# The Differentiated Petroleum Potential of the Spectrum of Types of Passive Margins

Pedro Victor Zalán, ZAG Consultoria em Exploração de Petróleo Ltda., Rio de Janeiro, Brazil



This paper was prepared for presentation during the 15th International Congress of the Brazilian Geophysical Society held in Rio de Janeiro, Brazil, 31 July to 3 August, 2017.




## Abstract

Passive Margins can nowadays be classified as Magma-Poor or Sedimentary (Manatschal, 2004; Péron-Pinvidic et al., 2013 and 2015; Unternehr et al., 2010), Volcanic (Geoffroy, 2005; Stica et al., 2014) and Transitional (Zalán, 2014), once crustal structure, phased evolution and compositional filling of the associated rifts are taken into account. The three comprise a spectrum of passive margins resulting from different modes of thermo-tectonic evolution during the rupture and breakup of mega-continents (Zalán, 2015 and 2016) (Figure 1).

The different modes described also result in a differentiated petroleum potential. Magma-Poor Margins present wide and thick rift sequences developed during the stretching, thinning and exhumation modes. Large packages of lacustrine organic-rich shales are present in the grabens, as well as different types of reservoirs such as microbialites, coquinas, sandstones and fractured volcanics/basement. Eventually there may be so much oil generated in the rifts that a large amount may migrate upwards and be stored in post-rift reservoirs (turbidite sandstones, shallow marine carbonates). Additionally, localized pods of generation of marine source rocks deposited during global oceanic anoxic events, as well as of prodeltaic organic-rich shales, may develop during the Drift Stage sourcing more hydrocarbons to post-rift reservoirs. Petroleum systems associated to both the Rift and Drift Stages may be extremely rich, such as in the Santos, Campos, Espírito Santo Basins in Brazil and in the Kwanza and Congo Basins in Angola and Congo.

On the other hand, Volcanic Margins barely contain any sedimentary deposits inside their grabens, if any. Volcanic and volcanic-derived rocks (SDRs, mostly) fill the underlying rift entirely. So, the chances for source rocks in the Rift Stage are close to nil. At first glance, Volcanic Margins are devoid of petroleum potential in the Rift Stage. However, as the rifting takes place in intense volcanic mode, the thermal subsidence that follows creates a large amount of depositional space. The Drift Mega-Sequences of Volcanic Margins are much thicker and well developed than in Magma-Poor Margins. The Pelotas Basin in Brazil presents a Drift Stage with thicknesses of up to 9 km. This allows for the extensive maturation of marine source rocks developed during global oceanic anoxic events and deposited in the lower parts of this stage and the generation of large quantities of hydrocarbons. Slope and basin plain turbidites constitute the major reservoirs, mostly in stratigraphic traps. The passive margin that straddles southern Brazil Uruguay and most of Argentina may present significantly rich petroleum systems in their Drift Stage. The same potential may be envisaged for their homologous marginal basins of Namibia and Western South Africa.

The Transitional Passive Margins possess the same petroleum potential of Magma-Poor Margins in the proximal domains (onshore, shallow to deep waters) and that of Volcanic Margins in the more distal domains (ultra-deep waters). Such is the case of the Sergipe-Alagoas, Potiguar and Ceará Basins in northeastern Brazil.


## Introduction

Volcanic Passive Margins (VPM) are impinged directly by strong mantle plumes that carry a lot of heat, and, thus, magma. Magmatic activities are abundant **before**, **during** and **slightly after** rifting. This allows for extreme ductility and hyper-extension of the continental crust and a very quick evolution from the inception of rupture to the final concurrent crustal and lithospheric breakup (Rift Stage). Grabens are filled mostly by sub-aerial volcanic material, mostly under the form of Seaward-Dipping Reflectors (SDRs). Magma-Poor Margins (MPPM) develop the furthest away from the surfacing mantle plumes; thus their Rift Stage is either devoid or poor in magmatism. The evolution of MPPM takes longer and involves temporally and spatially concatenated mechanisms of stretching, thinning and hyper-extension of the continental crust practically devoid of magma. This stepped evolution of rifting allows for the continental crust to breakup and for the lithospheric mantle to exhume. The final lithospheric breakup, however, is carried out by asthenospheric magma. Transitional Passive Margins (TPM) are located slightly away from the impinging mantle plume or right above a weaker plume. TPM start in the same way as Magma-Poor Margins, developing sedimentary rifts; but, towards the end, they evolve into Volcanic Passive Margins in the vicinities of the imminent breakup. As in VPM, no mantle exhumation occurs in the TPM.

