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A phase of transient subsidence, sediment bypass and deposition of regressive–transgressive cycles during the breakup of Iberia and Newfoundland

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ABSTRACT

Seismic, outcrop and well data from West Iberia and Newfoundland are used to investigate sediment stacking patterns during continental breakup as a function of tectonic subsidence. In West Iberia, two *breakup sequences* are revealed on seismic data by marked strata offlap oceanwards from the present-day continental shelf. This character is similar to Newfoundland, where correlative strata comprise Lower Cretaceous–Cenomanian coarse-grained siliciclastics accumulated around local sediment-source areas. The interpreted data reveal that the two *breakup sequences*: 1) materialise sediment bypass onto continental-slope depocentres that experienced important tectonic subsidence during continental breakup, but without showing typical syn-rift growth packages; 2) generate specific forced-regressive stratigraphic intervals that relate to uplift and exhumation of the proximal margin. Subsidence and sediment stacking patterns in both West Iberia and Newfoundland reflect similar continental breakup processes as they evolved from the upper lithosphere- to their mantle-breakup stages. On both margins, coarse-grained siliciclastic units on the proximal margin give rise to thick shaley successions in deep-water basins. This work also confirms that in a setting dominated by a significant sediment influx, yet lacking the burial rates of continental slope basins in Newfoundland, West Iberia comprised accommodation-driven basins during continental breakup, not necessarily sediment starved. As a corollary of our analysis, we classify *breakup sequences* around the world based on the characteristic lithologies of their regressive–transgressive depositional cycles.

1. Introduction

Rift basins developed on future continental margins experience periods of enhanced subsidence that precede continental breakup by 10s of Ma (Peron-Pinvidic and Manatschal, 2009; Pérez-Gussinyé, 2012; Brune et al., 2014; Jeanniot et al., 2016). Yet, the last stages of rifting leading to continental breakup also record tectonic uplift on proximal areas of continental margins, exhuming older syn-rift strata deposited landward from a hinge zone (Jansa and Wade, 1975), or slope fault system (Alves et al., 2009). Hinge-zone exhumation accompanies the continental breakup process *per se* (Braun and Beaumont, 1989), and reflects the characteristic two-stage plate breakup evolution of Huismans and Beaumont (2011). According to these authors, type I margins as West Iberia and Newfoundland experience crustal-necking breakup before mantle breakup is finally achieved. Type II margins such as SE Brazil and West Africa, which are wider and show a thinner upper lithosphere when compared with type I, record mantle-breakup at first before the crust is ruptured in a second regional event. Fault-cantilever models, depth-dependent stretching, isostatic compensation of mass during necking and lithospheric rupture, shear heating and mineral-phase transitions in the mantle, have all been invoked to explain hinge-zone uplift as a function of margin types and relative magmatic inputs (e.g. Kusznir and Ziegler, 1992; Braun and Beaumont, 1989; Huismans and Beaumont, 2011; Hartz et al., 2017).

Following the recognition of continental breakup as a prolonged event, Soares et al. (2012) identified a *breakup sequence* in NW Iberia and related it to the two-step breakup of continental margins in Huismans and Beaumont (2011). The *breakup sequence* partly correlates with the depositional hiatus of *breakup unconformities* formed on the proximal margin (e.g. Falvey, 1974; de Graciansky and Chenet, 1979) and is associated with a discernible unconformity-bounded stratigraphic sequence of regional

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extent, showing distinct depositional architectures to older (syn-rift) strata and younger (drift) units (Fig. 5 in Soares et al., 2012). This *breakup sequence* marks the transitional period that spans from the onset of continental breakup to the establishment of thermal relaxation as the main process controlling subsidence on fully rifted margins, regardless of the type of non-volcanic margin (type I or II), age(s) of continental breakup (Beranek, 2017), or the relative importance of magmatism to the breakup process *per se*.

This work goes beyond the published models to reveal that continental breakup in West Iberia and Newfoundland was associated with widespread (forced) regression, and sediment bypass towards continental-slope basins, in response to the exhumation of large parts of the proximal margin (Figs. 1a and 1b). We demonstrate that bypass units in continental-slope basins off West Iberia are composed of siliciclastic intervals that were chiefly deposited by gravitational processes in a tectonically active setting. We show that bypass units record a gradual transgression to form marked regressive–transgressive (R–T) depositional cycles. These depositional cycles were generated as West Iberia and Newfoundland evolved from their upper lithosphere (crustal) breakup stage to mantle breakup and ocean spreading. They form depositional sequences resolved at seismic, borehole and outcrop scales (Figs. 1c and 1d). In summary, this paper addresses the following research questions:

a) What is the architecture of *breakup sequences* in continental-slope basins, and how these strata are identified on seismic data as stratigraphic markers of continental breakup?
b) How the stacking patterns documented at borehole and outcrop relate to the subsidence histories of continental-slope and distal sedimentary basins offshore West Iberia and Newfoundland?
c) Can *breakup sequences* be classified based on their key lithological character (and depositional facies) along the Atlantic Ocean and other rifted continental margins?

2. Data and methods

2.1. Seismic and borehole analyses

Regional (2-D) seismic data from West Iberia and Newfoundland are used together with unpublished outcrop and well data (Fig. 1). The criteria of Driscoll et al. (1995), Sinclair (1995), Alves et al. (2009) and Soares et al. (2012) are used in the identification of key tectonic events affecting the North Atlantic region (Figs. 2a to 2c). Relative dates for seismic and stratigraphic units at borehole and outcrop are based on published and unpublished information from the Lusitanian Basin (Atrops and Marques, 1986; Wilson et al., 1989; Hiscott et al., 1990; Alves et al., 2003a, 2003b; Dinis et al., 2008; Turner et al., 2017), Porto Basin (Moita et al., 1996), Iberia Abyssal Plain (Wilson et al., 1996, 2001; Eddy et al., 2017), proximal NW Iberia (Groupe Galice, 1979; Boillot et al., 1989; Murillas et al., 1990, Tucholke and Sibuet, 2007), and on published data from the Canadian and Irish margins (Driscoll et al., 1995; Sinclair, 1995; Williams et al., 1999; Shipboard Scientific Party, 2004; Gouiza et al., 2017; Dafoe et al., 2015).

Unpublished information from exploration wells Pe-1, Go-1, 20B-1, 5A-1 and Lu-1 in West Iberia, together with dredge data published in Mougenot et al. (1979), are used locally to corroborate our seismic-stratigraphic interpretations. DSDP Site 398 and ODP Sites 637–641, 897–901 and 1065–1070 comprise important information used to correlate seismic-stratigraphic units across West Iberia (Fig. 1b). In detail, DSDP Site 398 drilled into Hauterivian syn-rift strata to reveal a turbidite-rich succession with intercalated debrites in West Iberia. ODP Site 1069 drilled into basement rocks and Berriasian–Valanginian syn-rift strata (unit 6) blanketed by Albian–Turonian sediment (unit 5) (Wilson et al., 2001). This same unit 5 was later correlated with the *breakup sequence* by Soares et al. (2012) (Fig. 2c).

Borehole data from Newfoundland are interpreted based on open-source information from BASIN-Natural Resources Canada (NRCan). The interpretations in this paper also benefit from published data in Tankard and Welsink (1987), Tankard et al. (1989), Withjack et al. (1998), Shipboard Scientific Party (2004) and Dafoe et al. (2015).

2.2. Well and pseudo-well backstripping

In this study, we use 1-D Airy backstripping techniques to derive the tectonic subsidence-uplift history (i.e. in the absence of sediment and water loading; Watts and Ryan, 1976; Steckler and Watts, 1978) at borehole and pseudo-well locations along the West Iberia and Newfoundland margins (Fig. 1). We analyse backstripping results from nine (9) wells on the continental shelf and upper continental slope of West Iberia (in Cunha, 2008), build eight (8) pseudo-wells in West Iberia's continental-slope basins (Fig. 1b) and six (6) well models offshore Newfoundland (Flemish Pass and Orphan basins) (Fig. 1a).

Offshore Newfoundland, subsidence models are based on published stratigraphic information from Natural Resources Canada (NRCan Basin Database) (Fig. 1a). The available paleoenvironmental data, and published palaeogeographic reconstructions (e.g. Sibuet et al., 2012), suggest shallow-water deposition during the Early Cretaceous, deepening to outer neritic and bathyal (>200 m) environments in the Late Cretaceous and Cenozoic.

The well models for the proximal margin of West Iberia were built using data from completion reports and geophysical logs (e.g. neutron porosity, sonic and density logs). Paleoenvironmental data indicate neritic (shelf) depositional environments (<200 m) in most proximal wells throughout the Mesozoic and Cenozoic (see Cunha, 2008 and Supplementary Table 1 for details on data utilised and associated uncertainties), except for wells Pe-1, Lu-1 located on the upper continental slope (Fig. 1b).

The pseudo-wells compiled for the slope basins of West Iberia (PW-1 to PW-8, Fig. 1b) are based on reliable stratigraphic constraints interpreted along TGS seismic profiles, which were depth-converted using: a) stack velocity data from TGS, and b) constraints from wide-angle seismic data (*in* Cunha, 2008). In the backstripping calculations we account for a rapid increase in paleowater depths during the latest Jurassic–Early Cretaceous as a result of advanced rifting leading to continental breakup, a character: a) in agreement with paleoenvironmental data from ODP Sites on the Iberia Abyssal Plain (e.g. Concherio and Wise, 2001; Wilson et al., 2001; Mohn et al., 2015; Figs. 2b and 2c), and b) correlating with the ages of the syn-rift and *breakup sequences* documented in this study. Due to the lack of reliable paleoenvironmental constraints beyond the continental shelf, a large uncertainty (up to 1800 m) was assumed for paleowater depths during the modelling.

