A FAST NOVEL APPROCH TO LOCATE CONTINENT-OCEANIC BOUNDARY OVER SOUTH AMERICAN PASSIVE MARGIN

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Abstract

Continental Oceanic Boundary (COB) is of regional interest for continental passive margin for providing a limit to petroleum exploration, to delimitate the exclusive economic zone and also to help understanding the tectonic environment. The mapping of COB usually requires rigorous modelling using several geophysical datasets, e.g. gravity, magnetic, seismic and geochemical data. The basic criterion for identification of crustal types along margins is the difference in basement morphology associated with geophysical fields and bathymetry, varying from continent to ocean. In this paper, we proposed a novel, effective and enhanced methodology to correlate the geomorphological features of different crustal types using Tilt and Theta parameters from Bouguer gravity maps. Correlation between them can be established by determining angles between the gradient directions of Tilt and Theta parameters. Very small angles (~ 0º) provides direct correlation, however, large angles (~ 180º) give inverse correlation. Change in correlation from inverse to direct marks the COB location. We applied our new approach for the entire South American Passive Margin (SAPM) consisting of Equatorial, central and southern segments. COB results along SAPM shows very good agreement with previous available results from recent plate reconstruction studies. The major features such as lineaments, ridges and Fractures Zones over SAPM also show a good correlation as outlined by this study.

Introduction

Continental-oceanic crustal boundary (COB) is much important in plate tectonic reconstructions, subsidence behaviour of passive margin, limit to sediments accumulation, heat flow characteristics, and favourable trap conditions for 'oil finders'. So accurate and/or, precise mapping of COB is a priority task in hydrocarbon exploration over frontier prospective areas of offshore continental margins. South American Passive Margin (SAPM) has a long history of rifting and plate separation during Gondwana break-up and opening of mid and south Atlantic oceans and it depicts different structural units and tectonic settings. The rifted continental crust generally characterized by a complex structure with development of extensional features while the oceanic crust is usually undisturbed. COB shows a step in basement surface topography resulting from volcanic activity during early phase of sea-floor spreading along equatorial segment of SAPM, basement surface in spreading basins gets more rugged with many diffractions such as evaporites in central segment of SAPM and oceanic crystalline basement characterized by SDRs in southern segment of SAPM (Fig. 1). Gravity and/or magnetic anomalies and bathymetry mostly correlates well and gives a better information about source location, permitting the demarcation of the COB. Jilinski et al. (2013) introduced the concept of correlation with angular differences between gradient directions of potential field and bathymetry. They also showed the advantages of the technique over most common conventional techniques to find the COB. This technique correlate lateral bathymetric, density and magnetization changes and act as an effective edge-detection attribute. They also demonstrated the ability of angular difference technique over Southwest African Margin (Pawlowski, 2008; Hirsch et al., 2009) and West African Transform Margin (Flinch et al., 2009).

We applied a novel, enhanced and effective methodology to correlate the geomorphological features associated with different crustal types. In this new method, we produced a correlation image between enhanced parameters derived from Bouguer gravity data: the Tilt parameter, arctangent of the ratio between first vertical derivative and total horizontal derivative, and Theta parameter, defined as arccosine of the ratio between total horizontal derivative and analytical signal. Both Tilt and Theta parameters have better enhanced edge detection attributes. The main improvement over Jilinski et al. (2013) methodology is due to observed noise reduction and regional key contribution through enhanced parameters as compared to the direct correlation between free air and bathymetry.