The petroleum potential of these types of passive margins will obviously be a function of the areal extension, thickness, nature of the filling and duration of the Rift and Drift Stages; as well as of the contemporaneous thermal gradients.

## Petroleum Potential of Magma-Poor Passive Margins

MPPM are the richest passive margins in terms of hydrocarbon resources. Their longer and more extensive Rift Stage originates diffuse rifting and lots of grabens with plenty of accommodation space (Figure 2). The deficiency in volcanic material allows for the sediments of the most varied nature to fill such space. Larger and/or smaller lakes, with variable depths of water develop and alternate among fresh, brackish or hypersaline environmental conditions. Sedimentation of thick and localized packages of organic-rich shales may occur during syn-rift peaks of tectonic subsidence, or of thinner, but widespread packages of organic-rich shales during ensuing or intercalated stages of thermal subsidence. Source rocks are, thus, plentiful. The high geothermal gradients that commonly go along with the stretching/thinning of the lithosphere may account for early peaks of hydrocarbon generation, even during the Rift Stage. Sandstones and limestones of the most diverse nature also fill up the grabens and provide different types of reservoirs. Eventually, fractured basement or syn-rift volcanics may also contribute with additional storage capacity.

The thickness of the Drift Stage of MPPM varies a lot and will depend upon the tectonic domain of the underlying rift section. Thermal subsidence will be greater upon highly stretched and thinned portions of the continental crust, but, most notably, upon hyper-extended crust. Localized proximal necking and distal hyper-extended domains will control the location of hydrocarbon kitchens in the drift section (Figure 2). The source rocks could be shales of openly marine anoxic, transitional hypersaline or mixed terrestrial/marine prodeltaic nature. Reservoirs are usually marine carbonates and transitional to turbidite sandstones. The presence of salt packages impart vigorous deformation and the individualization of mini-basins. The continuous and phased maturation of rift-related source rocks during the thermal subsidence phase may inject different hydrocarbon phases into the Drift Stage reservoirs.

The traps are predominantly of structural nature in the rift section and of both structural and stratigraphic character in the drift stage (Figure 2).

Prime examples of petroleum-rich MPPM are the Campos, Santos, Espírito Santo, Congo and Kwanza Basins in the South Atlantic, the Gulf of Mexico in the Central Atlantic and the Eastern Coast of Canada in the North Atlantic.

**Petroleum Potential of Volcanic Passive Margins**

VPM develop in the areas of the mega-continent directly impinged by the swiftly ascending mantle plume. Such plumes carry a lot of heat and, thus, originate an absurd volume of magma. The continental crust becomes extremely frail and radical ductility and hyper-extension take place in a rapid manner. The very quick evolution of the Rift Stage, from the inception of rupture to the final concomitant crustal and lithospheric breakup, leads to the creation of huge and deep grabens that are concurrently filled up by the immense volumes of outpouring magmas. Most of the action takes place subaerially. Deposition of clastic and carbonate sedimentary material barely takes place, if any. Lakes, if developed, are also hastily filled by lava deltas, constituted of prograding foresets of hyaloclastites and pillow lavas. Chances for the development of source rocks are close to nil. As a preliminary conclusion, while the sections containing the SDRs are not drilled by the petroleum industry, the petroleum potential of the rift section is seen as very low.

On the other hand, the Drift Stage may attain great thicknesses, due to the strong thermal subsidence that follows the scorching volcanic Rift Stage. Early marine incursions during times of global oceanic anoxic events may deposit organic-rich shales that will undergo gradual and enormous burial at the base of the section. The overall shape of the Drift Stage is a sag basin, with its depocenter located upon the necking zone of the underlying continental crust (Figure 3). Such depocenter will be the locus of hydrocarbon generation that will be expelled towards the continental slope. If salt and mobile prodeltaic shales are absent the drift section will lack deformation and most of the migration will take place laterally and updip. Reservoirs will be predominantly turbidite sandstones deposited in the slope realm. Contourites and contourite-modified turbidites may eventually constitute reservoirs as well (Viana et al., 2002; Mutti et al., 2014)..

Traps are predominantly of stratigraphic nature, consisting of updip pinchout of turbidite channels, lobes and submarine fans; and eventually of contourite constructions (Figure 3). Fractured volcanic buildups underneath the source rocks may be added to the list.