For the pseudo-wells in West Iberia, and for all modelled exploration wells from Newfoundland, we use the default compaction curves provided by the Genesis petroleum systems modelling software Zetaware Inc. (see Supplementary Tables 1 and 2 for parameterisation). For the eustasy term of the backstripping equation we assume the Steckler and Watts (1978) sea-level curve, which is based on the backstripping analysis of wells offshore USA's East Coast, where the syn- and post-rift depositional records are well preserved. It should be noticed that potential basin exhumation events have not been modelled due to the lack of apatite fission-track and organic matter maturity data. Thus, the upward shifts observed in tectonic subsidence curves for the proximal margin of West Iberia are due to sea-level rises in the absence of sedimenta-

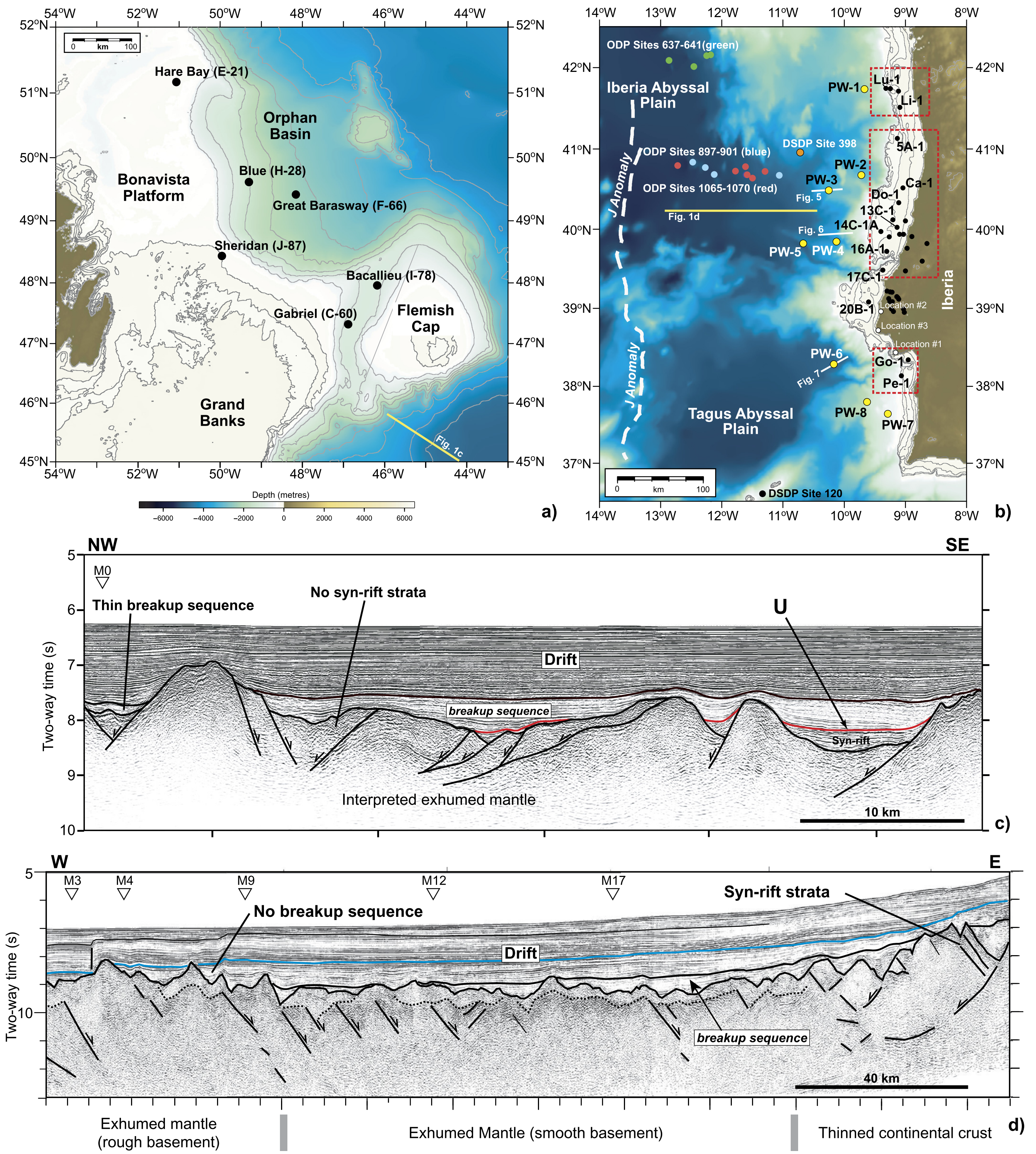

Fig. 1. a) Bathymetric map from offshore Newfoundland highlighting the seismic and borehole data interpreted in this work. b) Bathymetric map of West Iberia highlighting the location of industry wells, DSDP and ODP wells, pseudo-wells (PW-1 to PW-8), and interpreted seismic data. Red boxes indicate the areas in West Iberia in which borehole data were modelled. Outcrop locations 1 to 3 are also highlighted on the map. c) Interpreted segment of the SCREECH 2 seismic transect acquired across the Newfoundland margin. The U reflection is marked in red, and represents a bright seismic reflection that overlies transitional crust throughout the Newfoundland Basin (Karner and Shillington, 2005). At some places, the rugged basement between fault blocks may consist of slumped serpentinite. d) Interpreted segment of the IAM9 seismic transect across the Iberia Abyssal Plain margin. The IAM9 transect is located about 40 km south of the drilling transect LG12. The seismic profile (Pickup et al., 1996) shows open triangles that refer to M-Series magnetic anomalies interpreted by Srivastava et al. (2000). Vertical grey lines mark the limit between thinned continental crust and transitional lithosphere on the right and the boundary between smooth and rough basement within transitional lithosphere on the left. See Figs. 1a, 1b and 3a for location of the seismic profiles, which show an interpretation modified from Sibuet and Tucholke (2012). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

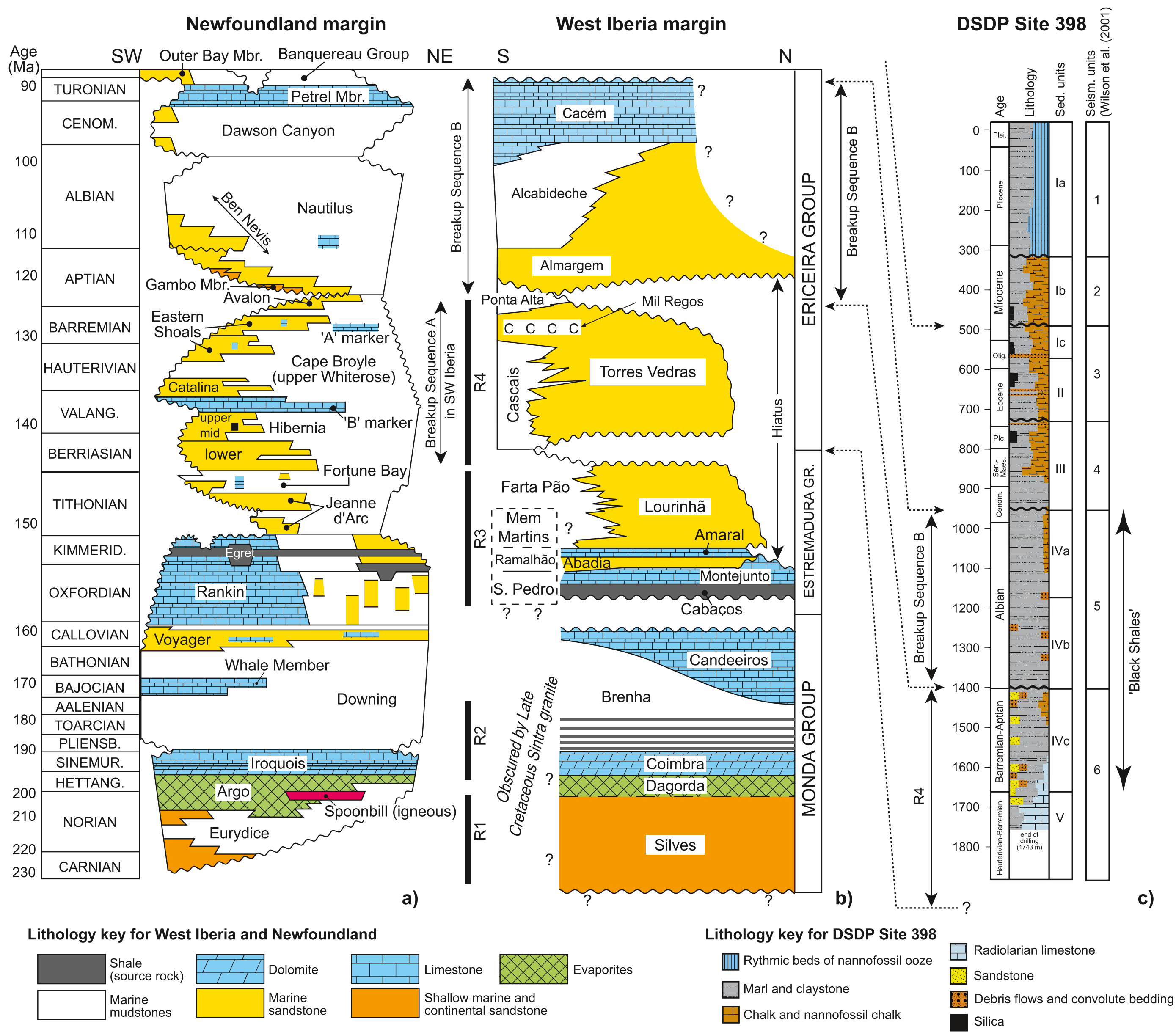

Fig. 2. Stratigraphic panels correlating units in both Newfoundland and West Iberia from the onset of continental rifting in the Triassic, to its end in the Turonian. a) Stratigraphy of the Jeanne d'Arc Basin and its NE continuation towards the Flemish Pass Basin. Note that *breakup sequences* A and B occur on both the Newfoundland and West Iberian margins. b) Stratigraphy of the Alentejo, Lusitanian and Porto basins on the proximal margin of West Iberia. Note the marked hiatus between Aptian and Upper Jurassic strata in NW Iberia, in the region to the north of the Nazaré Fault (see Fig. 3a). c) Lithological data for DSDP Site 398 revealing the character of syn-rift strata, Breakup Sequence B and drift units drilled offshore Porto. The panel in a) was modified from Sinclair (1995). The panel in b) is modified from Wilson et al. (1989). The column in c) is based on Groupe Galice (1979) and Réhault and Mauffret (1979). (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

tion, e.g. in the Berriasian–Valanginian, Cenomanian and Turonian–Maastrichtian.