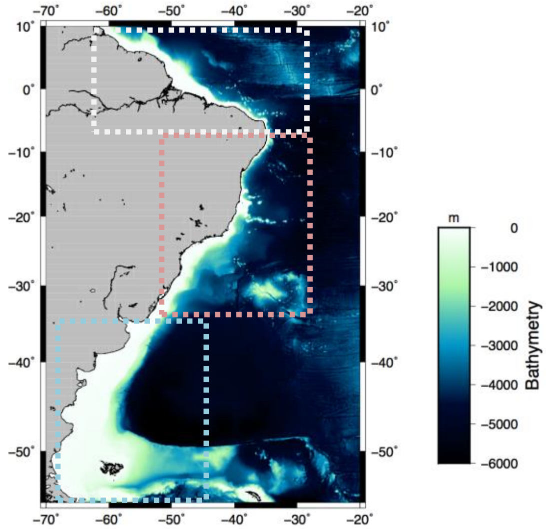

Figure 1: *Bathymetry over South American Passive Margin (SAPM) showing main physiographic features along equatorial (shown by dashed gray rectangle), central (dashed light red rectangle) and southern (light blue dashed rectangle) segments.*

Estimating Correlation

We estimated the correlation between two images using the angles between their gradient directions. The correlation angle between Tilt and Theta may be computed as:

$$\theta_c = \cos^{-1}\left(\frac{\nabla(Tilt).\nabla(Theta)}{|\nabla(Tilt)||\nabla(Theta)|}\right)$$

Where $\nabla(Tilt)$ and $\nabla(Theta)$ are the gradients of Tilt and Theta which estimate changes in Tilt and Theta values in all three directions of Cartesian coordinates, and $|\nabla(Tilt)|$ and $|\nabla(Theta)|$ are the magnitude of Tilt and Theta gradients. If correlation angle is 0^o, both vector gradient parameters point the same direction and are either increasing or decreasing, indicating direct correlation between them. If correlation angle is 180^o, one field increases while other decreases, resulting in inverse correlation between them. Over continents, where mantle is deep and low-density sources predominate, both Tilt and Theta parameters follows inverse correlation as Tilt increases (from minus to zero value) and Theta decreases (from positive to zero value). Over oceans, where the shallow mantle produce regional high-density sources, Tilt increases (from zero to positive values) and Theta increases (from zero to positive values), resulting in direct correlation (Maurya et al. 2016). Thus, a change in correlation from inverse to direct locates the regional boundaries representing the COB.

Computation of Bouguer Gravity over SAPM

The bathymetric map of the study area (Fig. 1) was obtained from ETOPO1 (Smith and Sandwell, 1997) and depict main physiographic features along the entire South Atlantic Passive margin (SAPM). Sandwell's marine gravity grid over SAPM reveals a continuous, prominent and elongated high gravity anomaly close to the shelf edge that trends subparallel to the coastlines (Fig. 2a). Such elongated "edge effect" positive gravity anomalies are most commonly observed features at passive continental margins (Rabinowitz and LaBrecque, 1979; Watts and Fairhead, 1999). However, due to the inherent ambiguity in potential field interpretations, the possible genetic cause of these anomalies is not always clear. In particular, their cause has been ascribed in many margins to the difference in depth to major lateral, near-seafloor density contrasts, the equivalent depth difference of base crust compensation (Talwani and Eldholm, 1972; Tsikalas et al., 2005), juxtaposition of continental and oceanic crust (Rabinowitz and LaBrecque, 1979; Bauer et al., 2000), and magmatic underplating (Watts, 2001).
Bouguer Gravity anomaly over SAPM (Fig. 2b) was computed from Sandwell's marine gravity models after applying corrections for Bouguer slab, curvature and terrain corrections with FA2BOUG code (Fullea et al. 2008). Reduction densities for crust and seawater considered as 2670 and 1030 kg/m^{3,} respectively. To achieve best terrain corrections for rugged topography areas we used high-resolution SRTM topography grid with ~ 15" resolution to input the detailed topography in FA2BOUG. As Bouguer, gravity varies with lateral density and Moho topography. Therefore, it may demarcate the continent-ocean boundary with more refinement. Strong positive Bouguer anomaly up to 400 mGal were observed over oceanic regions of SAPM whereas, Bouguer gravity is mostly negative, with lower limit of -75 mGal, for continental domain and / or transitional crust. Generally, Bouguer gravity relatively reduced for oceanic features having topography at ocean floor, which may be possibly related to the Moho topography compensation (making it deeper) beneath those regions of SAPM.

