Earth and Planetary Science Letters 484 (2018) 168–183

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

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

Tiago M. Alves [a,*], Tiago Abreu Cunha [b]

[a] 3D Seismic Lab – School of Earth and Ocean Sciences, Cardiff University – Main Building, Park Place, Cardiff, CF10 3AT, United Kingdom
[b] Integrated Geochemical Interpretation Ltd., The Granary, Hallsannery, Bideford, Devon EX39 5HE, United Kingdom

ARTICLE INFO

Article history:
Received 22 June 2017
Received in revised form 28 November 2017
Accepted 30 November 2017
Available online xxxx
Editor: P. Shearer

Keywords:
continental margins
tectonic subsidence
transient phase
continental breakup
sediment bypass
forced-regression

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

* Corresponding author.
E-mail address: alvest@cardiff.ac.uk (T.M. Alves).

https://doi.org/10.1016/j.epsl.2017.11.054

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-