Although not adequately explored yet, the VPM of the South Atlantic (Pelotas Basin in Brazil, together with Uruguay, Northern Argentina, Namibia and Western South Africa) may hold significant volumes of hydrocarbons in their Drift Stage packages.

**Petroleum Potential of Transitional Passive Margins**

TPM start their development in the same manner as MPPM, with numerous and extensive grabens filled predominantly by sedimentary rocks. As rifting progresses and a significant amount of magma start to pour into the basin the hyperextended ductile crust exhumes and new grabens are now filled by SDRs. These inundated areas will constitute the future site of the continental crust breakup and when this happens these newly laterally accreted volcanic grabens will comprise the distal portions of the passive margin (Figure 4).

The petroleum geology and potential of the proximal settings (onshore, shallow to deep waters) are similar to those of MPPM. The distal portions of the margin (deep to ultra-deep waters) will present the petroleum geology and potential similar to those of VPM (Figure 4).

Prime examples of petroleum-rich TPM are the Sergipe-Alagoas, Potiguar and Ceará Basins in Northeastern Brazil and the Gabon and continental Equatorial Guinea Basins in West Africa. In the Sergipe-Alagoas Basin both the proximal MPPM and distal VPM portions are definitely proved to be rich in hydrocarbons.

## Conclusions

Magma-Poor (MPPM), Volcanic Passive Margins (VPM) and their gradations as Transitional Passive Margins (TPM) may develop in an integrated context of breakage of a supercontinent. Their nature will depend on how close or far they are from the impingement points of the underlying mantle plumes. VPM develop in their close vicinity, MPPM develop the farthest away and TPM develop in intermediate positions. MPPM present high potential in both Rift and Drift Stages. VPM may present high potential only in the Drift Stage. The Kudu gas discovery in Namibia may indicate some potential in the **proximal** portion of the Rift Stage of a VPM. TPM present moderate potential in both the Rift and Drift Stages.

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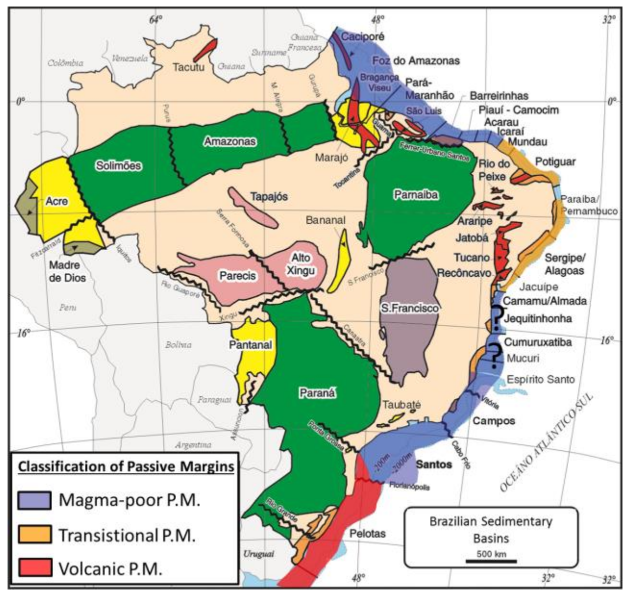


Figure 1 – Map displaying the classification of the Brazilian passive margins (from Zalán, 2015). Passive margins are classified as Magma-Poor Passive Margins (MPPM, in blue), Volcanic Passive Margins (VPM, in red) and Transitional Passive Margins (TPM, in orange). Interrogation tags in Cumuruxatiba to Camamu-Almada Basins indicate lack of adequate knowledge in order to surely classify those basins. Typical VPM filled with SDRs run from Argentina, through Uruguay, into the Pelotas Basin. Typical MPPM displaying exhumation of mantle can be found in Santos, Campos and Espírito Santo Basins in the Southeastern Margin and in the Barreirinhas, Pará-Maranhão and Foz do Amazonas Basins in the Equatorial Margin. Transitional Passive Margins, displaying the coexistence of proximal sediment-filled grabens with distal SDR-filled grabens, are characteristic of the region encompassing the Jacuípe to the Mundaú Basins in Northeastern Brazil.

