ROLE OF THE CRUSTAL DETACHEMENTS DURING RIFTING, INSIGHTS FROM LABRADOR SEA

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Abstract. The Labrador Sea is part of the Atlantic rift system which opens during Early Cretaceous times in the intracontinental domain. The rifting stage continues and generates an expansion center, with the establishments of an oceanic ridge during Late Cretaceous-Paleocene times. The rifting was asymmetric with a gradual propagation northward. The Cretaceous stretching and thinning of the continental crust led to the development of the transitional domain, with a controversial origin either thinned continental or oceanic. With this study, we bring new evidences for the presence of exhumed upper mantle in the transition domain based on geometry of the detachment faults, typical "S" shape, and we emphasize the role of the detachments in the rifting of continental crust and its ultimate break-up. We observed the lateral change, from South to North, of the continental to oceanic crust transition, from a step-up to a step-down. Based on, we suggest that it might reflect the changes in the upper versus lower plate position of the Labrador Sea, a change accommodated across the Snorri Fracture Zone.

Key words: Labrador Sea, detachment, rifting, S shape reflectors, hyperextended

1. INTRODUCTION

Rifts are long lasting systems, where extensional processes are stretching and ultimately breaking continental crust and lithosphere. In advanced stages, mid oceanic ridge spreads and asthenospheric material reached the surface and forms the new oceanic lithosphere/crust (Péron-Pinvidic & Manatschal, 2008). The streaking and breaking of continental crust are accommodated by the formation of brittle normal faults in Upper Crust and by the development of large-scale detachment's at Lower crustal level (Lister & Davis, 1989; Wernicke, 1985). After the crustal break-up, the upper mantle extension and exhumation takes place on lithospheric detachments, up to the lithospheric break-up with the emplacement of asthenospheric material along high angle faults at mid oceanic ridge (Péron-Pinvidic & Manatschal, 2008).

Processes as above described have been previously recognized along the Labrador-Newfoundland margin, which evolved from a continental rift during the Early Cretaceous to a full oceanic domain, with the expansion center occurrence in the Paleocene-Eocene interval (Chian *et al.*, 1995; Srivastava & Roest, 1999). Up to the lithosphere break-up point, the continuous slow extension rate led to the streacking and thinning of continental crust, with the development of a transitional domain having a controversial origin, *i.e.*., either thinned continental or upper serpentinized mantle (see also Keen *et al.*, 2018). With this study we aim to bring new data on the architecture of the transitional domain and its limits, especially the one with the oceanic domain. The understanding of the role played by the crustal detachments during rifting is also emphasized herein.

2. GEOLOGICAL SETTING

The Labrador Sea is a small oceanic basin, approximately 900 km wide, with its continental margins formed by the rifting of the North American craton within the Cretaceous and Early Tertiary times (Balkwill *et al.*,, 1990). This event was followed by the development of a thermal sag basin in the Late Cretaceous, with rifting migrating to the present day adjacent deep water (Dickie *et al.*, 2011).

The Late Mesozoic-Early Cenozoic times were characterized by seafloor spreading around Chron 31 (end of the Cretaceous, Maastrichtian stage) and attachment of the oceanic crust to the transitional crust. A major change in the direction of the seafloor spreading in the Labrador Sea occurred in the Early Eocene at Chron 25 (Roest & Srivastava, 1989; Oakey & Chalmers, 2012) when Greenland separated from Eurasia (Fig. 1). Spreading ended around Chron 13, at the Eocene-Oligocene boundary. The post seafloor spreading phase spans the Neogene (Dickie *et al.*, 2010). According to Keen *et al.* (2011), the southern and central regions of the basin are flanked by nonvolcanic rifted margins, while the northern part shows volcanic nature of this margin.

3. METHODOLOGY

The study is based on a regional database containing seismic, gravimetric and magnetic information, as well as boreholes drilled on the continental shelf for oil and gas exploration. The seismic dataset includes both unpublished and published data. The new multi-client long-offset data set acquired in 2011-2012 by TGS in partnership with PGS and Nalcor covered the slope and deep-water areas.

