Similarities and Differences between Magma-Poor and Volcanic Passive Margins – Applications to the Brazilian Marginal Basins

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Abstract

Passive margins are presently classified in a spectrum of types that have as end-members Magma-Poor (MPPMs) and Volcanic Passive Margins (VPMs). VPMs develop atop or in the close vicinity to the impingement of mantle plumes or of strong and concentrated mantle-derived thermal anomalies upon mega-continents. A series of thermal anomalies/plumes can encroach under a continental mega-plate causing intense volcanism and severe localized thermal weakening of the lithosphere. VPMs are invariably associated to Large Igneous Provinces (LIPs). Crustal deformation in VPMs during the rifting phase is dominated by volcanism under the form of Seaward-Dipping Reflectors (SDRs), severe crustal dyking and widespread hyper-extension. The propagation of fracturing/faulting/rifting linking the thermally weak zones leads to the breakage of the mega-continent into two or more continents and micro-continents. MPPMs develop along the linking rift zones in the areas situated at great distances from the surface expression of the thermal anomalies or plumes; thus, with very reduced influence of volcanism when compared to VPMs. Crustal deformation in MPPMs during the rifting phase is dominated by crustal stretching and thinning without the influence of thermal weakening due to intrusions or volcanism. Hyper-extension occurs in MPPMs in lesser amount than in VPMs. In both types of margins the final breakup of the lithosphere is always promoted by magma from the asthenosphere reaching the surface to create spreading ridges and oceanic crust. Consequently, even in MPPMs volcanism may play an important role in the latest stages of rifting, in the outermost realms of the continental margin. Transitional Passive Margins develop in intermediate positions where VPMs grade into MPPMs and vice-versa.

Magma-Poor Passive Margins

MPPMs were defined and have been extensively studied in the last 12 years (Manatschal, 2004; Manatschal et al., 2007; Péron-Pinvidic and Manatschal, 2009 and 2010; Péron-Pinvidic et al., 2013). These studies relied on: (1) field studies carried out in the Alps and Pyrenees, where ancient Tethyan passive margins are exhumed and preserved amidst intensive folding and thrusting, and (2) the results of deep sea drilling in the conjugate margins of Iberia and Newfoundland. Ultra-deep seismic sections available to the petroleum industry in the last six years were interpreted and analyzed utilizing these new concepts, mostly in the South Atlantic. The scant publication of these results show a good correlation between the theoretical concepts and the crustal structure underlying the Brazilian and West African passive margins (Zalán et al., 2009 and 2011; Zalán, 2013; Unternehr et al., 2010; Kumar et al., 2012).

In the Southeastern continental margin of Brazil, the prolific Santos, Campos and Espírito Santo Basins constitute prime examples of Magma-Poor Passive Margins (Zalán et al., 2009 and 2011; Zalán, 2013). Based on the results obtained by these authors in the interpretation of ultra-deep seismic sections shot by ION/GXT an idealized model for these types of margins was developed (Figure 1). Going from onshore to offshore, the following domains of the underlying continental crust can be usually recognized in an overall taper profile: (A) the original, unstretched continental crust, with thicknesses in the order of 32-35 km, eventually 40 km; followed by (B) a first mild necking zone, where the crust thins from 32 to around 25 km, above which a hingeline in the shallow basement marks the border of the sedimentary basin, succeeded by (C) stretched continental crust, where stretching is significant (with several grabens on top) and thinning is not, although clearly present. The next domain is (D) thinned crust, where both stretching and thinning are very significant. It can be represented by a single significant necking zone amidst the stretched continental crust, above which an aulacogen is developed (Block H of Manatschal and co-workers) or as a gradual continuation of the taper profile from stretched to thinned crust. The rule in these three Brazilian basins is that a (E) continental ribbon (with thicknesses close to original crust) of resistant continental crust follows the internal necked zone (thinned crust). The continental ribbon passes abruptly into the (F) hyper-extended crust, most of the time via two large-scale crustal faults. The hyper-extended domain is characterized by extreme thinning of the crust and the rheological coupling of lower and upper crust into a single unit that displays extreme extensional brittle strain. Several highly rotated seaward-dipping normal faults seem to detach in the Moho. Its thickness may vary from 10 to 0 km in a highly variable horizontal distance (narrow to wide). Numerous deep grabens developed on top of this region. As the hyper-extended domain thins away (tapers out) (G) exhumed mantle invariably follows, forming a continuous belt of variably serpentinized material circa 1500 km in length and 15-70 km wide. The exhumed mantle displays the same brittle strain of the adjacent hyper-extended crust and may hold grabens of significant size atop of it. The Continental-Oceanic Crustal Boundary (COB) (H) is usually placed at the external limit of the exhumed mantle. Oceanic crust (I) follows, with crustal thicknesses ranging between 9-14 km.