3. Geological setting

3.1. Newfoundland margin

The Grand Banks area comprises a series of large sedimentary basins that are parallel to the continental slope to the south (Jeanne d'Arc, Flemish Cap Basins), and to the north towards the Orphan area (Fig. 3a). The Orphan Basin experienced continental breakup after the Aptian–Albian boundary, making it slightly younger than the Grand Banks basins (Gouiza et al., 2017). In comparison, the Jeanne d'Arc and Flemish Cap basins have strong affinity with SW Iberia in terms of the ages of main stratigraphic units and their continental breakup histories. The Newfoundland Margin is, nevertheless, characterised by a much wider (up to 350 km) and sediment-laden continental shelf (Grand Banks region) recording up to 18 km of strata (Tankard and Welsink, 1987).

The Grand Banks are located within the Appalachian orogenic belt and underlain by Precambrian–Paleozoic basement rocks of the Avalon terrane (Haworth and Keen, 1979). On a regional scale, its structure is characterised by an area of relatively unstretched crust, the Bonavista Platform, which extends 100–200 km to the east of Newfoundland (Fig. 3a). The Bonavista Platform is surrounded by a number of Meso-Cenozoic rift basins that form an arcuate pattern between the Charlie Gibbs and the Newfoundland Fracture Zones (e.g. Tankard and Welsink, 1987). The geometry and distribution of these basins is primarily controlled by the Mesozoic reactivation of pre-existing tectonic fabrics in Paleozoic rocks (Haworth and Keen, 1979; Enachescu, 1988).

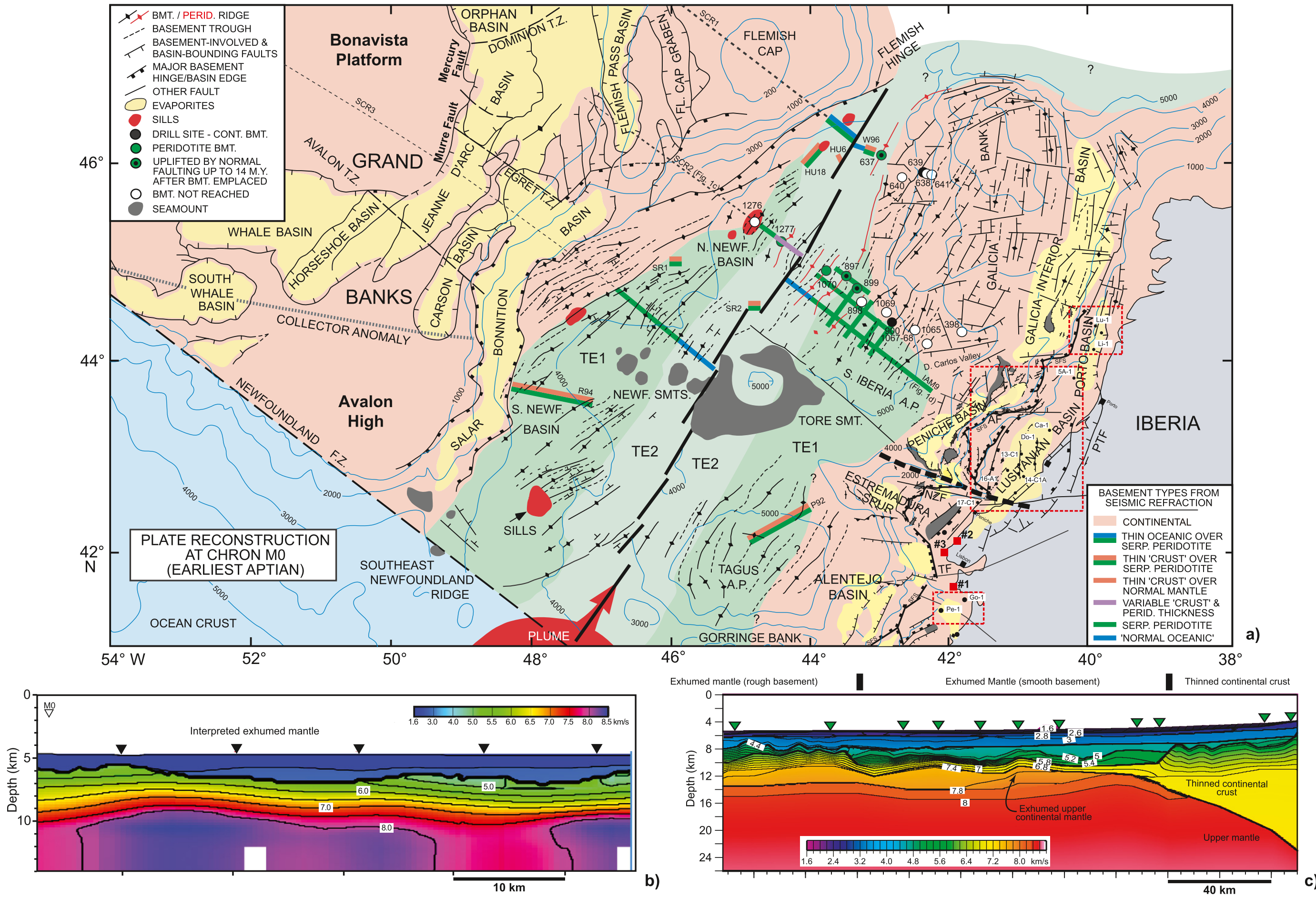

Fig. 3. a) Paleogeographic evolution of West Iberia and Newfoundland. The figure highlights the main sedimentary basins in Newfoundland and West Iberia, and principal structures separating different highs and depocentres on the two margins. Red dotted boxes highlight the location of wells modelled in this paper. Seismic profiles in Figs. 1c and 1d are also shown in the map. The map is modified from Tucholke and Sibuet (2007). b) Refraction profile across the seismic line in Fig. 1d, as adapted from Dean et al. (2000). Triangles show Ocean Bottom Seismometer (OBS) locations on the sea floor. Numbers are velocities in km s^{-1}. c) Velocity model for the seismic profile in Fig. 1c, as modified from Van Avendonk et al. (2006). Triangles show OBS locations on the sea floor. Numbers are velocities in km s^{-1}. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

The main rift basins in the Grand Banks region are the Orphan Basin in the north, the Jeanne d'Arc, Flemish Pass and Carson basins in the central sector, and the Whale and Horseshoe basins in the south (Fig. 3a). They are characterised by distinct basin styles and are separated by 1st-order transfer faults (Tankard and Welsink, 1987). In the Jeanne d'Arc and Carson basins, listric normal faults (the Murre and Mercury faults) accommodate relatively large amounts of extension (Fig. 3a). These faults cut deep into the crust and sole out in dipping-to-the-west intracrustal décollements (Tankard and Welsink, 1987; Driscoll et al., 1995).

The Jeanne d'Arc Basin is the largest syn-rift basin in the Grand Banks region, and was established in the Late Triassic with the accumulation of fluvial and lacustrine sediments, followed by widespread deposition of evaporite deposits during the latest Triassic–earliest Jurassic period (Tankard and Welsink, 1987) (Figs. 2a and 3a). This first rifting episode is followed by pronounced post-rift thermal subsidence, which records the accumulation of over 5 km of interbedded sequences of marine sandstones, shales and carbonates during the Middle Jurassic (Tankard and Welsink, 1987; Grant, 1988) (Fig. 2a). The Upper Triassic–Middle Jurassic stratigraphic sequence in Newfoundland is similar to that found in the Lusitanian and Porto basins, along the onshore portion and continental shelf of West Iberia, but is 2–3 times thicker (e.g. Tankard and Welsink, 1987; Wilson et al., 1989) (see Fig. 3b).

The onset of the Late Jurassic rift event in the Grand Banks is marked by a basinwide unconformity. This short-span rift episode is followed by the deposition of carbonates (Rankin Formation), shales (Egret Formation) and coarse-grained sandstones in the Jeanne d'Arc Formation (Tankard and Welsink, 1987; Tankard et al., 1989; McAlpine, 1990) (Fig. 2a). These formations, and overlying Cretaceous deposits in Newfoundland, have lateral equivalents in West Iberia (Figs. 2b and 2c).

3.2. West Iberia margin

West Iberia comprises a rifted continental margin with more than 40 discrete sub-basins recognised in deep-offshore regions (Alves et al., 2009). Major tectonic lineaments subdivide West Iberia into a SW Sector associated with the Tagus Abyssal Plain, and a NW Sector associated with the development of the Iberia Abyssal Plain (Figs. 1b and 3a). The continental slope dips gently to the west in SW Iberia, where thick Cretaceous–Cenozoic sediments were accumulated oceanwards of a wide region of Late Cretaceous–Early Cenozoic exhumation and erosion (Alves et al., 2003a; Pereira et al., 2011, 2017). In contrast, the continental shelf of NW Iberia is limited by the 100–120 m isobaths and does not exceed 60 km in width. Beyond the continental shelf of NW Iberia, an abrupt bathymetric drop was created by a slope fault system that separates continental-slope basins from the proximal Lusitanian and Porto basins since, at least, the late Mesozoic

(Figs. 1b and 3a). Seamounts along the continental slope of West Iberia generally comprise non-volcanic rift-related horsts, some of which were uplifted during latest Cretaceous–Cenozoic inversion (Mougenot et al., 1979; Alves et al., 2003a).

Basement units beneath the continental margin of West Iberia comprised, at the time of the Triassic rift onset, a set of thick Variscan terrains (Capdevila and Mougenot, 1988). Crustal thickness is considered to have been substantially larger at this time in West Iberia when compared to Newfoundland, which occupied a more peripheral position in relation to the Variscan Orogen (Capdevilla and Mougenot, 1988; Mohn et al., 2015). The Variscan basement of West Iberia's deep-offshore basins has recently been interpreted as part of a new terrain (Ribeiro et al., 2013). In the absence of data proving this later postulate, it is plausible to consider the Variscan terrains of West Iberia as continuing offshore following the general NW to ESE trends recorded at outcrop. This assumption is based on evidence from offshore basins, with NW- to ESE-trending rift-related structures developing over (and mimicking) Variscan structures and the trends of the basement fabric documented onshore. However, the extent and limits of some of the Variscan terrains are not fully known underneath the deep-offshore basins of West Iberia.