In all, six calibration wells were employed to tie the stratigraphic units and sequence boundaries with the formation tops and chronostratigraphic ages (Fig. 2). The wells have been drilled on the shelf, at a water depth between 100m and 350m.

A total of ten seismic horizons have been extended from the continental shelf to the deep basin margin. Due to the lack of well control in the deep-water area, the paleomagnetic chart and maps of the magnetic anomalies have been used extensively.

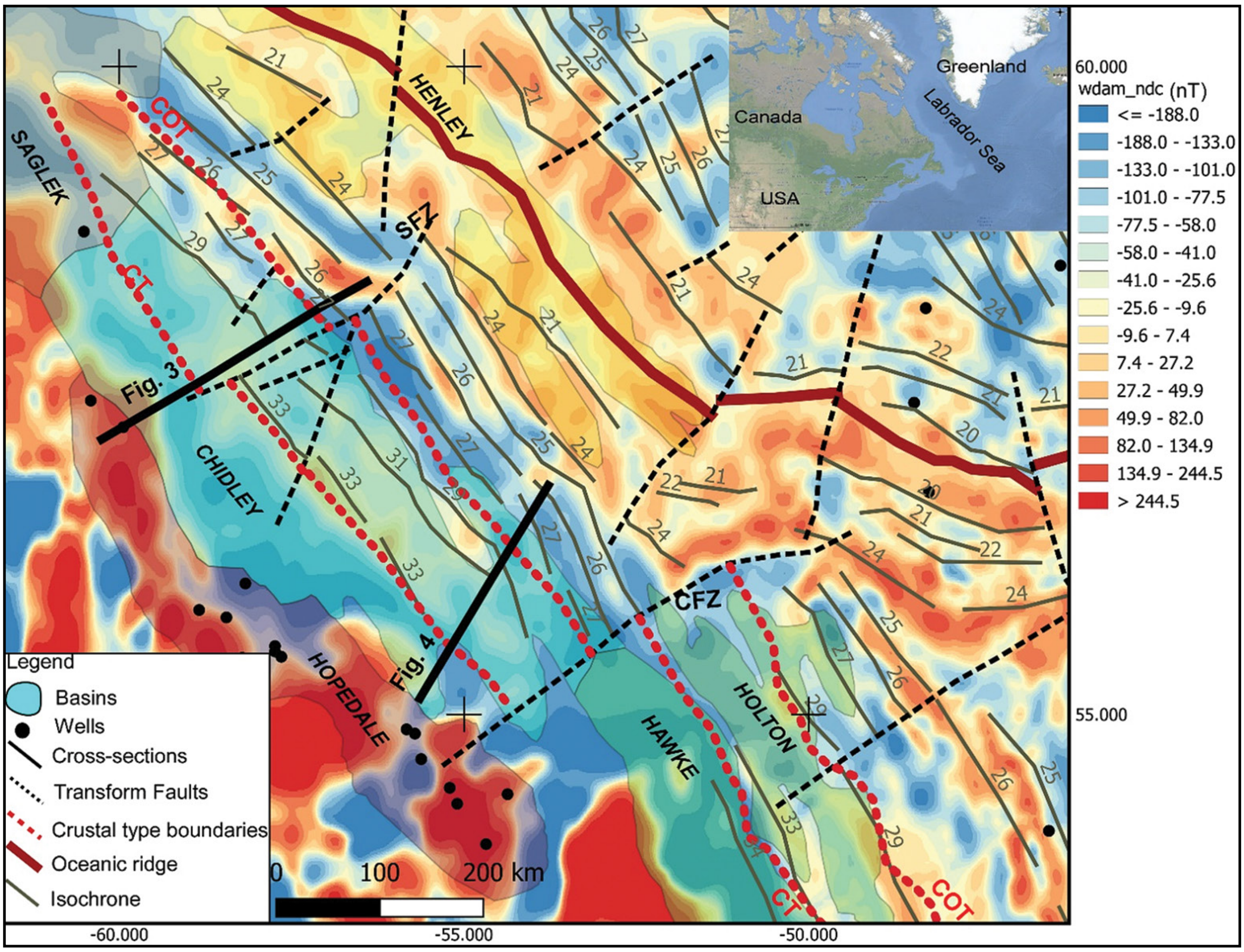

Fig. 1. Map showing the architecture of the Labrador Sea, redrawn after Gouiza & Paton, 2019 and Keen *et al.*, 2018. Magnetic map after Maus *et al.*, 2007.Inset the Google Earth map of NE Canada and Greenland. CT-Continental/Transition crust limit; COT – Transitional/Oceanic crust limit; CFZ-Cartwright Fracture Zone; SFZ- Snorri Fracture Zone. Inset is the extract Google Earth map with the location of the studied area.