This idealized profile (Figure 1) may show some variations. For instance, in the Espírito Santo Basin there are no clear H-Block and continental ribbon. The overall profile is a narrow continental margin with a regular high taper profile (original, to stretched, to thinned and then to hyper-extended crustal domains in a short distance). The Santos Basin is a very wide continental margin with an overall boudinage crustal profile of very low taper, constituted by two necking zones and two intercalated continental ribbons.

The problem of the ever existing exhumed mantle in MPPMs has been challenged by several authors in the last years (for example, Kumar et al., 2012). However, this is mostly due to two reasons: (i) the analysis of individual reflection seismic sections where there is a lack of high-definition in the complicated passage between continental and oceanic crusts and the exhumation of the mantle does not stand out clearly, and (ii) to numerical models based on seismic refraction lines and gravity modelling along single profiles, where the typical values of 8 km/sec and 3.3 g/cm^3 are never found at the COB level. The first argument is usually weakened when a regional mapping of several ultra-deep seismic lines is performed instead of the sole interpretation of single lines. In a large array of regional ultra-deep lines, there are always two or more lines that will clearly show the exhumation of the mantle between the hyper-extended continental crust and the tabular oceanic crust. These high-definition lines will calibrate the interpreter eyes and will help them to recognize exhumation in seismic sections of poorer definition. The second argument can be explained by the fact that exhumed mantle shows variable degrees of serpentinization, from total at the surface to unknown decreasing percentages with depth. This phenomenon can change the properties of the resulting serpentinite to values (seismic velocities and densities) as low as of the surrounding lithologies, such as high-grade metamorphic rocks in the continental side and MORB basalts in the oceanic side. So, these indirect tools will never detect typical mantle values in the serpentinized exhumed mantle. We reinforce our view that exhumation of mantle is a must at MPPMs.

Volcanic Passive Margins

Volcanic Passive Margins have been less studied and understood than Magma-Poor Margins. The field works carried out by Prof. Laurent Geoffroy in both Eastern and Western continental margins of Greenland and in the Afar Triangle are examples of such studies (see, for example, Geoffroy, 2005; Geoffroy et al., 2011). They had shed some light on the structure and composition of these margins. Ultra-deep seismic sections available to the petroleum industry were interpreted and analyzed utilizing the concepts developed in these works, mostly in the South Atlantic. The Pelotas Basin in Brazil and the Namibian margin in West Africa are prime examples of Volcanic Passive Margins. The recent publication of these results (Stica et al., 2014) concluded that this type of margin shows an abrupt and dramatic crustal thinning, passing from an original, unstretched crust directly into hyper-extended crust.