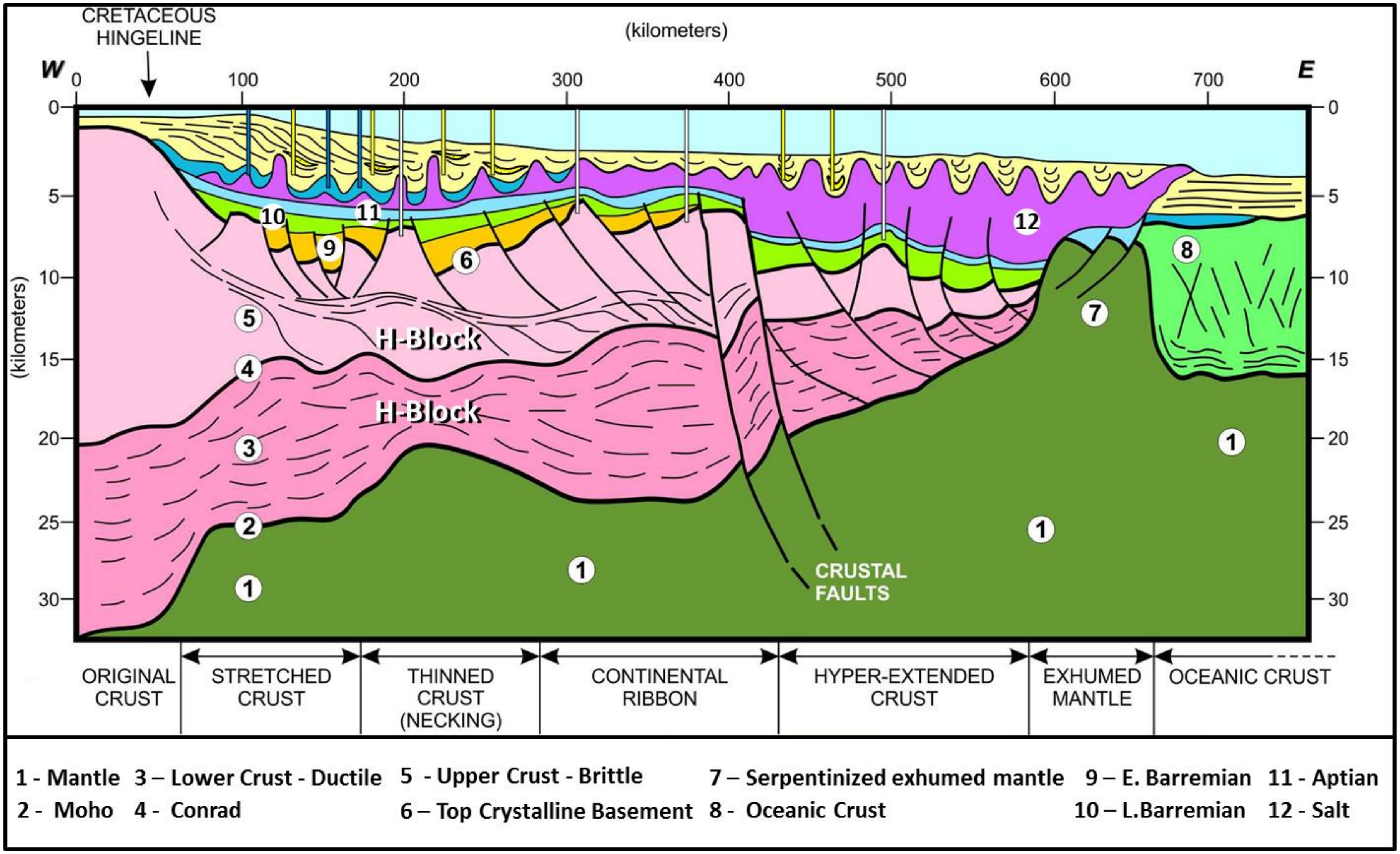


Figure 2 - Schematic geological model valid for the Magma-Poor Passive Margin Santos, Campos and Espírito Santo Basins of Southeastern Brazil, displaying the common strain domains of the continental crust (pink colors) and its contact with oceanic crust via an intervening exhumed mantle. Based on Zalán (2014 and 2015). Potential hydrocarbons accumulations should be sought in the Rift Stage fault blocks (white wells), in the Drift Stage albian carbonate (dark blue strata) pillows situated immediately above the salt (blue wells) and in stratigraphic traps in Late Cretaceous and Cenozoic turbidites (yellow wells).