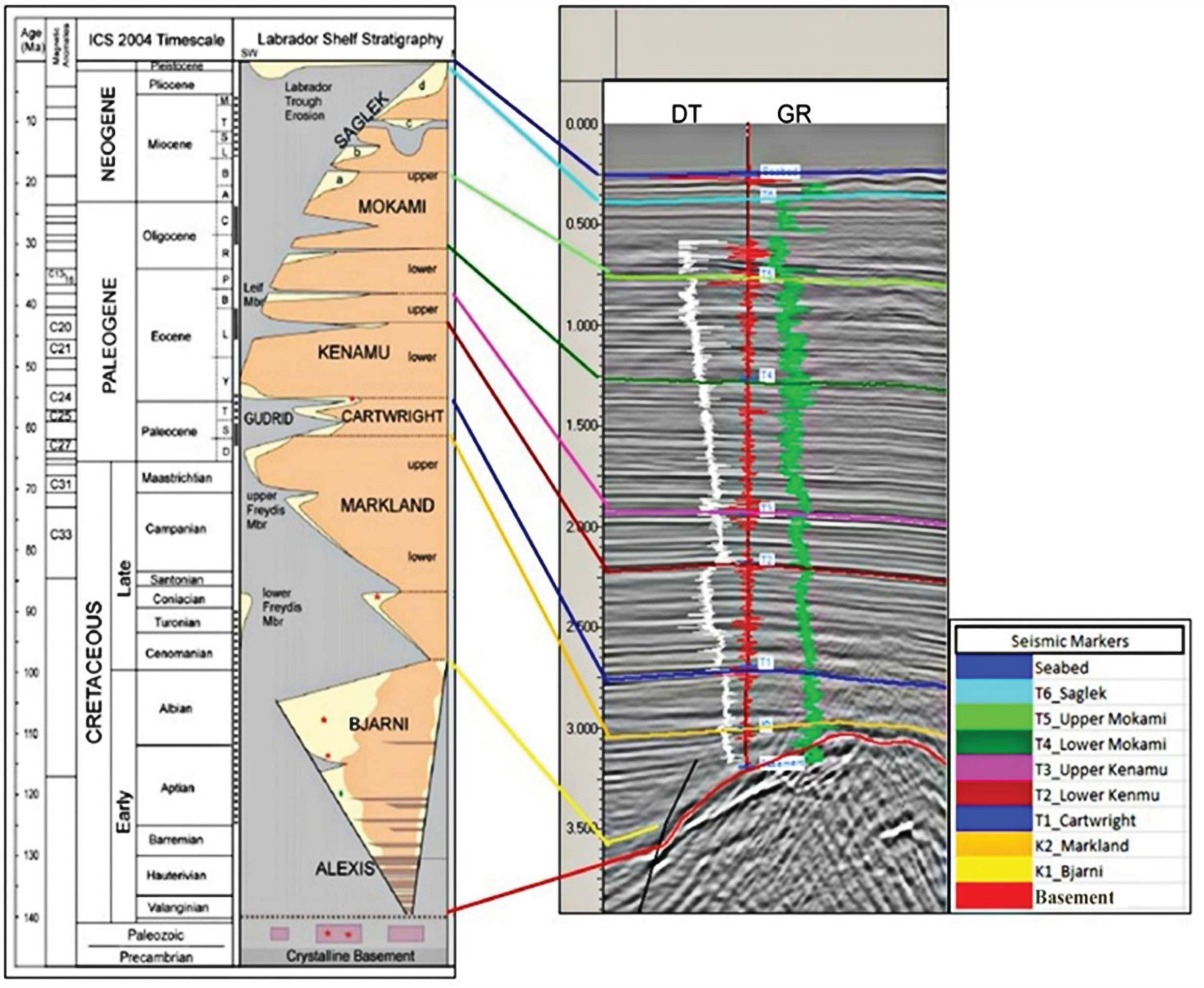

Fig. 2. Well seismic tie in the Saglek Basin. Information used: biostratigraphic ages, lithologies, DT and GR logs.