3.3. Mesozoic syn-rift and breakup sequences

Sedimentary basins in West Iberia reveal three major Mesozoic syn-rift episodes: Triassic (rift 1), Sinemurian–early Pliensbachian (rift 2) and late Oxfordian (rift 3) (Stapel et al., 1996; Leinfelder and Wilson, 1998; Alves et al., 2003b) (Fig. 2b). Rift 4 is recorded in continental-slope basins west of the Lusitanian Basin, Porto Basin, and in the zone of 'transitional' crust drilled by ODP Legs 149 and 173 (Figs. 2c and 3a). Late Oxfordian–early Kimmeridgian extension in the Lusitanian Basin marks the onset of ocean spreading in SW Iberia (Wilson et al., 1989) or, as also suggested, precedes it by a few millions of years (Valanginian; Pinheiro et al., 1992, 1996). Alternative models consider continental breakup in SW Iberia as coinciding with the oldest magnetic anomaly in the Tagus Abyssal Plain (M20; 147 Ma), i.e. being late Tithonian in age (Srivastava et al., 2000) (Figs. 2b and 3a). Such an age correlates with rifting and continental breakup in the southern part of the Grand Banks, and with the significant syn-rift subsidence recorded in the basins around the Bonavista Platform, Northern Newfoundland, during the Early Cretaceous (Wilson et al., 1989; Sinclair, 1995; Nova Scotia Department of Energy, 2016). Hence, the oldest breakup unconformity in Iberia should be earliest Cretaceous in age and restricted to SW Iberia (Alves et al., 2009). This first breakup unconformity precedes a younger Aptian–Albian stratigraphic boundary developed in the northernmost portion of West Iberia into the Bay of Biscay (Soares et al., 2012; Eddy et al., 2017). Multiple *breakup sequences* were thus deposited in both West Iberia and Newfoundland as continental breakup propagated northwards and oceanwards. In West Iberia, as in Newfoundland, the youngest *breakup sequence* occurs above the Aptian–Albian unconformity (U reflector offshore Newfoundland), and is shown as a transparent to low-amplitude interval of black shales topped by strong seismic reflections in the 'drift' sequence (Figs. 1c and 1d).

4. Outcrop evidence of sediment bypass during continental breakup

In West Iberia, the bases of two Berriasian–Valanginian and Aptian–lower Turonian *breakup sequences* are marked by the sudden influx of coarse-grained siliciclastic deposits, and follow an architecture typical of forced-regressive systems tracts (e.g. Plint and Nummedal, 2000). Figs. 4a–4c show examples of these forced-regressive episodes at coastal outcrops in the Lisbon region.

At location #1 (Espichel Cape), the Berriasian forced regression is marked by prograding (deltaic and fluvial) sandstones and conglomerates deposited over marine sands (Farta Pão formation) and karstified upper Jurassic limestones (Rey et al., 2006) (Fig. 4a). Berriasian sandstones and conglomerates, part of Breakup Sequence A, correlate with widespread sand belts (deltaic and fluvial) that prograded from north and northeast during a main stage of basement rejuvenation and fault activity (Alves et al., 2009). At location #1, the Berriasian forced regression is marked by the sudden influx of quartz-pebble conglomerates and sandstones (Vale de Lobos unit, Rey et al., 2006), which are representative of continental environments with very minor marine influence (Fig. 4a). This episode gives gradually way to a transgressive maximum around the Valanginian–Hauterivian boundary, i.e. synchronously with the rift-climax stage recorded by DSDP and ODP data in NW Iberia (Groupe Galice, 1979; Wilson et al., 2001). The Berriasian forced-regressive unit is a lateral equivalent of nodular lime mudstones with cyclinid foraminifera, minor sandstones and oyster-encrusted firmgrounds outcropping northwest of Lisbon. Close to Lisbon, the Berriasian forced-regressive strata are also unconformable over lowstand units (Farta Pão formation); these latter deposited at the end of the Late Jurassic, and marine carbonates and marls of the Mem Martins unit (Wilson et al., 1989) (Fig. 2b).

Location #2 (Praia da Calada) shows a similar regressive event in the form of upper Berriasian unchannelised sandstones (Torres Vedras formation; Breakup Sequence A) accumulated over uppermost Jurassic–earliest Berrianian channel-fill and flood-plain deposits representative of fluvial environments (Lourinhã Formation) (Fig. 4b). At this location, the base of upper Berriasian strata is erosional and dominated by quartz-pebble conglomerates and sandstones (Fig. 4b). Shale-bearing sandstones and thin (cm-scale) intervals of grey mudstone occur towards the top of this regressive unit, where *Thalassinoides* and *Skolithos* burrows are also observed.

Location #3 (Praia da Crismina), records the sudden influx of shallow-marine sandstones in Breakup Sequence B over shaley carbonate-shelf deposits (Rey et al., 2006) (Fig. 4c). Lower Aptian carbonates are overlain by fine and medium-grained micaceous sandstones of upper Aptian–Albian age, which represent braided-river and estuarine deposits marking the base of the Almargem formation (Rey et al., 2006) (Figs. 2b and 4c). Conglomeratic levels, representing channel-fill deposits, occur inland from location #3, and are lateral equivalent to shelval and fluvial siliciclastics deposited above uppermost Jurassic strata north of Nazaré (Dinis et al., 2008). These deposits reveal transgressive 2nd-order cycles until the Turonian (e.g. Rey et al., 2006; Soares et al., 2012).

5. Correlative forced-regressive units in offshore basins

5.1. Newfoundland margin

In the Jeanne d'Arc and Flemish Pass Basins, multiple siliciclastic intervals correlate with forced-regressive strata in West Iberia (Figs. 2a and 2b). In both West Iberia and Newfoundland, regressive intervals are associated with continental breakup in some margin sectors, while recording syn-rift extension in sectors that were not yet posed to full breakup (Wilson et al., 2001; Soares et al., 2012; Eddy et al., 2017).

Figs. 2a and 2b show a correlation panel between such a regressive strata and equivalent shales/mudstones in deep-water basins. Of importance is the recognition of the Torres Vedras formation in West Iberia as equivalent to the Hibernia/Catalina/Eastern Shoals/Avalon Formations in Newfoundland, and the Almargem formation as equivalent to the Ben Nevis Formation (Fig. 2). All these units comprise fluvial/deltaic to siliciclastic shelf units on both margins, and are interbedded with shaley intervals associated with

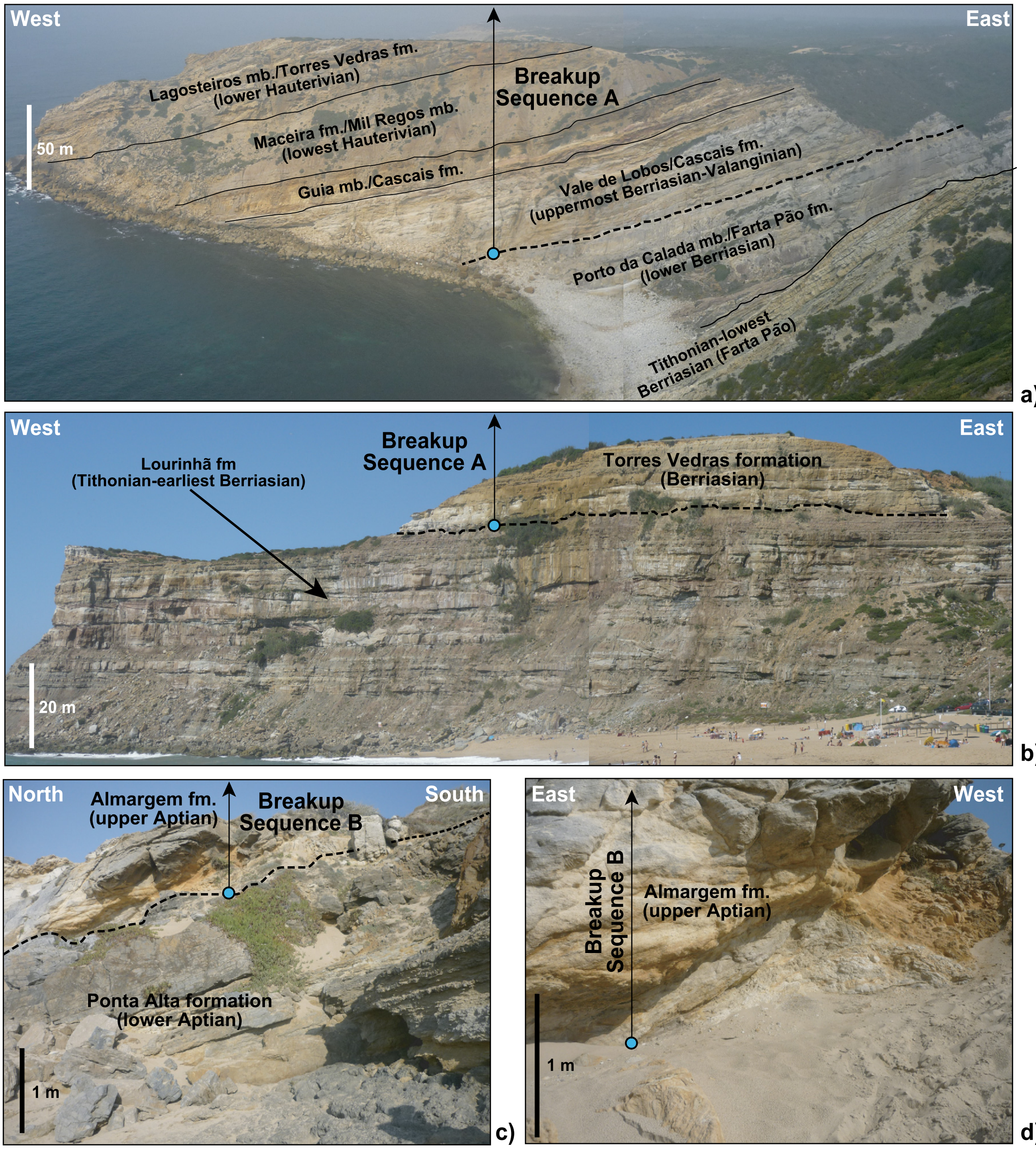

Fig. 4. Selected photographs showing key outcrops of *breakup sequences* A and B. See Figs. 1b and 3a for location. a) Location #1 (Espichel Cape) south of Lisbon showing the base of the Vale de Lobos formation, which represents the forced-regressive episode marking the base of Breakup Sequence A (Fig. 2). b) Location #2 (Porto da Calada) illustrating the base of Breakup Sequence A and the influx of unchannelised fluvial material in the Torres Vedras formation. c) and d) Base of Breakup Sequence B at Location #3 (Praia da Crismina) as documented at outcrop. At this location, fluvial sandstones of Aptian age were emplaced over a karst surface topping carbonates of the Ponta Alta formation (see Fig. 2b).

transgressive episodes. Clastic influence from continental sediment sources was more pronounced in West Iberia's continental shelf and onshore basins, and should lead to deeper marine facies in continental slope basins, in essence equivalent to the Cape Broyle and Nautilus Formations offshore Newfoundland (Fig. 2a).

