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Research paper

The tectono-stratigraphic evolution of distal, hyper-extended magma-poor conjugate rifted margins: Examples from the Alpine Tethys and Newfoundland–Iberia

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ABSTRACT

In order to capture the general tectono-stratigraphic framework of a magma-poor conjugate rifted margin, two examples have been analysed and compared, the seismically imaged and drilled Iberia–Newfoundland rifted margins (*e.g.* seismic sections SCREECH1-ISE1) and the fossil distal Tethys rifted margins exposed in the Alps. The Lower Austroalpine and the Ligurian Briançonnais units exposed in SE Switzerland and NW Italy respectively, are here considered and described for the first time as conjugate margins. They form, like the Iberia–Newfoundland rifted margins, conjugate upper and lower plate margin. Both pairs of margins show a similar first-order morpho-tectonic arrangement. Using the Top of Pre-Rift Succession (TPRS) and the Base of Post-Rift Successions (BPRS) as stratigraphic marker levels and two Syn-Tectonic Sequences ($STS_{1\&2}$) three major rift domains can be identified, which experienced different evolutions and preserved different stratigraphic architectures:

i) The proximal margin, soled by normal, 30 ± 5 km thick continental crust. It is characterized by widespread fault-bounded graben/half graben basins filled by the STS_1 showing growth structures followed by a succession (time-equivalent unit to STS_2) that does not show any evidence for syn depositional tectonic activity.

ii) The upper plate distal margin, floored by thinned to ultra-thinned continental crust. It can be subdivided into a distal "high" and a distal "low" separated by a major fault system. The "high" is characterized by the occurrence of a marked syn-rift unconformity leading to the erosion and/or non deposition of the whole syn-tectonic sequence ($STS_1 + STS_2$); the "low" displays complete stratigraphic successions in which the STS_2 becomes very characteristic and exclusive of this part of the margin.

iii) The lower plate distal margin, floored by hyper-extended crust, exhumed crust and subcontinental mantle. The pre-tectonic sequence and the STS_1 are only present inside extensional allochthons that are excised from the upper plate and passively transported on top of major exhumation faults. The STS_2, deposited during the formation of the most distal domain, is mostly formed by clasts derived from the dismantling of the extensional allochthons and of the surrounding exhumed basement. It is overlain by deep marine turbidites and hemi-pelagic sediments. The nature of basement (serpentinized mantle and hydrated upper or lower continental crust) will selectively condition the composition of the STS_2 in the distal lower plate margin.

The recognition of a complex rift stratigraphy in the two conjugate pairs of margins shows that simple stratigraphic models are unable to describe the complete evolution of rifted margins from their initial stage, preserved in the proximal margins to the final evolution leading to upper and lower plate margins in the conjugate distal margins. This paper describes for the first time the stratigraphic relationships at distal conjugate rifted margins, which is a key to understand the rift evolution and architecture of these yet little investigated systems.

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1. Introduction

Since the late seventies the Iberia–Newfoundland margins have been extensively studied during successive drilling campaigns (*e.g.* Deep Sea Drilling Program (DSDP) 47B (Sibuet et al., 1979) and Ocean Drilling Program (ODP) Legs 103, 149, 173 and 210 (Boillot et al., 1987; Sawyer et al., 1994; Whitmarsh et al., 1998; Tucholke et al., 2004) and seismic surveys (LUSIGAL: Beslier et al., 1993; ISE: Sawyer et al., 1997; DISCOVERY 215: Discovery 215 Working group, 1998; SCREETCH: Shillington et al., 2004). As a result, these margins have been imaged and interpreted with reflection seismics (*e.g.* Mauffret and Montadert, 1987; Krawczyk et al., 1996; Reston et al., 1996), with refraction surveys (*e.g.* Chian et al., 1999; Dean et al., 2000; Van Avendonk et al., 2006) and with drill hole data (Manatschal et al., 2001; Wilson et al., 2001; Tucholke and Sibuet, 2007). Key findings were the discovery of wide areas floored by subcontinental serpentinized mantle rocks exceeding hundred kilometres in width and resting between the thinned continental and oceanic crusts (*e.g.* Beard and Hopkinson, 2000; Boillot et al., 1992; Dean et al., 2000; Pickup et al., 1996; Abe, 2001; Hébert et al., 2001). Although the processes controlling mantle exhumation and crustal thinning are still a matter of debate (*i.e.* Ranero and Pérez-Gussinyé, 2010; Lavier and Manatschal, 2006; Reston and McDermott, 2011), evidence for extensional detachment faults responsible for crustal thinning and unroofing of mantle rocks at the seafloor have been demonstrated at the Iberia–Newfoundland rifted margins (Chian et al., 1999; Krawczyk and Reston, 1995; Reston et al., 1996; Manatschal et al., 2001) and suggested for other margins (*e.g.* East India margins; Nemčok et al., 2013; Pindell et al., 2014; Brazilian margin; Zalan et al., 2011, and South China Sea; Franke, 2013). Nevertheless, at present the Iberia–Newfoundland rifted margins still remain the only magma-poor rifted margins for which both high-quality seismic and drill hole data are available. Therefore, they are considered as the type-example of a magma-poor pair of conjugate rifted margins (Whitmarsh et al., 2001). Since the late nineties, the comparison between the Iberia–Newfoundland and remnants of the Alpine Tethys margins exposed in the Alps enabled to stress the relationships among basement rocks, extensional detachments and syn-tectonic sediments (Manatschal and Bernoulli, 1999; Wilson et al., 2001; Masini et al., 2013). The comparison between modern and fossil examples including combinations of field observations, drill hole data and seismic interpretation enables to provide a general template and to enhance the understanding of the tectonic evolution of this type of margins (*e.g.*Mohn et al., 2011 and Masini et al., 2013 for the Alps; Tugend et al. 2014 for the Pyrenees; Fig. 1). Previous studies demonstrated the strong tectonic affinity between the Alpine Tethys and Iberia–Newfoundland margins (Manatschal and Bernoulli, 1999; Manatschal et al., 2007) that represents the starting assumption of this paper. Using the same approach but for the first time integrating data from conjugate pairs of the two best studied magma-poor rift systems, we first describe the tectono-stratigraphic framework of these magma-poor rifted margins. We analyse the depositional settings and sedimentary record of basins found along both the conjugate margins preserved in the Alps (Fig. 2) and we compare them with the seismically imaged and drilled basins offshore Iberia–Newfoundland (*i.e.* conjugate sections SCREECH1-ISE1, Fig. 3). Despite of the peculiarity of each rifted margin, in this study we describe the general first-order stratigraphic features and the depositional architecture with the aim to propose a tectono-stratigraphic model that can be applicable to other magma-poor rift systems.

