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Ductile extensional shear zones in the lower crust of a passive margin

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ABSTRACT

We describe and interpret an unpublished set of ION Geophysical seismic reflection profile showing strong organized seismic reflectors at the base of the continental crust of the Uruguayan volcanic rifted margin. We distinguish two main groups of reflectors in the lowermost continental crust. A first group, at depths ranging from 32 km below the continent to 16 km in the continent–ocean transition, comprises reflectors continuous over tens of kilometers, peculiarly visible near the mantle–crust boundary. A second group of reflectors dipping toward the ESE (oceanward) is widely distributed in the lower crust. These reflectors are slightly curved and tend to merge and become sub-parallel with the first group of reflectors. Together they draw the pattern of thick shallow-dipping top-to-the continent shear zones affecting the lower continental crust. Such sense of shear is also consistent with the continentward dip of the normal faults that control the deposition of the thick syn-tectonic volcanic formations (SDR). A major portion of the continental crust behaved in a ductile manner and recorded a component of top-to-the continent penetrative simple shear during rifting indicative of a lateral movement between the upper crust and the mantle.

1. Introduction: the mechanics of the crust at rifted margins

The behavior of the lower crust in extensional settings is still poorly understood and may be variable from place to place. Based on observations from the Alpine inverted margins, some authors propose a brittle, strong mafic and felsic lower continental crust constituted of gabbros and dry granulites (Mohn et al., 2012). Although the lithology of the lower crust seems well constrained for the Alpine Tethys system (Müntener et al., 2000; Mohn et al., 2012), this might not be the case along other margins worldwide. Due to its strong lateral and vertical heterogeneity and to a variable thermal gradient, the lower crust can be hot and weak enough to flow and deform in a ductile way (McKenzie, 1978; Dewey, 1986). This variability of the lower crust composition and inheritance could lead to different rheological mechanisms but, so far, the internal structure of passive margins was poorly imaged, especially in magma-rich passive margins where thick and reflective volcanic formations tend to hide the underlying signal. The existence of major ductile shear zones within the middle and lower crust of rifted margins has been suggested by numerical models (Hopper and Buck, 1996; Michon and Merle, 2003; Lavier and Manatschal, 2006; Huismans and Beaumont, 2011, 2014) but these shear zones have not yet been reported from present day passive margins. We present an unpublished industry seismic profile (ION Geophysical) across the Uruguayan magma-rich passive margin that provides high quality images of the intruded lower continental crust. The data present significant features that we interpret in favor of low-angle asymmetrical ductile shear at the base of the continental crust. By analogy with field and map examples, we determine a top to the continent sense of shear that is consistent with the kinematics of low-angle normal faults, dipping toward the continent, that controls the geometries of the Seaward Dipping Reflectors (SDR) formation.

2. Geological setting

The study area is located offshore the coast of Uruguay, in the Punta del Este sub-basin, in the southern tip of the Pelotas basins (Stica et al., 2014) – Fig. 1A. The present-day structure of the Uruguay Margin results from the break-up of Gondwana and subsequent opening of the South Atlantic Ocean during the Late Jurassic–Early Cretaceous (e.g.: Rabinowitz and LaBrecque, 1979; Gladczenko et al., 1997). In contrast to the magma-poor margins lying farther north in the Santos, Campos and Espirito Santo basins, the study area is characterized by thick wedges of SDR (up to 8 km) and is devoid of post-rift salt deposits (Stica et al., 2014;

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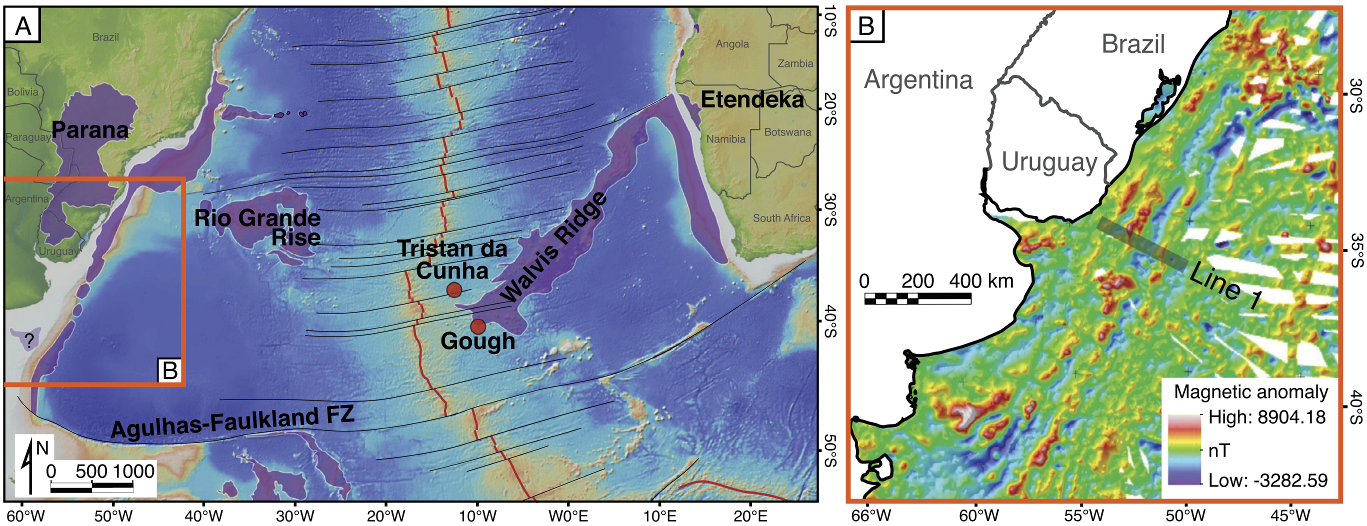