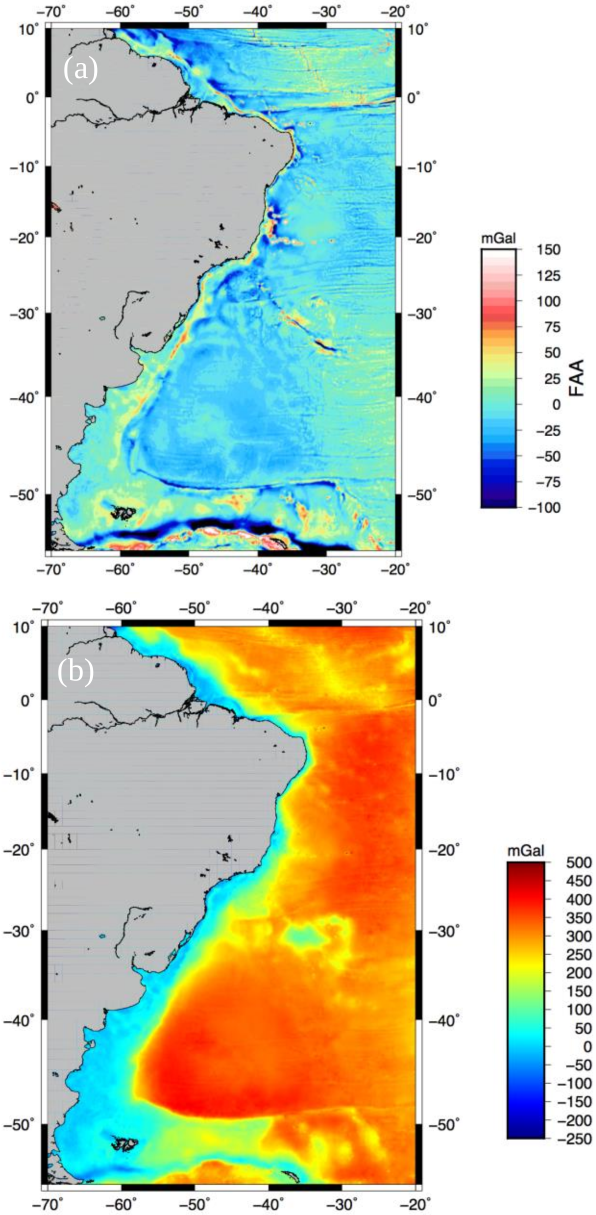

Figure 2: *Free air Marine gravity models (a) from Sandwell et al. (2014) and deduced Bouguer gravity (b) from FA2BOUG code over SAPM. Prominent elongated free air gravity high (a) showing 'edge effect' along entire SAPM. Bouguer gravity (b) is positive over oceans, negative over continents.*

Results and Discussion

The enhancement images for Tilt (Fig. 3a) and Theta parameters (Fig. 3b) were estimated using Bouguer gravity anomalies over SAPM. Over regional boundaries (vertical derivative of Bouguer anomaly is zero), which makes both Theta and Tilt as zero. Thus, both parameters may sense the edge between two different crustal domains with significant lateral density contrast and makes possible COB demarcation. Additionally, Tilt can also distinguish between continental (regionally low-density sources, as mantle is deep) and oceanic (regionally high-density sources, as mantle is shallow) domains of SAPM. Negative Tilt recognizes continents, whereas positive Tilt mostly depicts oceanic crust. In case of Theta, it may signify the regional edges with small theta values. Tilt map of SAPM is mostly negative over rifted extended transitional crust, positive over the oceanic crust and zero for the Continental oceanic crustal boundaries. Moreover, negative tilt also observed over Lineaments, Fracture zones and Ridges belonging to SAPM. Theta map of SAPM region (Fig. 3b) in the equatorial segment depicts sharp edges mostly, whereas, central segment presents more spread edges possibly over extensive evaporite sequences and southern segment shows prominent broad edges possibly related to Seaward Dipping Reflectors (SDRs).