Their results and the regional mapping of the Pelotas Basin allowed the establishment of an idealized crustal structure model for Volcanic Passive Margins (Figure 2). Going from onshore to offshore, the following domains of the underlying continental crust can be usually recognized (Figure 2): (T) the original, practically unstretched continental crust, with thicknesses in the order of 40-45 km, with few small grabens (filled mostly by sediments) preserved on top of the flat crystalline basement; followed by (U) a tremendous necking/flexing of the upper crust, where it thins from 45 to around 20 km, above which a hingeline in the shallow basement dips deeply and may form the flexural boundary of mega-rifts as thick as 25 km, succeeded by (V) a wide and dramatic necking zone where the crust may thin to thicknesses of about 15-10 km. In this domain extremely deep grabens may develop (up to 20 km thick). The filling of these grabens is made up of enormous SDR wedges. We speculate that some of the filling in the inner parts of the grabens may be sedimentary in origin, but still secondary in relation to the volcanics. In this necking zone hyper-extension mingles upper and lower crust into a single rheological unit that displays both ductile and brittle deformation. Moho jumps from depths of 45 km to 20 km. The Moho stabilizes at (W) displaying a relatively constant depth throughout the (X) hyper-extended crust (thicknesses less than 10 km), most of which is covered by huge rifts filled completely with SDRs. This domain is the realm of the deep and ultra-deep waters of the VPMs. The COB (Y) is usually placed where the SDRs abut against the tabular body of oceanic crust. No signs of exhumed mantle can be seen. Oceanic crust (Z) follows, with crustal thicknesses ranging around 7-11 km, tapering very gently towards the mid-oceanic ridge.

The distance between this pivotal thinning and the COB may vary considerably along the strike of some of the basins (from 50 to 200 km; Stica et al., 2014) and it is not related to a “normal” rheological taper profile, as in Magma-Poor Margins. These differences in the width of the margin may be explained by intensive injection of dykes in the continental crust causing more or less lateral dilatation, or by regional variations in the rate of crustal stretching. The rift faults dip invariably landwards and the sequences filling the grabens in such margins are nearly entirely made up of SDRs. Field exposures of SDRs in Greenland are entirely volcanic in origin (basaltic lava flows and intercalated tuffs).

Transitional Passive Margins

Transitional Passive Margins, displaying internal/proximal grabens filled with sediments resting side-by-side with external/distal grabens filled with SDR packages, have been frequently observed in the seismic sections of the Ceará, Potiguar, Sergipe-Alagoas and Jacuípe Basins of Northeastern Brazil (Figure 3). Moreover, interdigitation of Volcanic and Magma-Poor Passive Margins may occur, creating a transitional passage between basins, such as is the case in the fuzzy geological boundary between the Pelotas and Santos Basins in Southern Brazil. We consider such margins as transitional stages between the two end-members described.

Classification of the Brazilian Passive Margins

The Brazilian passive margins can be classified according to the types of passive margins considered above (Figure 3). According to present knowledge, the Pelotas Basin is the only classical VPM of Brazil. From Santos to Camamu-Almada, in the Eastern Margin, and from Barreirinhas to Foz do Amazonas in the Equatorial Margin, we can find fine examples of MPPMs. The region that encompasses the Jacuípe to Mundaú Basins, in Northeastern Brazil, displays the coexistence of proximal sediment-filled grabens with distal SDR-filled grabens; thus, imparting to this region the classification of Transitional Passive Margins.