5.2. West Iberia margin

Figs. 5–7 show seismic profiles crossing the Iberia and Tagus Abyssal Plains. The profiles highlight distinct intervals of chaotic to partly continuous seismic reflections that terminate against the slope fault system, i.e. offlapping the continental slope but not showing typical syn-rift growth packages, and thus reflecting widespread regressive events in West Iberia. Two distinctive features are observed in these essentially chaotic seismic units: a) draping and thinning of strata onto slope-bounding faults and associated bathymetry, which occurred together with enhanced footwall degradation and axial flow(s) of sediment parallel to syn-rift topography; b) a predominance of mass-wasting and turbiditic deposits in these successions, as also revealed by DSDP and ODP borehole data (Figs. 2c and 3a). Such a depositional pattern is strongly clustered along syn-rift faults that bound both the modern continental slope and older (Mesozoic) rift basins.

Offlapping, regressive stratigraphic intervals were drilled by wells Pe-1 and Go-1 in SW Iberia, and Li-1 and Lu-1 in NW Iberia (Figs. 1b and 3a). Wells Li-1 and Go-1 are located on the proximal margin, on what was the Cretaceous continental shelf at the time of continental breakup. In contrast, wells Lu-1 and Pe-1

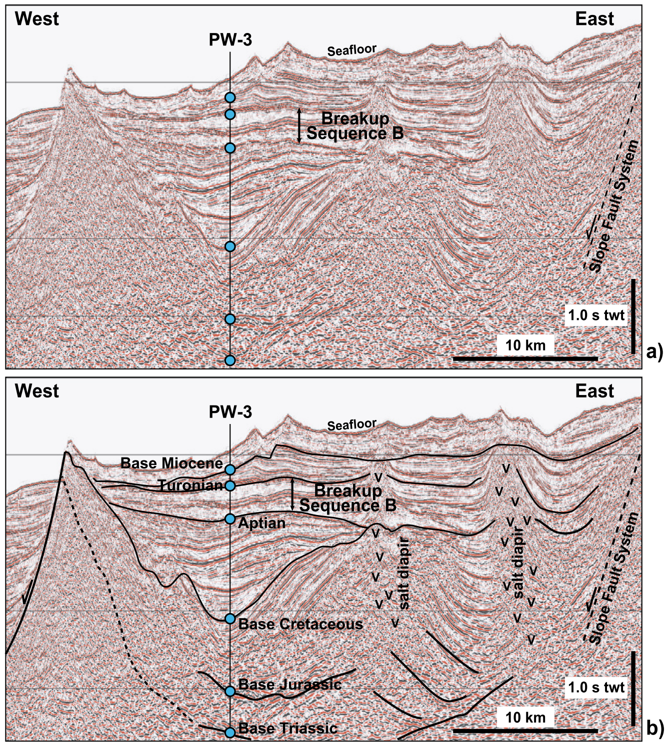

Fig. 5. a) Uninterpreted and b) interpreted seismic profile from NW Iberia highlighting the location of pseudo-well 3 (PW-3), the time-depth of key seismic markers used to model subsidence, and the relative position of Breakup Sequence B. The location of the seismic profile is shown in Fig. 1b.

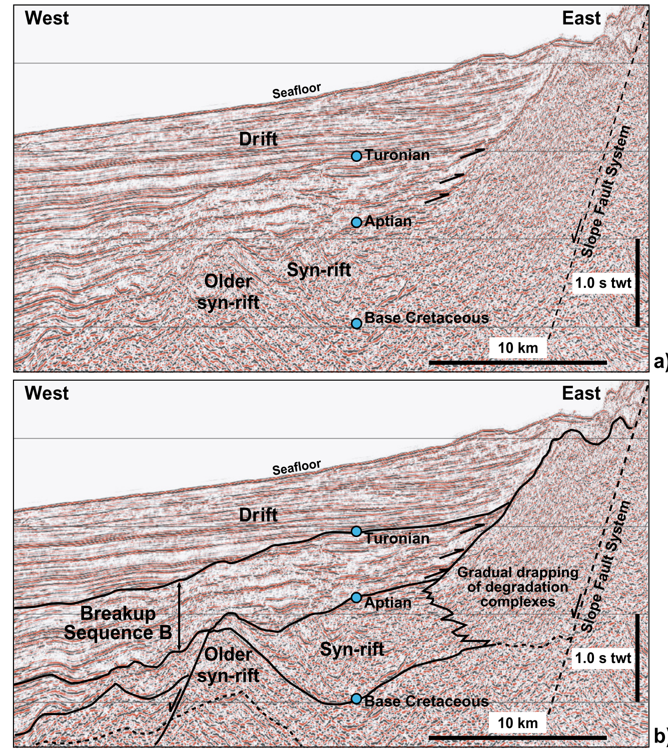

Fig. 6. a) Uninterpreted and b) interpreted seismic profile from NW Iberia revealing the time-depth of key seismic markers used in our subsidence models, and the relative position of Breakup Sequence B. The location of the seismic profile is shown in Fig. 1b.

were drilled in upper slope areas flanking continental-slope basins (Figs. 1b and 3a).

5.2.1. SW Iberia

The basal, regressive strata in wells Go-1 and Pe-1 (SW Iberia) correlate with the regressive upper Berriasian siliciclastics (at the base of Breakup Sequence A) outcropping in locations #1 and #2 (Figs. 1b, 3a and 8a). Onshore, the sequence reflects shallow marine to fluvial environments (Dinis et al., 2008), and marks the onset of continental breakup in the Tagus Abyssal Plain (Figs. 2b, 3a and 8a). This first regressive episode is followed by a transgressive event of probable Hauterivian age that is equivalent to a maximum flooding episode in the Cape Broyle Formation, offshore Newfoundland (Fig. 2a). This flooding episode is recorded, in West Iberia, by the Santa Suzana and Maceira members of the Cascais formation (Rey et al., 2006) (Fig. 2b).

5.2.2. NW Iberia

On continental-shelf and onshore basins of NW Iberia there is a recognised hiatus between uppermost Jurassic strata and regressive Aptian siliciclastics (Almargem formation; Wilson et al., 1989) (Fig. 2b). A similar regressive system to the Almargem formation, of shallow marine to fluvial affinity, coincides with the onset of continental breakup in the Iberia Abyssal Plain (NW Iberia) during the late Aptian (Wilson et al., 2001; Soares et al., 2012; Eddy et al., 2017) (Figs. 2b). Whereas in well 5A-1 almost all Cretaceous strata are missing, well Lu-1 crossed >800 m of Cretaceous units that record a marked increase in tectonic subsidence during the Early Aptian (Fig. 9).

In NW Iberia, regressive strata at the base of Breakup Sequence B were deposited above tilted siliciclastics and marls of lower Aptian and older ages (Figs. 2b, 5 and 6; see also Mohn et al., 2015). At DSDP Site 398 and ODP Site 641, this same Aptian regressive event is recorded by the sudden influx of coarse debris flows and slumped material accumulated in between intervals of black shales (Réhault and Mauffret, 1979; Soares et al., 2012) (Fig. 2c). Clastic influence from continental sediment sources was pronounced at this stage, contrasting with older syn-rift strata below and with post-Cenomanian drift units. In parallel, fault-scarp erosion is documented by the presence of breccias and debris flows with reworked Calpionellid-bearing limestones at borehole (Sibuet and Ryan, 1979; Dupeuble et al., 1987). These strata represent shallow marine facies typical of near-emergent footwall blocks (see also Azéma and Jaffrezo, 1983). Importantly, Breakup Sequence B reflects tectonic reactivation along the West Iberia margin, with marked rejuvenation of local sediment sources.

6. Analysis of tectonic subsidence curves

6.1. Newfoundland continental-slope basins

The backstripping results for Newfoundland reveal a marked contrast between extensional basins inboard of a continental slope fault system, where Lower Cretaceous (possibly including uppermost Jurassic) strata sit on top of Paleozoic basement (wells E-21 and J-87; NRCAN Basin database), and more distal basins to the east of this same system (wells F-66 and H-28; Figs. 1a, 3a).

The onset of latest Jurassic–Early Cretaceous extension in Newfoundland is interpreted to coincide with an episode of enhanced subsidence in continental-slope basins, with deposition of forced-regressive strata that are equivalent to the lower Hibernia Formation in the Jeanne d'Arc Basin (Fig. 2a). The age of this marked subsidence pulse is consistent with that inferred from well backstripping in the Jeanne d'Arc basin (Bauer et al., 2010), but of higher magnitude in continental-slope basins. The tectonic subsidence curves also suggest some diachronism between the Late Jurassic–Early Cretaceous rifting of the West Orphan (F-66), North Flemish Pass (I-78) and Southern Flemish Pass (C-60) basins, al-

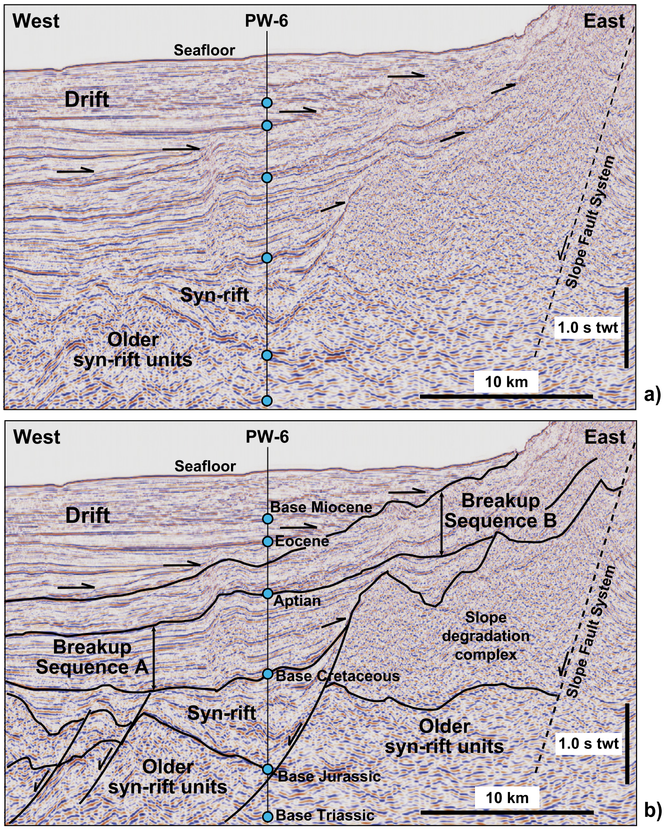

Fig. 7. a) Uninterpreted and b) interpreted seismic profile across SW Iberia with the location of pseudo-well 6 (PW-6), the time-depth of key seismic markers used in our subsidence models, and the relative position of Breakup Sequences A and B. The location of the seismic profile is shown in Fig. 1b.

though in this latter the upper Early Cretaceous subsidence pulse may be associated with post-rift wrenching (Foster and Robinson, 1993). A final period of subsidence is then recorded in the Late Cretaceous–early Paleogene as Greenland and Canada were rifted apart (Hosseinpour et al., 2013), with large volumes of sediment being deposited in the West Orphan Basin at this time (wells H-28, J-87 and E-21) (Fig. 8c).