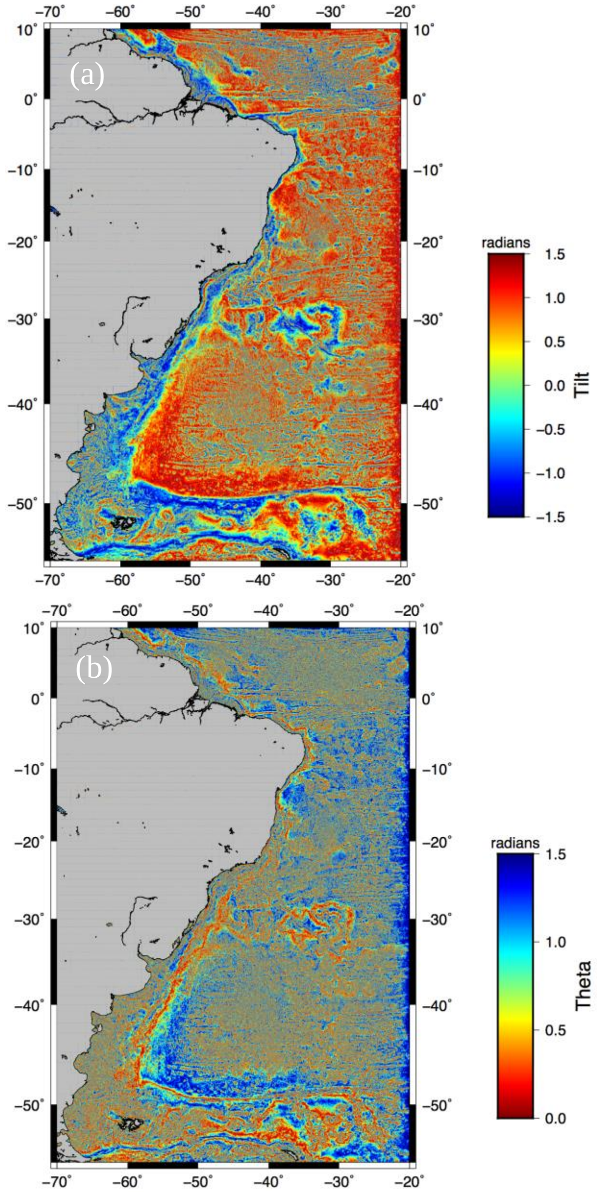

Figure 3: *Tilt (a) and Theta (b) parameters over SAPM derived from Bouguer gravity. Positive tilt signifies ocean, negative tilt represents continents and both tilt and theta equal zero depicts the regional boundaries.*

The correlation image between bathymetry and free-air anomaly over SAPM by previous methodology (Jilinski et al. 2013) is shown in Figure 4a, whereas, correlation image from Tilt and Theta parameters of Bouguer gravity described in new methodology over SAPM is shown in Figure 4b. It can be seen that first correlation image from Jilinski methodology (Fig. 4a) does not show distinct change in correlation except some regions, possibly due to absence of prominent outer high; however, correlation image from new methodology shows a fairly clear transition in correlation from inverse to direct over entire SAPM, allowing the demarcation of COB with less ambiguity, as marked by white dashed lines in Figures 4a and 4b. Moreover, main improvement over Jilinski et al. (2013) methodology is due to observed noise reduction and regional key contribution through enhanced parameters as compared to the direct correlation between free air and bathymetry. In fact, correlation between free air and bathymetry influenced by local complex geology associated with magma 'poor' and magma 'rich' regions over SAPM. The COB is varying along entire SAPM region (Figure 4b), being relatively wide in equatorial segment, narrow for northeastern central segment, wide for southern central segment, becoming mostly wide nearby southern segment. COB results along SAPM (shown by white dashed line) show very good agreement with recent published COB results (shown by green dashed line) from plate reconstruction (Muller et al. 2016) except for some localized areas. Additionally, correlation images also depicts major Fracture Zones of both south and mid-Atlantic oceans, Ridges, and Lineaments for entire SAPM continental passive margin as enhanced parameters are inversely correlated over them.