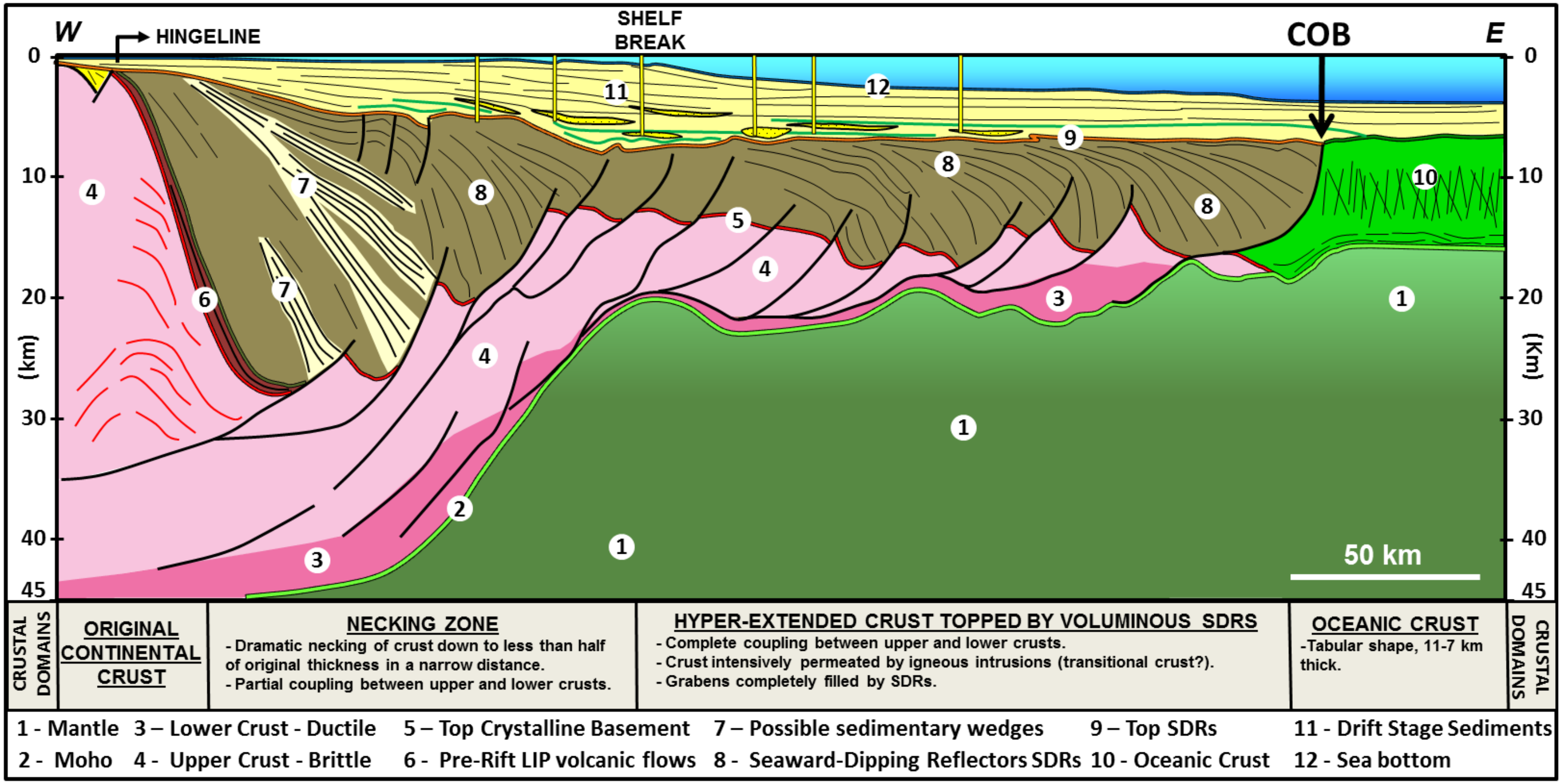


Figure 3 - Schematic geological model valid for the Volcanic Passive Margin Pelotas Basin of Southern Brazil, displaying the common strain domains of the continental crust (pink colors) and its blurred contact with oceanic crust without an intervening exhumed mantle. Based on Zalán (2014 and 2015). Potential hydrocarbons accumulations should be sought in the Drift Stage stratigraphic pinch outs of turbidite bodies (yellow wells). Since there is no deformation in the drift section the closer the turbidites are to the basal mature source rocks (green strata in 11) the greater their chance of having had access to the migration of hydrocarbons.