4. ARCHITECTURE OF THE LABRADOR SEA MARGIN DETACHMENTS

The first order features observed on the regional lines suggests that the entire margin architecture is shaped by extensional/gravitational structures, while the upper part is mark by shelf collapse structure; there, both normal and revers faults co-exist (no space creation), the lower, deeper part being shaped by a system of normal faults (Figs. 3 and 4). The high angle faults are separating the deep basin filled with Lower Cretaceous sediments and locally, in the proximal domain (Fig. 3) cut upwards the younger Upper Cretaceous-Lower Eocene sediments (Fig.4). The normal fault system has a classical configuration of graben/half-graben and horst geometries, well developed in the southern domain (we refer to north and south domain in relation with their position to SFZ), where individual faults offset is higher as compared with the northern domain (compare the Lower Cretaceous faults system in Figs. 3 and 4).

An exception is the master fault in the west corner of the section, while the others have usually a reduced offset (Fig.3). The other exception is the limit of the oceanic crust, which in this case is in a “step-up” style with oceanic Moho higher than continental Moho in the section north of SFZ Fault (Fig. 3), and a step-down style south of this major transform fault, with continental Moho in a higher position than Oceanic Moho (Fig. 4). In both cases the transfer is controlled by an eastward dipping detachment at a deeper level and by an antithetic or synthetic high angle faults system. In the first case the angle and offset are higher and steeper (Fig.3) and the faults are synthetic with the Oceanic Moho reflector, while in the southern domain the faults are antithetic (eastward dipping) at the main “continental” detachment, with a reduced offset, as compared with the northern domain.

Regarding the continental/transition (CT) and then the transitional to oceanic crust limits (COT), we pointed out these limits are depicted by the observed geometries. In our interpretation, we have chosen a more internal position of the CT boundary, at the point where the major jumps occur on the detachment, *i.e.* the first development of “L” shape reflectors (Fig. 3 and 4). At Chron 33 (Campanian) south of SFZ Fault and at Chron 30 (Maastrichtian) north of it.