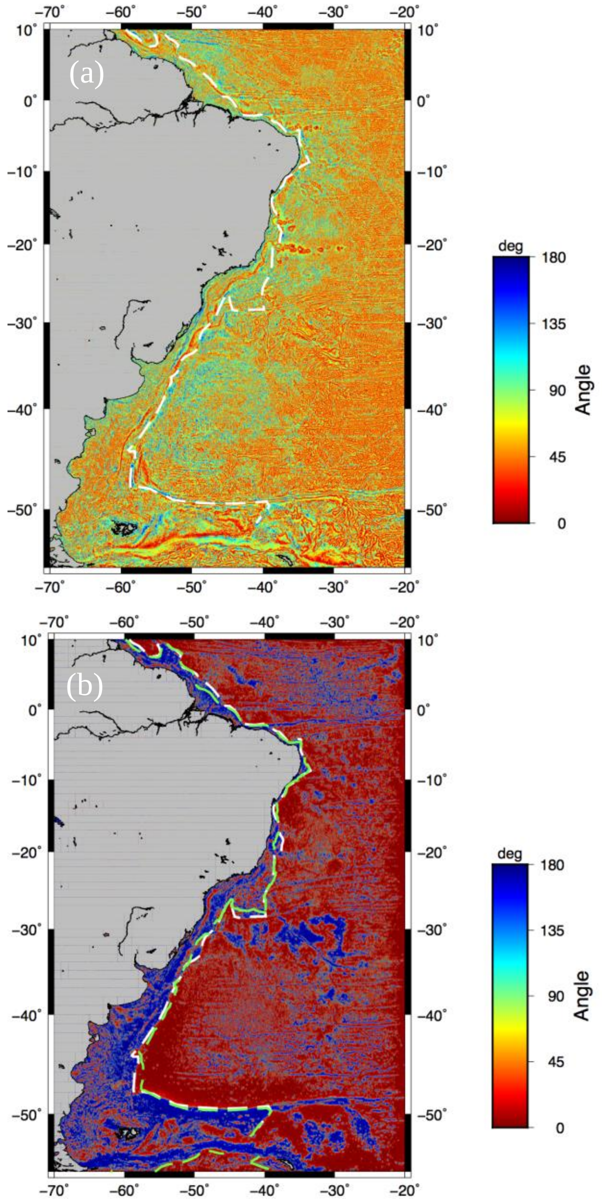

Figure 4: *Correlation image derived from the angles between vector gradients of (a) free air and bathymetry (old methodology from Jilinski et al. 2013) and (b) tilt and theta parameters (new methodology discussed). if angles are 0, means both parameters are directly correlated (both are increasing or decreasing) and if angles are 180, both parameters are inversely correlated (one is increasing and other is decreasing). Dashed white line shows COB from present study and dashed green line represents the COB from Muller et al. (2016) recent plate reconstruction studies.*

Conclusions

The proposed methodology to demarcate COB is novel, very effective, simple, fast and can be easily implemented in other regions of the world. New methodology shows significant improvement over previous Jilinski et al. (2013) methodology. Crustal nature distinguished into three different domains - continental, oceanic and transition zones - using correlation angles between enhanced parameters Tilt and Theta. Tilt increases and theta decreases towards crustal boundary from the continent and both tilt and theta increases towards ocean from the crustal boundary. Therefore, correlation angles between them are 180º over continental or transitional crust and 0º over oceanic crust. Thus, change in correlation marks the Continental Oceanic crustal Boundary. Both tilt and theta parameters depicts clear distinct signatures over crustal boundaries associated with very small change of Bouguer gravity in vertical direction. COB extent is quite variable for SAPM, mostly wide over central equatorial segment, southern central segment and almost entire southern segment and relatively narrow for southern equatorial and northeastern central segment. COB demarcation is more difficult over regions with complex extensional tectonics dominated by both magma poor (observed in evaporitic sequences) and magma rich (associated to volcanic events) margins of SAPM. Additionally, features such as Fracture Zones, Ridges and Lineaments shows good correlation and are well outlined in this study.

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