6.2. West Iberia continental shelf (exploration wells)

All modelled exploration wells from West Iberia show pronounced basement subsidence during Late Triassic–Early Jurassic rifting, followed by post-rift thermal quiescence (Fig. 8d). This prolonged period of quiescence was followed by a major depositional hiatus reflecting the exhumation of structural highs marginal to subsiding basins during Late Jurassic–Early Cretaceous rifting (e.g. wells 14C-1A, Do-1 and 5A-1; Figs. 1b, 3a and 8d). In essence, the Late Jurassic–Early Cretaceous rifting episode was focused to the west of the continental shelf and, consequently, tectonic subsidence curves in proximal (shelf) areas, around wells 14C-1A, Do-1 and 5A-1, contrast with that inferred at well Lu-1 located on the upper continental slope of NW Iberia (Porto Basin; Figs. 1b, 3 and 8d). A similar pattern of accelerated subsidence is recorded in continental-slope basins offshore Newfoundland during this time period (Figs. 1a and 8c). In contrast, well Pe-1 in SW Iberia records pronounced subsidence in the late Mid Jurassic–early Late Jurassic, a character suggesting diachronism of rifting along West Iberia (Alves et al., 2009) (Fig. 8d).

6.3. West Iberia continental-slope basins (pseudo-wells)

Pseudo-wells PW-1 to PW-3 in the Galicia Interior and Northern Peniche basins (Fig. 3a), show 'typical' syn-rift subsidence during the Late Triassic–Early Jurassic, followed by prolonged, Early to Late Jurassic tectonic quiescence. The latest Jurassic–Early Cretaceous rift event is then characterised by an acceleration in tectonic subsidence associated with an increase in paleowater depths (Fig. 9d). In contrast, PW-5 and PW-4 (located on structural highs) only show moderate to very moderate Mid–Late Jurassic subsidence. (Fig. 9d).

In SW Iberia, PW-6 to PW-8 suggest sag-like subsidence, at a near-constant rate, throughout the Late Triassic–Late Jurassic. In PW-6 and PW-8, located on the continental slope, Early Cretaceous subsidence is well defined, and occurs together with a marked increase in paleowater depths, as also constrained by borehole data on the shelf and seismic-stratigraphic information (see Alves et al., 2009). This same pulse was followed by prolonged, typical post-rift tectonic quiescence after 90 Ma (Turonian) (Fig. 9d).

We tested the models' sensitivity to large uncertainties in the syn- and early post-rift paleowater depths, between a conservative (shallow) and maximum value, with a variation of up to 1800 m. As depicted in Fig. 9c, the assumption of an uncertainty range for paleowater depth changes the relative proportions of syn- and post-rift subsidence, and has implications for the parameterisation of the rift model and of crust/mantle stretching factor estimations (e.g. Stewart et al., 2000). This uncertainty, however, does not necessarily affect the interpretation of *breakup sequences*, which show specific seismic-stratigraphic patterns (and distributions) on regional seismic data (Figs. 1c, 1d and 5–7). In most wells drilled on the continental shelf, the uncertainty in paleowater depths is relatively small (<100 m).

7. Discussion

7.1. Sediment influx into slope basins during continental breakup

The principal question arising from our subsidence models, and interpreted seismic-stratigraphic data, is why has such a moderate volume of material been accumulated on the continental slope and rise of West Iberia whereas, comparatively, continental-slope basins in Newfoundland show significantly thicker Cretaceous and Cenozoic strata? The geometry and subsidence histories of tilt-blocks in Newfoundland are key to understand this difference; they form extended crustal blocks off the Grand Banks and the Orphan Basin, some of which constituted barriers to sediment sourced from relatively broad areas (Tucholke and Sibuet, 2007; Dafoe et al., 2015). The relatively small size of Iberia as an isolated tectonic plate would have also hindered the sourcing of larger volumes of sediment into continental-slope basins. In addition to the latter point, the tectonic subsidence curves in this work show an important enhancement of subsidence in West Iberia that contrasts with basins in Newfoundland (Figs. 8c and 8d).

Enhanced subsidence in continental-slope basins of West Iberia can be explained: a) by continuous subsidence through the Jurassic–Early Cretaceous rifting phases, or b) by assuming a marked shift in tectonic subsidence towards the locus of continental breakup in the Tagus and Iberia Abyssal Plains, in the latest Jurassic–Early Cretaceous (see Alves et al., 2009). We now consider the latter hypothesis to be the most plausible, as the subsidence models in this paper quantify tectonic subsidence in excess of 3000 m in continental-slope basins of West Iberia during the crustal stretching phases that immediately preceded, and accompanied, continental breakup in the Iberia Abyssal Plain (Late Aptian–Turonian) and, presumably, in the Tagus Abyssal Plain

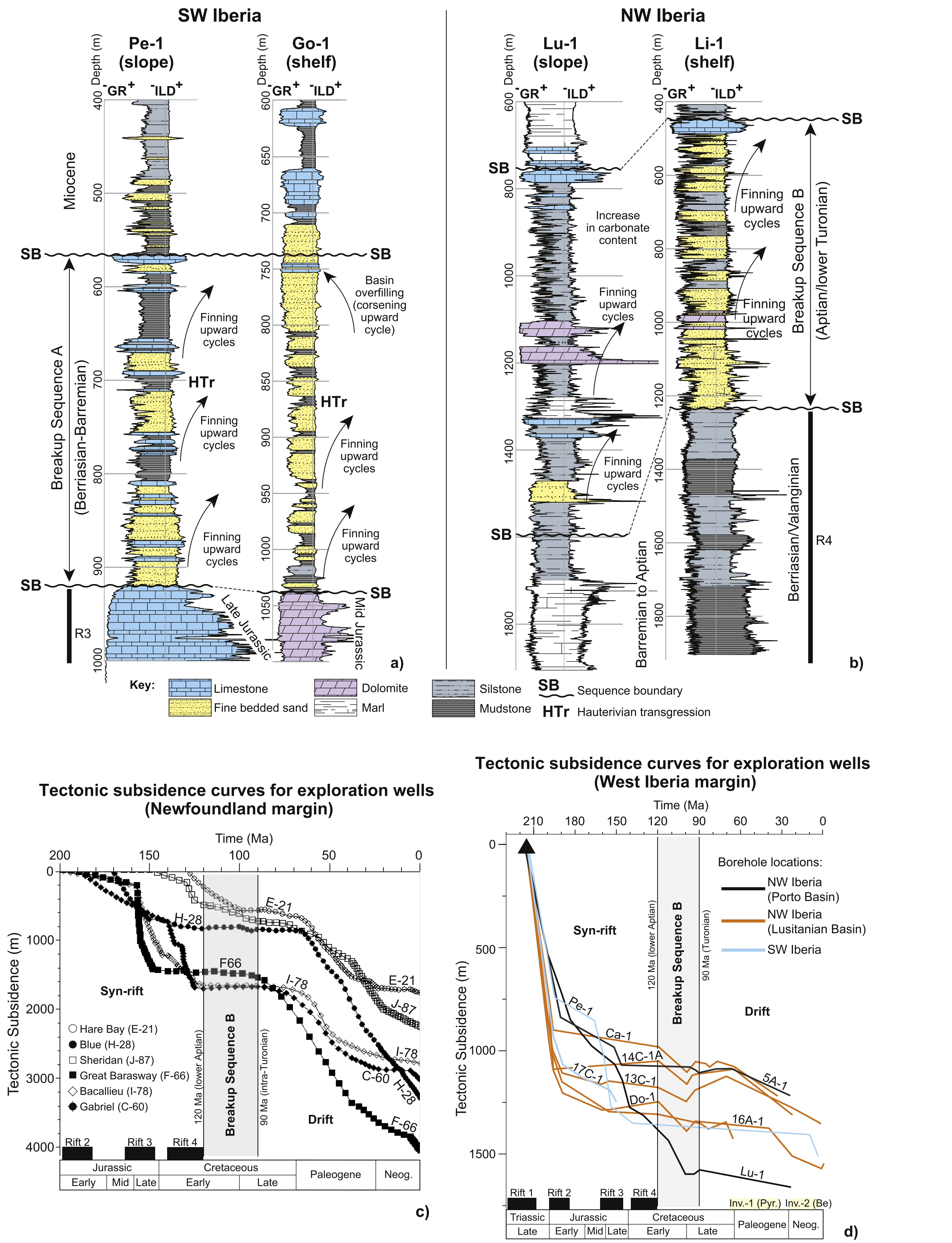

Fig. 8. a) Lithological, gamma-ray (GR) and deep-resistivity (ILD) for wells Pe-1 and Go-1 in SW Iberia, compared with b) wells Li-1 and Lu-1 in NW Iberia. c) Backstripped subsidence curves for key industry wells on the Newfoundland margin. d) Backstripped subsidence curves for key industry wells in West Iberia based on Cunha (2008). Location of wells in Figs. 1b and 3a. (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