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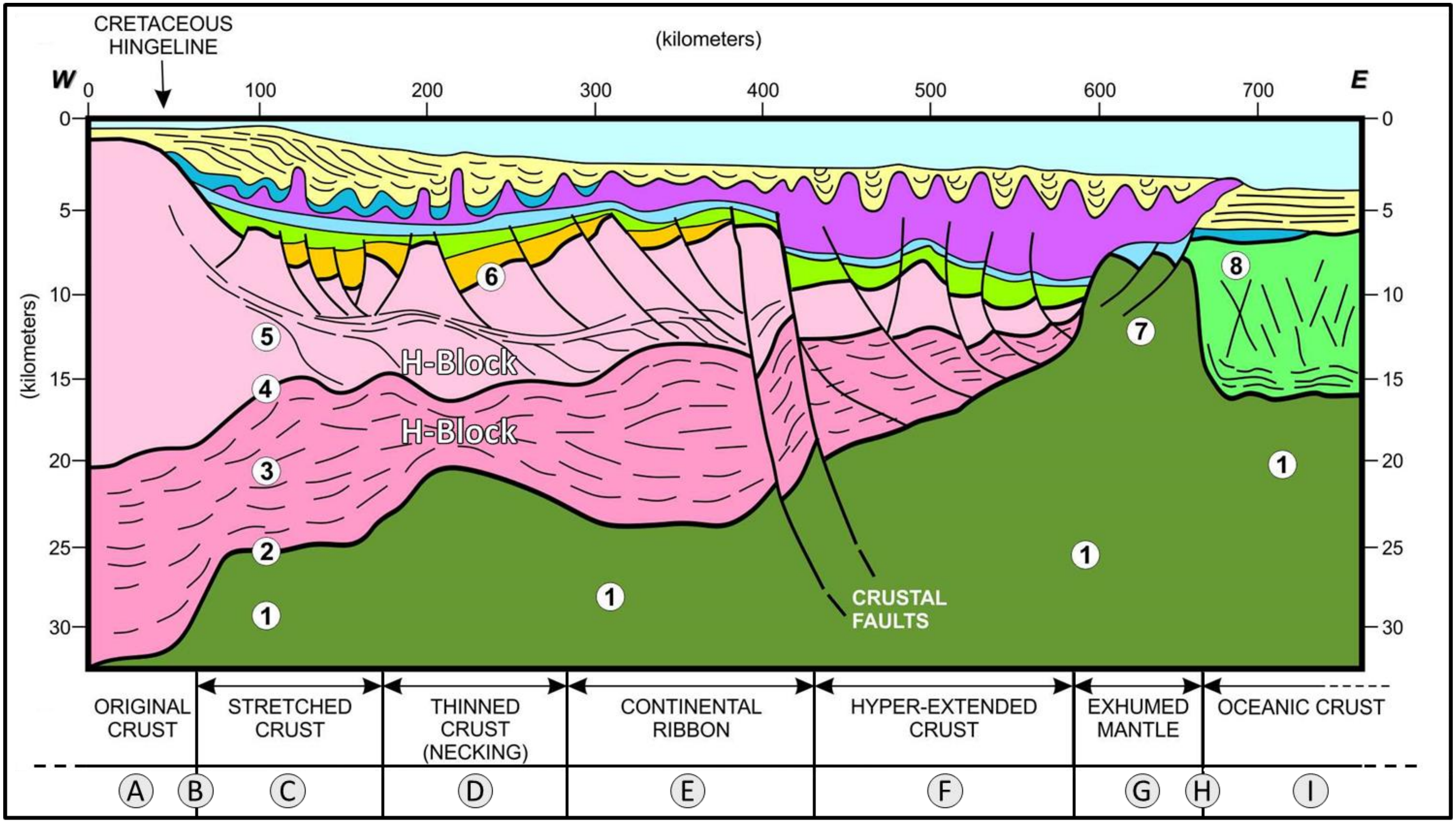

Figure 1 - Schematic W-E geologic profile valid for the Magma-Poor Santos, Campos and Espírito Santo Basins of SE Brazil, displaying the common strain domains of the continental crust (pink colors) and its contact with oceanic crust via an intervening exhumed mantle. Elements numbered as (1) mantle, (2) Moho, (3) lower ductile crust, (4) Conrad, (5) upper brittle crust, (6) top of crystalline basement, (7) exhumed mantle, and (8) oceanic crust. Sedimentary packages above (6) represent Barremian early syn-rift (dark yellow), Early Aptian climax syn-rift (green), Late Aptian late syn-rift (light blue), Latemost Aptian syn-rift evaporites (purple); Albian drift carbonates (dark blue), Cenomanian-Recent drift siliciclastics (yellow). Letters A to I represent crustal domains described in detail in the text. Based on Zalán (2013).