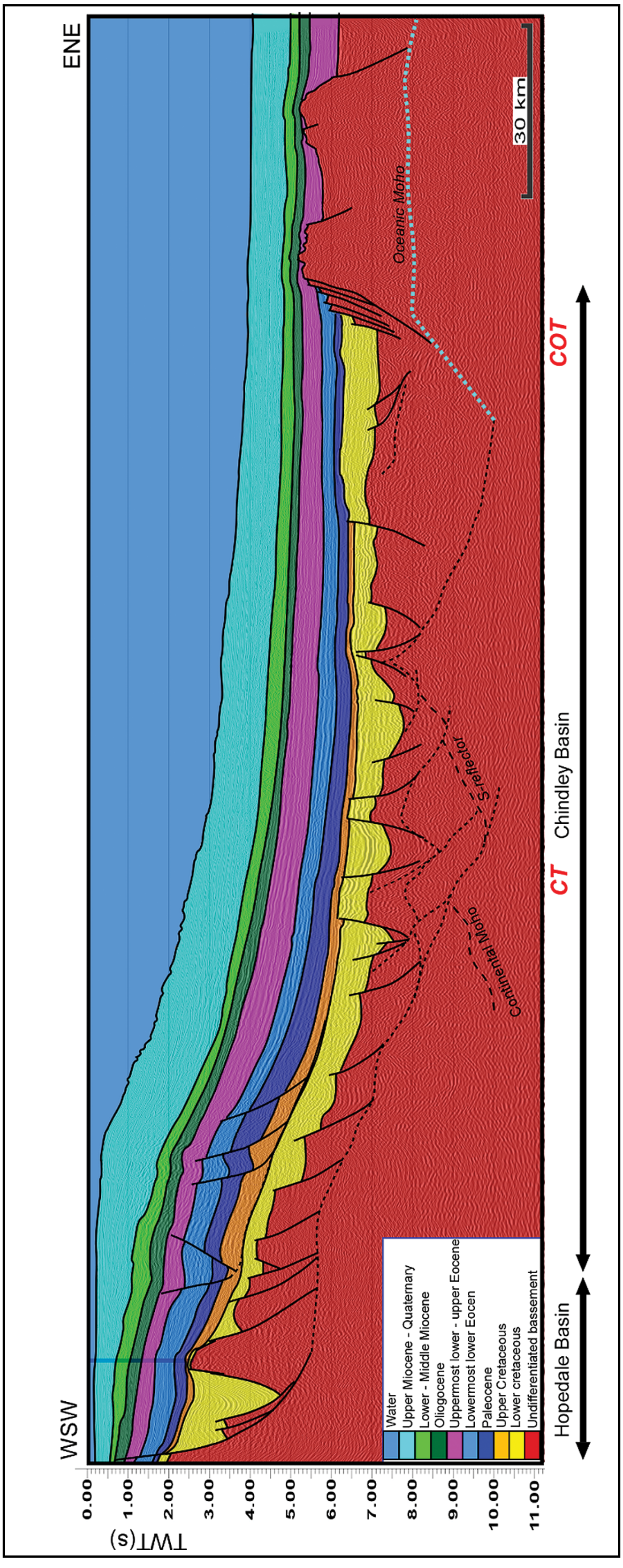

Fig. 3. Interpreted seismic line across the Labrador Sea. For localization see Fig. 1. Line redrawn after Gouiza & Paton, 2019.