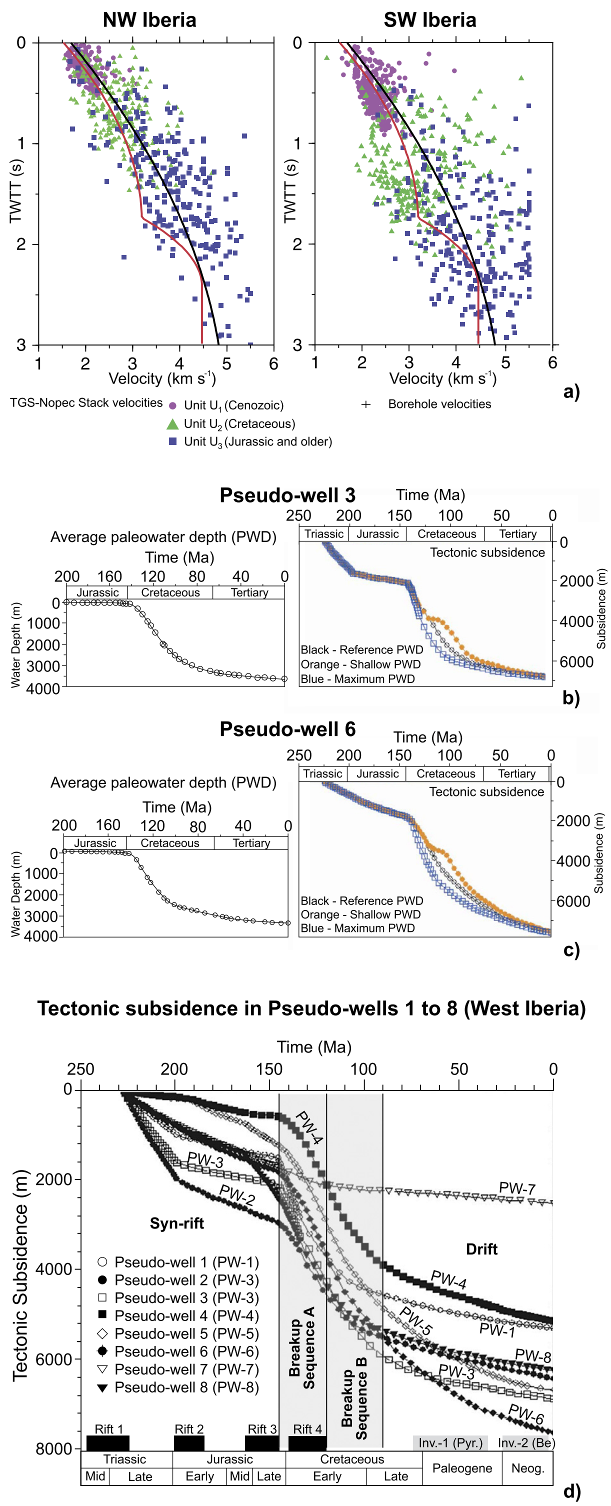

Fig. 9. a) Pre-stack velocity curves from TGS data interpreted in this work. On the two graphs are shown the p-wave velocity distributions for NW and SW Iberia. Average velocities were used in the subsidence models for pseudo-wells 1 to 8. The solid black line corresponds to the two-way travel time (TWTT) velocity function derived from the interval velocities in TGS seismic profiles (Cunha, 2008). The solid red line is the TWTT velocity function derived from Dean et al. (2000) for the Southern Iberia Abyssal Plain, based on wide-angle seismic data. b) Estimated paleowater depth and tectonic subsidence estimated for pseudo-well 3 (NW Iberia). c) Estimated paleowater depth and tectonic subsidence estimated for pseudo-well 6 (SW Iberia). d) Tectonic subsidence curves for pseudo-wells 1 to 8, NW and SW Iberia. Note the subsidence curves for reference (average), shallow (conservative) and maximum paleowater depths in Figs. 9b and 9c. The location of the pseudo-wells is shown in Fig. 1b. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

during the Early Cretaceous (Fig. 9). In essence, latest Jurassic–Early Cretaceous tectonic subsidence in continental-slope basins was more intense than that recorded during the Triassic–Middle Jurassic (Fig. 8c, 8d and 9). In comparison, after a peak in subsidence around the Oxfordian–Kimmeridgian boundary (Wilson et al., 1989), the Lusitanian Basin and onshore parts of the SW Iberia record widespread sea-level fall during the late Kimmeridgian, and subsidence was minimal on the proximal margin by the time rift 4 (Berriasian–early Aptian) was developing in NW Iberia (Fig. 2).

The recognition of >3000 m of Early Cretaceous subsidence in PWs 1–3, 5–6 and 8 indicates that subsidence in continental-slope basins of West Iberia did not result from the superposition of discrete extensional episodes, but rather from moderate, prolonged Triassic-Jurassic subsidence followed by an abrupt extensional pulse in the latest Jurassic–Early Cretaceous (Fig. 9). This same period of transient (and enhanced) tectonic subsidence is not only related to a shift in the principal locus of extension towards the present-day Tagus and Iberia Abyssal Plains; it also accounts for: a) the relatively large water depth of basins in West Iberia's continental slope, as observed at present, b) the generation of thick slope degradation complexes interfingering with and capping syn-rift packages in deep-offshore basins, and c) the passive draping of continental slope basins recorded after continental breakup was completed (Figs. 5 to 7). This passive draping, when combined with our modelling results, suggests that the period of enhanced tectonic subsidence along West Iberia started in the latest Jurassic (?Tithonian) and was essentially over by the Turonian (90 Ma) (Figs. 2 and 9d).

Considering that only 1-D backstripping was performed for this paper, we do not fully document the effects of flexural isostasy on tectonic subsidence, which is a widely accepted model to determine the deformation of the lithosphere associated with long-term (>1 Ma) geological loads, such as rifting and sediment (Watts, 2001 and references therein). Results from combined flexural backstripping and associated gravity modelling along West Iberia show, for instance, that the structure of the crust and associated gravity anomalies are best explained assuming a laterally varying effective elasticity for the lithosphere (T_e; a proxy for the long-term strength of the lithosphere), with a low T_e over stretched continental basement ($T_e \leq 10$ km), flanked by a stronger lithosphere in old oceanic and unstretched continental crust ($T_e \geq 15$ km) (Cunha, 2008; Cunha et al., 2010). These studies also show that Airy isostasy models may underestimate the amount of tectonic subsidence in the main depocentres along the slope-rise by up to 1 km, and rift flank uplift over the shelf by hundreds of meters. Such an uplift may explain the Mid Jurassic–Early Cretaceous hiatus recorded on the hinge zone separating the Lusitanian Basin from continental-slope basins, with significant volumes of sediments feeding these latter. Although It is not within the scope of this paper to assess or model the mechanisms that control rift-flank uplift, which may result from multiple processes (e.g. Rowley and Sahagian, 1986; Kusznir and Ziegler, 1992; Podladchicov et al., 1994; Hartz et al., 2017), such an analysis could provide valuable constraints on the magnitude of exhumation events inboard of continental-slope basins.

7.2. Depositional architecture of breakup sequences offshore Iberia and Newfoundland

Based on the tectonic subsidence data in this work, we postulate that significant mass-wasting and footwall degradation are associated with the continental breakup event on rifted continental margins, and that 'drift' units are gradually deposited during a prolonged episode of tectonic and thermal subsidence that: a) floods continental margins, and b) follows exhumation and uplift in proximal basins. On seismic and borehole data, continental breakup offshore NW Iberia records the deposition of turbidite successions and debrites that form a well-defined offlapping sequence on seismic data, particularly when associated with sand fairways that channelled siliciclastic material from the continental slope (Figs. 2a and 2b). In SW Iberia, the same phase of chaotic, offlapping sediment-bypass coincides with a marked period of subsidence in continental-slope basins, which is better represented by the deposition of Breakup Sequence A as a relatively younger slope degradation complex (Fig. 7). The two offlapping intervals represent successive continental breakup events; latest Jurassic–Early Cretaceous in SW Iberia, and late Aptian–Turonian in NW Iberia (Figs. 5–7).

One key observation is that strata reflecting mass-wasting and sediment bypass, associated with the maxima in subsidence rate recorded on pseudo-well data (150–90 Ma), are gradually draped by a thick interval of wavy to sub-parallel, low-amplitude seismic reflections on both West Iberia and Newfoundland (Figs. 1c, 1d and 5 to 7). This drape is interpreted to reflect 'drift' conditions on a fully rifted continental margin, and its initiation has been tentatively dated as Late Cenomanian–Turonian in NW Iberia based on industry and DSDP/ODP wells (Soares et al., 2012). In SW Iberia, Breakup Sequences A and B are also gradually draped by drift units, as shown in Fig. 7. In contrast, tectonic subsidence curves for Newfoundland are much more stable for the period spanning the Aptian–Turonian, and subsidence was chiefly enhanced at the end of the Cretaceous in response to migration of the syn-rift axis along the Labrador Sea into west Greenland (Fig. 8c).

This fact leads us to propose that the continental breakup event in Newfoundland was dominated by hyperextension and large horizontal displacements in crustal blocks, but records more moderate tectonic subsidence when compared to West Iberia. In fact, NW Iberia experienced widespread subsidence after complete separation of mantle lithosphere, with no major heave between crustal tilt-blocks accommodated after this stage. In this latter case, the presence of hyperextended tilt-blocks in parts of Newfoundland (Flemish Cap, Orphan Knoll) hints at significant crustal stretching, which is not as prominent in West Iberia's continental slope basins. In addition, we interpret that the draping of *breakup sequences* is phased on newly-formed continental slopes after lithospheric breakup is initiated. It is also diachronous as continental breakup migrates along the strike of continental margins, a character well marked in Newfoundland. Locally, it is capable of generating younger degradation complexes above *breakup sequences*, as recorded in SW Iberia as an example of this same diachronous process (Fig. 7). Hence, we support the view that footwall degradation on rifted continental margins may continue beyond the continental breakup events affecting distinct crustal segments (Huismans and Beaumont, 2011), thus generating footwall uplift and rotation away from the areas that evolve into full continental breakup at a given time, along a diachronous, migrating rift-continental breakup axis (see Alves et al., 2009).

In Newfoundland the deposition of successive sandstone-rich *breakup sequences* is followed by the deposition of the shaley Banquereau Group after the early Turonian (Sinclair, 1995), which represents the onset of drift strata in the Jeanne d'Arc Basin as rifting migrated to the Orphan Basin and Labrador Sea area (Fig. 2a). In NW Iberia, we denote the onset of the drift phase by widespread deposition of contourites (Wilson et al., 2001; Soares et al., 2014). Importantly, the end of the *breakup sequence* precludes a widespread condensed interval that spans the Santonian to the Maastrichtian (Groupe Galice, 1979; Wilson et al., 2001).

