanian Basin.
4) Tripartite continental, evaporite and marine facies associations spanning the Late Triassic to Early Jurassic in West Iberia, record the development of the seaway in this location, the south Laurasian Seaway.
5) This same tripartite stacking pattern is recorded in other parts of the North Atlantic, albeit with different ages in places. Hence, it is proposed that tripartite facies associations are an indicator of a common stratigraphic record of seaway formation all over the North Atlantic realm.

This paper proposes that the common tripartite stacking pattern recorded in various Mesozoic basins across the North Atlantic is an indicator of a common stratigraphic record of one or several seaways existing during the latest Paleozoic to early Mesozoic. Furthermore, we postulate that the continental-evaporite-marine succession exists in association with the generation of isolated depositional basins in seaways first filled with evaporites. Distinct palaeogeographic and geological settings for the different seaways considered in this work, formed in a early North Atlantic region, have therefore implications to the perhaps 'unique geological conditions' in which the Pangea continent was rifted.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.marpetgeo.2020.104705.

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