2. Methods and terminology

In this study different datasets are examined, *i.e.* seismic, drill hole and outcrop data derived from the conjugate Iberia–Newfoundland and Alpine Tethys rifted margins. While the Alpine stratigraphic sections are considered as "virtual boreholes", filling the lack of drill hole data from distal margins, the seismic data provide the framework for the large-scale interpretation of scattered outcrops observed in the Alps.

To stress the comparison among the different datasets we will use "reference levels" (Fig. 1), which preserve their validity and significance both in the seismic and in the stratigraphic sections. We will consider two main surfaces, the Top of the Pre-Rift Succession (TPRS in Figs. 1, 4 and 5) and the Base of Post-Rift Succession (BPRS; Figs. 1, 4 and 5). These horizons are tentatively traced along the SCREECH1-ISE1 profiles and inside the proposed stratigraphic panel of the two Alpine conjugate margins.

The TPRS level represents the top of the succession deposited before the onset of extension in a sector of the rifted margin (either proximal or distal upper or lower plate margin). As it will be discussed further in chapters 3 and 4, respectively for the southern North Atlantic and for the Alpine Tethys, the tectonic activity along rifted margins is usually poly-phase, distributed over a wide area during early rifting and more localized during final rifting (Masini et al., 2013). In some examples, such as for the Alpine Tethys or the North Atlantic it can be shown that hyper-extended systems can either develop into oceanic domains or may fail and shift (*e.g.* Dorè et al., 1999; Manatschal, 2004). In such systems the so-called top of the "pre-rift" succession may be diachronous at a regional scale. Therefore, the "local" top of pre-rift succession (TPRS) can be considered as isochronous only inside a portion of a rift-system. As a consequence the TPRS can be of different age across a margin, which implies that the syn-tectonic sequence can be of different age as well (*cfr.* STS_1 and STS_2). In this study we try to identify and discuss correlations of such stratigraphic marker horizons across the Alpine Tethys and Iberia–Newfoundland margins. The use of one and the same concept for both outcrop and seismic data shows that the application of such correlation is critical for the understanding of margins. While on a seismic section the TPRS level may be based on geometrical relationships derived from the seismic interpretation, in reality it may be formed by several $TPRS_l$ (TPRS local) that are of different ages along one and the same margin.

The syn-rift succession of the studied examples is composed of two different syn-tectonic sequences, here called STS_1 and STS_2. In the Iberia–Newfoundland margins they have been distinguished using geometrical relationships (*i.e.* the STS_2 is unconformable on top of the previous syn-tectonic succession) and dated through ODP drill-holes (STS_1: Tithonian to Berriasian; STS_2: Valanginian to Aptian; see Mohn et al., 2015). In the Alps they correspond to discrete syn-rift successions that unconformably lie one on top of each other and often differ for their main sedimentary character (STS_1 Hettangian-Sinemurian: STS_2; Pliensbachian-Callovian/Bathonian?) In both studied examples STS_1 is very characteristic for the proximal margin, while in the distal margin it is unconformably overlain by the STS_2. At the exhumed domain the STS_2 becomes the first depositional sequence overlying basement and the STS_1 is absent.

The BPRS level represents the base of the post-rift succession and it can be defined as the base of the first sediments deposited on top of the first oceanic crust (*e.g.* downlap onto first oceanic crust on a seismic section). For what concerns the stratigraphy of the distal Tethys margin, the BPRS is marked by the occurrence of radiolarian cherts, which are the first sediments overlying Mid Ocean Ridge basalts (MORB) in the Alpine ophiolitic successions. As discussed by Wilson et al. (2001) this assumption may be