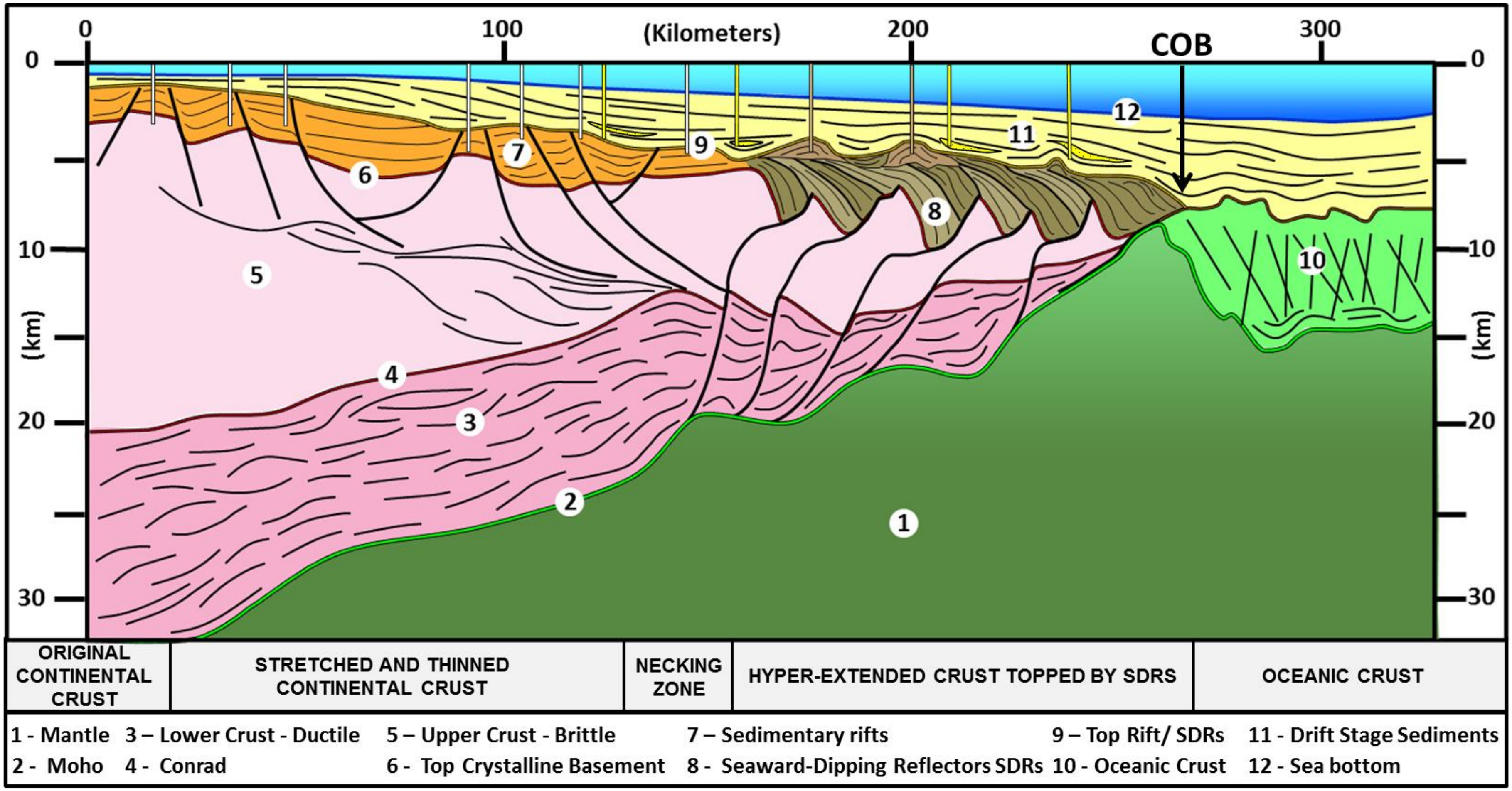


Figure 4 - Schematic geological model valid for the Transitional Passive Margin of the Sergipe-Alagoas, Potiguar and Ceará Basins of Northeastern Brazil, displaying the common strain domains of the continental crust (pink colors) and its blurred contact with oceanic crust without (?) an intervening exhumed mantle. Potential hydrocarbons accumulations should be sought in the Rift Stage fault blocks (white wells) and in the Drift Stage stratigraphic pinchouts of turbidite bodies (yellow wells). Since there is no deformation in the drift section the closer the turbidites are to the basal source rocks of the Drift Stage the greater their chance of having had access to the migration of hydrocarbons. Eventually, volcanic buildups in the uppermost SDRs may be targets for hydrocarbons that migrated laterally from the basal part of the drift section (brown wells).