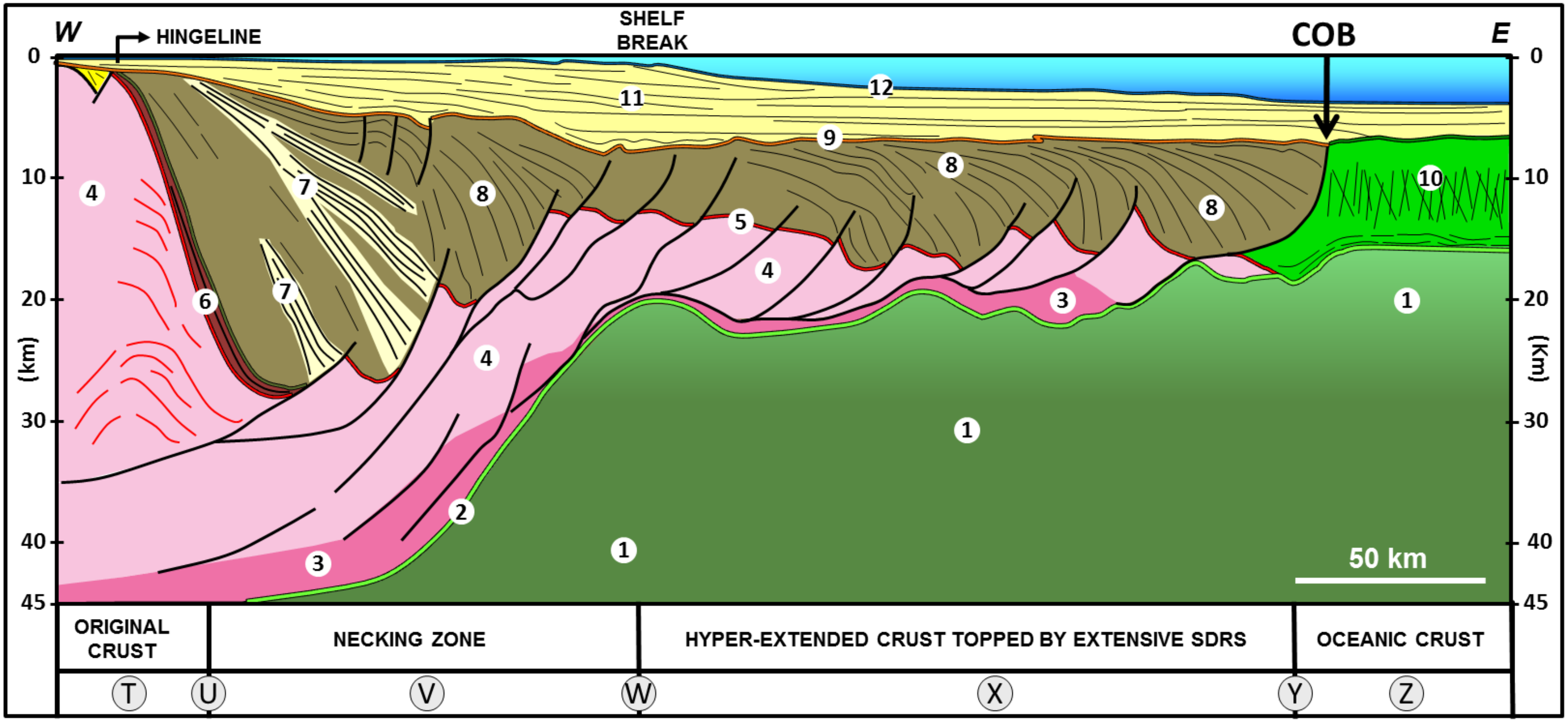

Figure 2 - Schematic W-E geologic profile valid for the Volcanic Pelotas Basin of Southern Brazil displaying the strain domains of the continental crust (pink colors) (line drawings partly based on Line 130 from ION-GXT Pelotas SPAN). Elements numbered as (1) mantle, (2) Moho, (3) lower ductile crust, highly reflective, (4) upper brittle crust, (5) top of crystalline basement, (6) pre-rift basalt traps, (7) possible syn-rift sedimentary facies, (8) syn-rift SDRs, (9) post-rift unconformity, (10) oceanic crust, (11) Drift Sequence, and (12) sea bottom. Letters T to Z represent crustal domains described in detail in the text. Interpretation of strain domains partly based on Stica et al. (2014).