Fig. 1. A: Regional map of the southern Atlantic Ocean modified from Gladczenko et al. (1997), Stica et al. (2014) and Soto et al. (2011). B: Magnetic anomaly map of the study area on the Uruguayan passive margin after Maus et al. (2009). Discontinuous SDR patches appear as strong positive magnetic anomalies (red and white). (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Franke et al., 2007). The intense magmatic activity responsible for the SDR formation is related to the thick lava flows of the Parana Large Igneous Province (LIP – Gibson et al., 2006). Equivalent traps on the Namibian conjugate margin and continent are known as the Etendeka LIP (Turner et al., 1994). Both tabular traps and associated SDR wedges on the South American and South African margins once constituted the South Atlantic LIP (Gladczenko et al., 1997) – Fig. 1B.

3. Data and interpretation

The seismic profile used in this paper belongs to ION's Uruguay SPAN deep reflection seismic dataset delivered in 2013 (Fig. 2). The ca. 350 km-long profile presented in Fig. 2 gives a remarkable overview of the margin from an unextended 33 km-thick continental crust to a well-established 6 to 8 km-thick oceanic crust. The profile shows several SDR wedges lying on continental blocks and tilted by continentward-dipping normal faults. The SDR are observed as far as the Continent–Ocean transition.

The prominent **M** reflector is located at depth ranging from 33 km below the continent to 16 km in the continent–ocean transition. On profile 1, the necking zone is divided into two shallow-dipping upward-convex ramps with one flat in-between. The two ramps concentrate the strongest seismic reflectors (Fig. 2). The dip of the **M** reflector ranges from 25° toward the continent at its maximum to 0° at the tip of the two ramps of the **M** reflector.

The upper part of the continental crust is relatively transparent whereas the lower part of the continental crust shows a strong reflective pattern. In the lower crust, we distinguish two main groups of reflectors (Fig. 2B and C). The **A** reflectors are thick and continuous; some can be followed without any interruption on length of several tenths of kilometers. They are often superimposed on **M** reflectors.

A second group of reflectors (**B** reflectors in Fig. 2B and C) dipping toward the ESE (oceanward) is widely distributed in the lower crust. These 5 to 10 km-long reflectors are slightly curved and tend to flatten and merge with **A** reflectors when approaching them. The amount and intensity of **B** reflectors seems to vary in strength along the profiles, they are notably abundant above the two upward inflexions of the **M** reflector.

The continental crust located between the uppermost crust and the very reflective lower crust presents a variable reflectivity. The reflectors are not as thick and continuous as they are at the base of the crust. Furthermore, the pattern drawn by these reflectors is more symmetrical with reflective **A** markers that seem to undulate with a 5 km to 10 km wavelength and circa 4 km vertical amplitude.

4. Discussion

4.1. A crustal-scale shear zone imaged by seismic reflection

The depth and geometry of the **M** reflector is consistent with the Moho drawn by Soto et al. (2011) in the area. This Moho is clearly marked and shows a staircase-geometry with two gently continentward-dipping ramps separated by a more silent domain.

Together, **A** and **B** reflectors draw a pattern that strongly resembles the ones observed in ductile shear zones of various scales (Fig. 3). The most characteristic feature calling for an analogy with ductile shear zones is the sigmoidal geometry of B reflectors when approaching A reflectors. Among many other examples, similar patterns are reported from the Great Slave Lake shear zone (Hanmer, 1988); the South Armorican Shear Zone (Gumiaux et al., 2004; Augier et al., 2010 – Fig. 3c and d); from the Bongolava–Ranotsara shear zone in southern Madagascar (Martelat et al., 2000 – Fig. 3e) or from the Pernambuco shear zone (Vauchez et al., 1995 – Fig. 3f). The **A** reflectors can be compared to the ductile shear planes whereas the **B** reflectors are evocative of planes and objects deflected by the ductile deformation and parallelized to the shear bands. The numerous **B** reflectors observed in the lower crust present sigmoidal shapes evocative of the pattern observed in metamorphic foliations close to ductile shear zones (Ramsay, 1980).

On many seismic profiles acquired around the world, it is common to observe a bright, apparently laminated lower crust (e.g.: Matthews, 1986). Strong reflections observed at the base of the crust are contrasting with the often less reflective appearance of the crystalline upper crust and upper mantle. Several authors demonstrated that both extensional and contractional mylonitic shear zones are reflective and can be traced over several kilometers on seismic reflection profiles (e.g.: Jones and Nur, 1984). Some of these can be used as kinematic indicators and allow deciphering between domains that underwent a dominant coaxial versus non-coaxial deformation (Torvela et al., 2013).

From the relationships between the shear planes (reflectors **A**) and the deformed sigmoidal layering (reflectors **B**) we can infer a top-to-the continent sense of shear (Fig. 2C). The general asymmetry of the ductile deformation and the shear sense deduced