7.3. Types of break-up sequences on continental margins

Original interpretations of continental breakup along continental margins have taken into account the deposition of post-rift strata that are distinct from the extensional (syn-rift) sequences below (Falvey, 1974; Braun and Beaumont, 1989; Tucholke and Sibuet, 2007). However, recent data have also recognised the accumulation of strata above syn-rift units that are attributed to 'transitional units', representing the cessation of rifting on continental margins. This is particularly the case in broad areas of SE Brazil, Equatorial Brazil, West Africa and the Gulf of Mexico (Beglinger et al., 2012b; Mohriak and Leroy, 2012; Pindell et al., 2014; Davison et al., 2012; Zhao et al., 2016). In Australia, post-breakup sequences of Mesozoic and older ages (reaching ∼2000 Ma) have been recognised in offshore and onshore basins above distinct breakup unconformities (Hall et al., 2013; Holford et al., 2014).

Fig. 10 documents *breakup sequences* in multiple areas of the world based on the characteristic lithologies of their regressive–transgressive (R—T) depositional cycles. The SE Brazil–West Africa conjugate records R—T cycles that are initiated by the deposition of shallow-water microbial carbonates, followed by >3 km-thick evaporites (Davison et al., 2012). In Equatorial Margins of Brazil and Africa, a similar R—T cycle is dominated by the accumulation of continental and shallow-marine strata (Greenhalgh et al., 2011; Roberts and Bally, 2012). In Iberia and Newfoundland, a two-fold distribution of regressive sandstones/conglomerates in proximal areas gives rise to shales (including black shales) and mass-transport deposits in deeper parts of the two margins. Similar depositional patterns have been documented on margins as distinct as East Greenland, NW Morocco Argentina and South China Sea, to give a few examples. Such a broad record of R—T cycles during continental breakup permit us to classify R—T cycles in *breakup sequences* throughout the world as: a) sandstone–shale, b) carbonate–evaporite, and c) sandstone–carbonate cycles.

A very important control on continental breakup is the presence of inherited basement structures, as recorded in most regions where margins were finally rifted apart (Buiter and Torsvik, 2014). Another control on the architecture of *breakup sequences* are the postulated differences in geometry (and evolution) between type I and type II margins, and between these and magma-rich margins with marked seaward-dipping reflectors and significant volcanism. We thus propose that the character of *breakup sequences* follows the classification in this paper, and reflects profound differences in terms of the sedimentary, tectonic and thermal histories of rifted margins during continental breakup.

8. Conclusions

Seismic, outcrop and backstripping well and pseudo-well modelling results justify, for the first time, the presence of offlapping strata deposited during continental breakup in West Iberia. This offlapping unit is associated with important tectonic subsidence in continental slope basins during continental breakup, and deposited a characteristic chaotic package that onlaps the continental slope to form an intermediate unit between drift and syn-rift strata. Similar strata occur in Newfoundland, Orphan and Flemish Pass basins. The main conclusions of this study are as follows:

(1) Strata offlap and associated deposition of chaotic strata during continental breakup were associated with an acceleration in tectonic subsidence between ∼150 Ma (Tithonian) and ∼90 Ma (Turonian), on both the West Iberia and Newfoundland margins. This acceleration was initiated during the last syn-rift stage leading to continental breakup, and records marked peaks during Breakup Sequences A and B.
(2) The tectonic subsidence curves in this work suggest a transient subsidence stage occurring between the end of the stretching pulse and the establishment of the continental slope as a distinct morpho-tectonic feature.

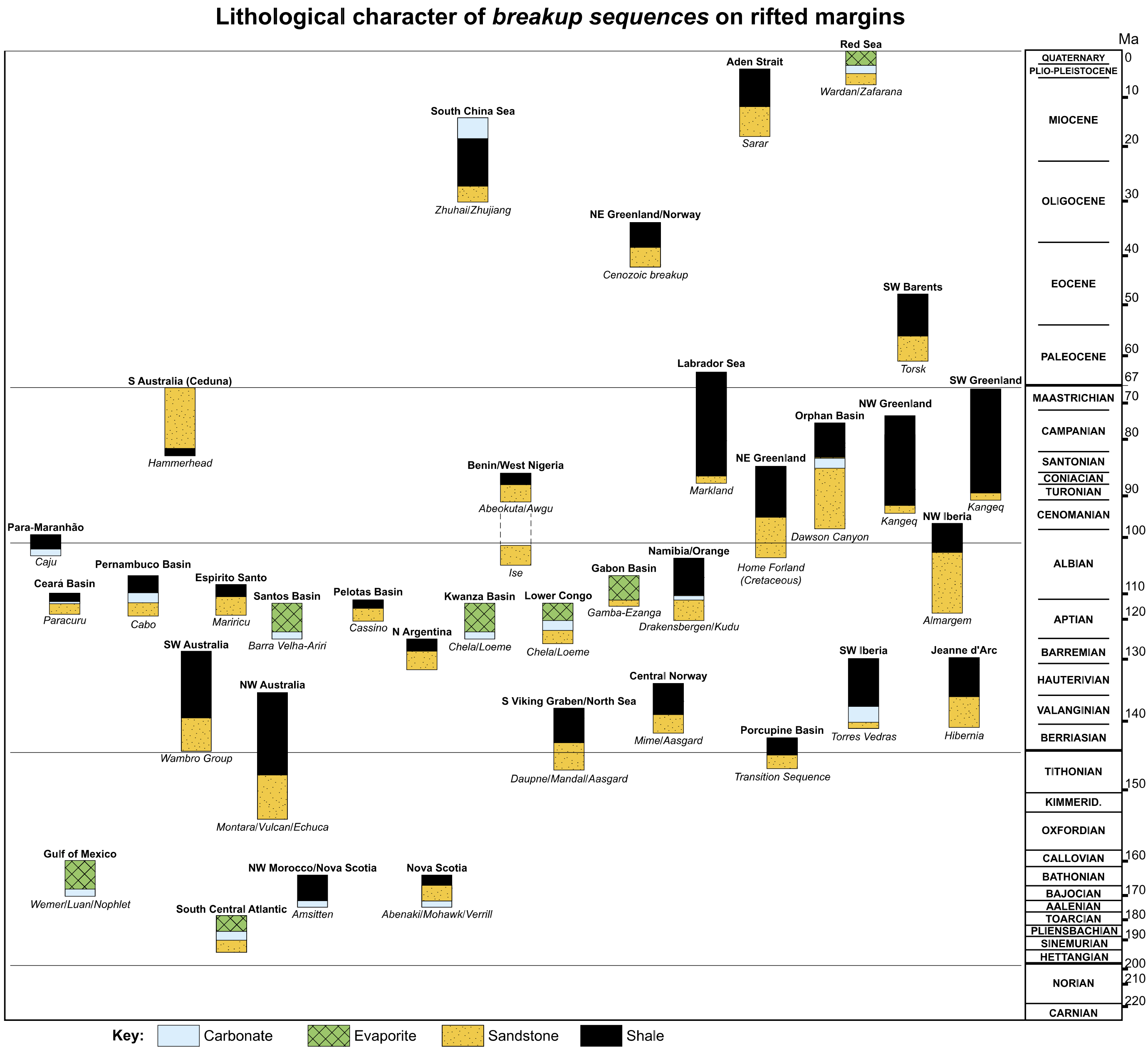

Fig. 10. Characteristic lithologies of regressive–transgressive depositional cycles in *breakup sequences* around the world. These *breakup sequences* can be divided in three main classes: a) sandstone–shale, b) carbonate–evaporite and c) sandstone–carbonate. Minor amounts of carbonate may occur in sandstone–shale breakup sequences. Geographic names (in bold) are shown together with the names of the stratigraphic formations representing *breakup sequences* (in italic). Stratigraphic information used for in this panel was taken from Klitgord and Schouten (1986), Horsthemke et al. (1990), Moore (1992), Chalmers and Pulvertaft (1993), Keeley and Light (1993), Light et al. (1993), Clark et al. (2014), Baker (1995), Sinclair (1995), Whitman et al. (1999), Chalmers and Pulvertaft (2001), Gabrielsen et al. (2001), Bradshaw et al. (2003), Kyrkjebo et al. (2004), Bird et al. (2005), Bosworth et al. (2005), Heine and Muller (2005), Brownfield and Charpentier (2006), Pedersen et al. (2006), Bueno et al. (2007), Condé et al. (2007), Córdoba et al. (2007), França et al. (2007), Moreira et al. (2007), Soares et al. (2007), Alves et al. (2009), Schettino and Turco (2009), Espurt et al. (2009), Zachariah et al. (2009), Beglinger et al. (2012a), Beglinger et al. (2012b), Mello et al. (2012), Soares et al. (2012), Kaki et al. (2013), Tamannai et al. (2013), Tari and Jabour (2013), Cazier et al. (2014), Schmidt (2014), Pindell et al. (2014), Brownfield (2016), Nova Scotia Department of Energy (2016), d'Almeida et al. (2016), Geissler et al. (2016), Howarth and Alves (2016), Ndiaye et al. (2016), Zhao et al. (2016), Biari et al. (2017), Gouiza et al. (2017) and Parsons et al. (2017). (For interpretation of the colours in this figure, the reader is referred to the web version of this article.)

(3) Changes in paleodepth (from shallow to deep reference values) used in the models do not change the overall profiles of tectonic subsidence, hence justifying the pronounced offlap revealed on seismic and borehole data as associated with continental breakup.
(4) Borehole data from West Iberia reveal finning-upward sequences in continental-slope basins, which reflect to a gradual deepening-upwards trend as continental breakup progressed into the drift stage.
(5) Earlier continental breakup in SW Iberia, when compared to NW Iberia, has led to enhanced Cretaceous subsidence and the putative stacking of two break-up sequences in continental slope basins.

As a corollary we suggest variable tectonic, paleogeographic and climatic settings acting on continental margins to result in distinct regressive–transgressive cycles, which can be classified as: a) sandstone–shale, b) carbonate–evaporite and c) sandstone–carbonate.

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Appendix A. Supplementary material

Supplementary material related to this article can be found online at https://doi.org/10.1016/j.epsl.2017.11.054.

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