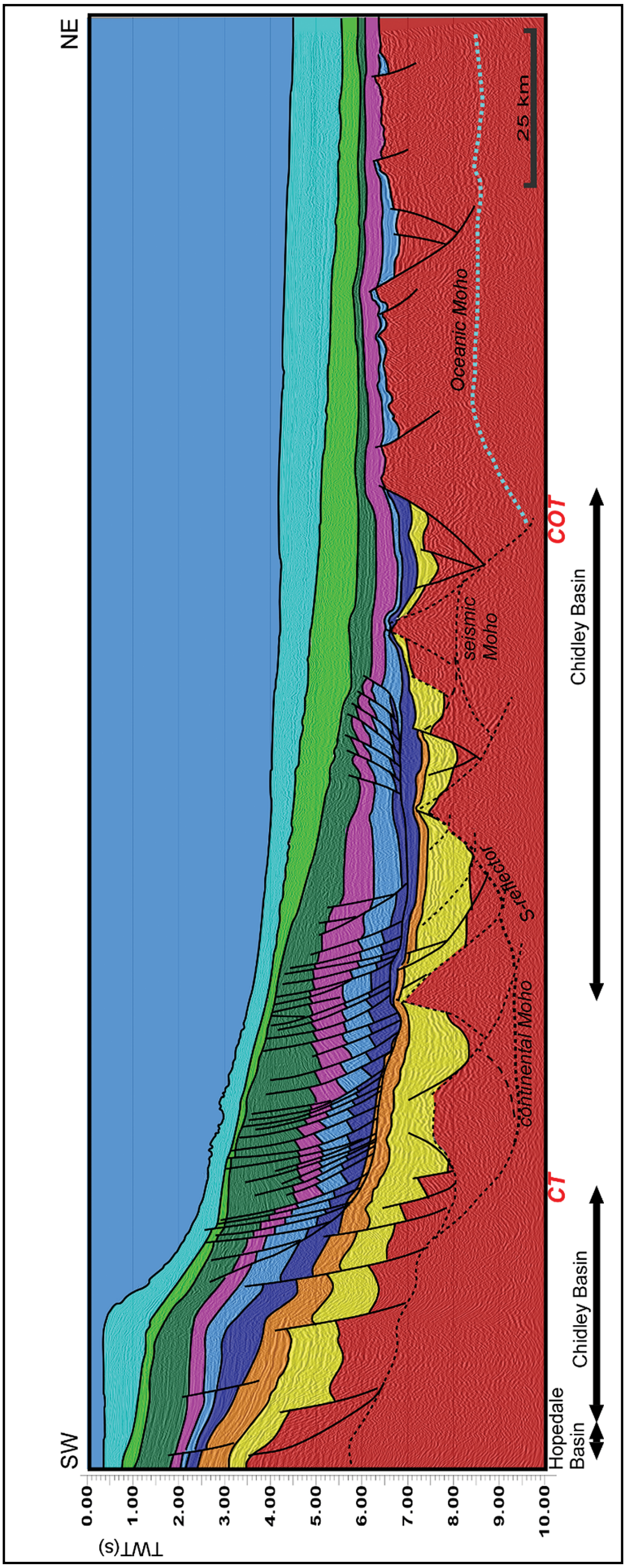

Fig. 4. Interpreted seismic line illustrating the transition from continental to oceanic crust. Line redrawn after Keen *et al.*, 2018.

In the case of the COT boundary, which at least geometrically is clear, we have emphasized it at the same position as Gouiza & Patton (2019), at Chron 29 south of SFZ Fault and at Chron 26, north of SFZ (Figs. 1, 3 and 4).

In between the oceanic and continental domain, the transitional domain has been developed (Fig. 1). Its internal architecture is defined by the presence of major detachment faults with classical L or S shape, on which normal high angle faults are rooted. The S shape geometry of the reflectors could be clearly interpreted in the center of the transition zone in both domains, with a possible second one closer to the COT and below it there is a flat reflector which might be the Moho discontinuity, in the southern domain (Fig 4). The S-shape reflector is crossed and displaced by several L shaped detachments.

We might interpret at least two generations of detachments, the older one cut and displaced by younger one (Figs. 3 and 4). In the southern domain a third generation can be interpreted at the COT zone, which marks the transition from transitional to oceanic domain (Fig. 4).

5. DISCUSSION AND CONCLUSIONS

The Labrador Sea margin architecture is the result of the main tectonic mechanism controlling the formation of different basins during the initial Lower Cretaceous continental rifting and the subsequent stretching and thinning of the continental crust and lithosphere (mechanic subsidence). The aforementioned feature was controlled by the formation of high angle normal faults in the intra-continental stage and large-scale detachments at higher extensional levels. The break-up of continental crust marks the transition from mechanically to thermally driven subsidence and setting of a passive margin in the proximal rift domain (closer to continental area).

The continental/oceanic crust boundary (COT) geometry shows different stages of evolution in the rift area. In the southern part the rift is older, as compared with the northern domain. However, the observed architecture must be related with the rift evolution and geometry, hence the Labrador Sea continental margin is either in an upper plate or in a lower plate position in comparison with its conjugated Greenland margin. To note that the transition was accommodated along SFZ transformed fault, a similar process that was described in the Southern Atlantic Margin (Péron-Pinvidic *et al.*, 2017). The along-strike change in tectonic configuration of the rifting might be the reason for the switch between magma-poor to magma-rich margin, north of SFZ, with the development of SDR; however future investigation is required to validate the model.

The S type reflectors geometry in the center of the transition zone might be interpreted as the limit of the exhumed serpentinized mantle, which previously has been inferred by Keen *et al.*, (2018) by modelling gravity data, however without describing the internal architecture of these zone. Hence, the S-shaped reflector represents in part the base of the continental crust (continental Moho in Figs. 3 and 4), which is uplifted and rotated, being coeval with the upper mantle exhumation. The process governing the transition from continental to oceanic lithosphere is controlled by the development of crustal and subsequent lithospheric scale detachments, on which takes place the thinning and breaking of the continental crust (linked to the formation of the transitional one), and subsequent breaking and exposure of upper serpentinized mantle. The ultimate stage is the breaking apart of the continental lithosphere and the formation of oceanic expansion center, which in the case of the Labrador Sea is clearly controlled by low angle detachments faults.

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