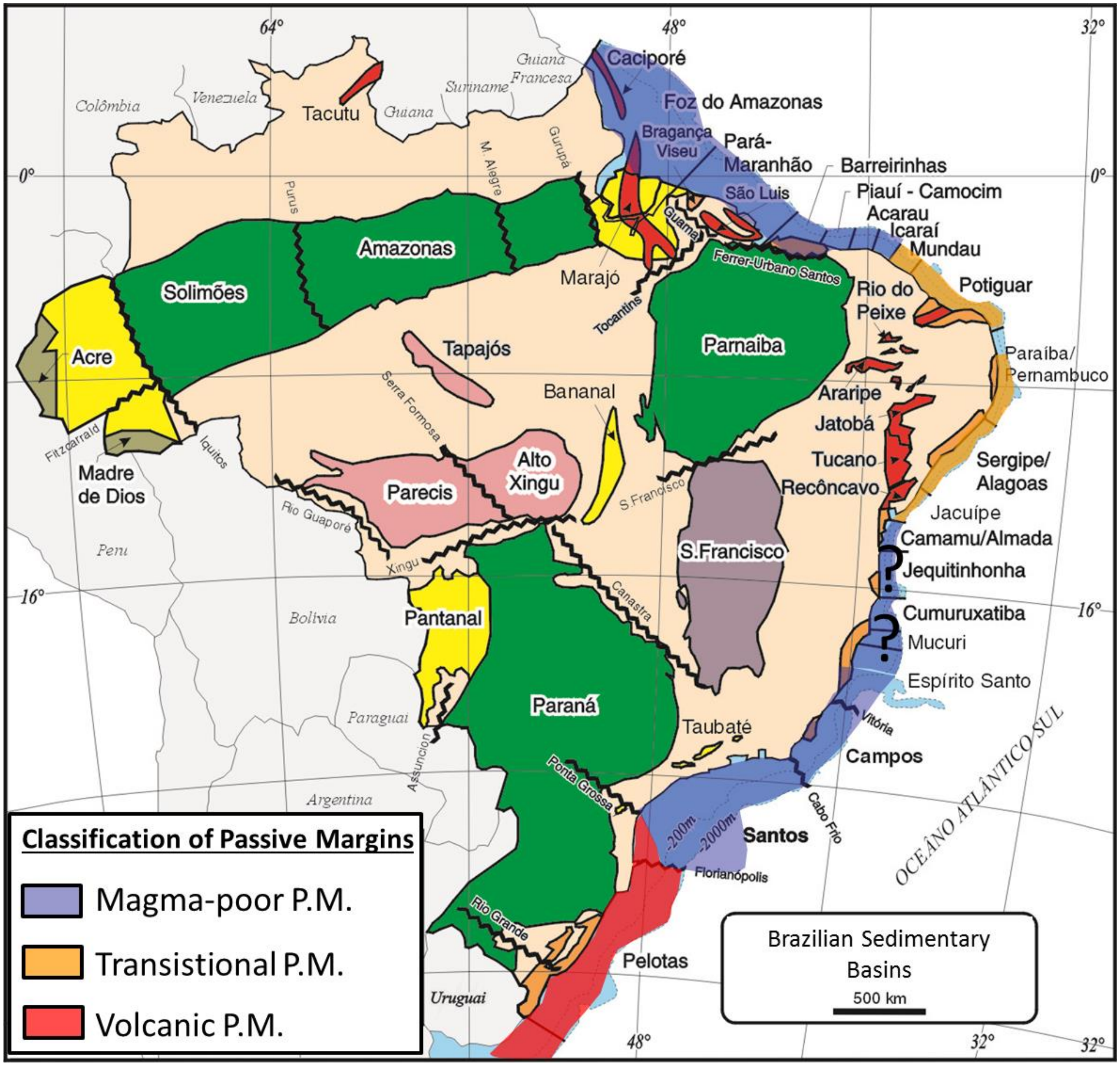

Figure 3 – Map of the Brazilian sedimentary basins (from Zalán, 2004). Marginal basins are classified as Magma-Poor Passive Margins (MPPMs, in blue), Volcanic Passive Margins (VPMs, in red) and Transitional Passive Margins (in orange). Interrogation tags in Cumuruxatiba to Camamu-Almada Basins indicate lack of adequate knowledge in order to surely classify those basins. Typical VPMs filled with SDRs run from Argentina, through Uruguay, into the Pelotas Basin. Typical MPPMs 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.