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Major controlling factors on hydrocarbon generation and leakage in South Atlantic conjugate margins: A comparative study of Colorado, Orange, Campos and Lower Congo basins

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ABSTRACT

We present a supra-regional comparative study of the major internal and external factors controlling source rock (SR) maturation and hydrocarbon (HC) generation and leakage in two pairs of conjugate margins across the South Atlantic: the Brazil (Campos Basin)–Angola (Lower Congo Basin) margins located in the "central segment", and the Argentina (Colorado Basin)–South Africa (Orange Basin) in the "southern segment". Our approach is based on the analysis and integration of borehole data, 1D numerical modeling, 2D seismic reflection data, and published reports. Coupling of modeling results, sedimentation rate calculation and seal-bypass system analysis reveal that: (1) oil window is reached by syn-rift SRs in the southern segment during the Early to Late Cretaceous when thermal subsidence is still active, while in the central segment they reach it in Late-Cretaceous–Neogene during a salt remobilization phase, and (2) early HC generation from post-rift SRs in the southern segment and from all SRs in the central segment appears to be controlled mainly by episodes of increased sedimentation rates. The latter seems to be associated with the Andes uplift history for the western South Atlantic basins (Campos and Colorado) and to a possibly climate-driven response for the eastern South Atlantic basins (Orange and Lower Congo). Additionally, we observe that the effect of volcanism on SR maturation in the southern segment is very local. The comparison of Cretaceous mass transport deposit (MTD) episodes with HC peak of generation and paleo-leakage indicators in the southern segment revealed the possible causal effect that HC generation and leakage have over MTD development. Interestingly, Paleogene leakage indicators, which were identified in the Argentina–South Africa conjugate margins, occur contemporaneously to low sedimentation rate periods. Nonetheless, present-day leakage indicators which were also identified in both pairs of conjugate margins might be related to seal failure events linked to eustatic sea-level drops.

1. Introduction

Following Gondwana continental break-up in the Mesozoic, and as the opening propagated northwards, the evolution of the South Atlantic basins was characterized by dividing transform fault segments, similar syn-rift geologic histories and marked post-rift diachronisms, not only between north and southern margins, but also between pairs of eastern–western margins.

Nowadays it is largely accepted that several South Atlantic passive margins host immense reserves of hydrocarbons (>41,000 MMBO, >32,000 BCFG) (USGS, 2000), and oil and gas discoveries in South American and Northwestern Equatorial African margins (e.g., pre-salt play potential at Brazilian and Angolan margins) (Durham, 2009; Steven et al., 2010) stress the need for deepening our understanding of the common factors that controlled petroleum system dynamics in these areas. A supra-regional analysis of these factors, either internal (i.e., thermal evolution, source rock quality, burial history) or external (i.e., sediment supply regional tectonics, eustasy, climate), by pairs of conjugated basins should allow to determine whether, and how, these differences and similarities in geological history are reflected in the evolution of the petroleum systems of individual basins.

Hence, in this study we have integrated and analyzed observations from two selected segments of South Atlantic conjugate margins: (1) the "central segment": offshore Brazil–Angola margins (Campos and Lower Congo basins) and (2) the "southern segment": offshore the Argentina–South Africa margins (Colorado and Orange basins) (Fig. 1). We then compared the possible driving factors that may have influenced the hydrocarbon generation and leakage in these basins. Attention was placed on the comparison of both the timing of hydrocarbon generation from syn- and post-rift source rocks (SRs) and past or present hydrocarbon leakage events recorded in the slope of the basins against variables such as: (a) changes in sedimentation rates and depositional-style (progradation to aggradation), (b) sea-level fluctuations and occurrence of mass transport deposits (MTDs), and (c) geologic events of uplift and erosion. Ultimately, we hope that our results may help to improve the regional understanding on the driving mechanisms

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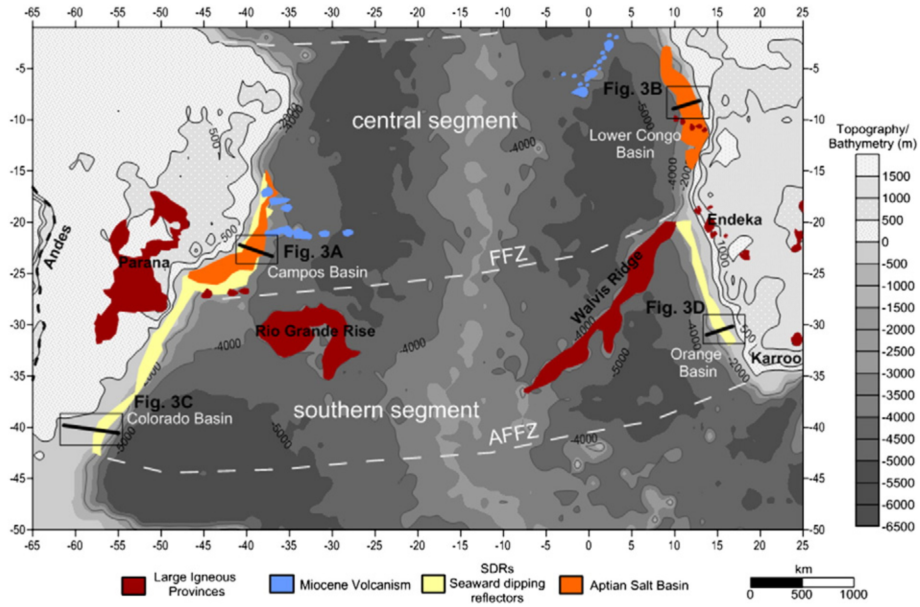

Fig. 1. General map of the South Atlantic Ocean (modified from Torsvik et al., 2009) draped on topography/bathymetry from ETOPO2 (www.ngdc.noaa.gov/). Boundaries between the two studied segments (Central and Southern) are indicated by dashed lines. FFZ: Florianopolis Fracture Zone, AFFZ: Agulhas–Falkland Fracture Zone. Seaward dipping reflectors (SDRs) dominate the margins located in the southern segment. Extension of the Aptian salt basin is shown in orange. The large magmatic topographic structures separating the studied segments correspond to the Rio Grande Rise and the Walvis Ridge. Locations of the key-seismic section of each of the studied basins are depicted (Fig. 3a to d).

of petroleum generation, migration, accumulation, and leakage in the South Atlantic.

2. Geological framework

The South Atlantic passive margins formed during Mesozoic time as a result of lithospheric extension followed by breakup of the Gondwana supercontinent (Blaich et al., 2011). The opening started in the southern portion and propagated towards the North with accompanying extensive deformation. Transform faults divided the South Atlantic into four segments, from South to North: the Falkland, Southern, Central, and Equatorial segments (Torsvik et al., 2009). Although the time and opening direction of the South Atlantic is still controversial, the diachronic opening clearly resulted in:

1) lateral symmetry and thickness discrepancies along the margin length, and the strike of thinned crust and continent–oceanic transitional domains (Blaich et al., 2011; Davison, 1997);
2) hot spot volcanism and large flood basalt eruptions from Late Jurassic (?)–Early Cretaceous to Quaternary (O'Connor and Duncan, 1990) resulting in the Walvis Ridge–Rio Grande Rise hot spot system, which is a prominent bathymetric feature separating the "magma-dominated" southern segment from a "magma-poor" central segment (Torsvik et al., 2009) (Fig. 1);
3) the establishment of Aptian salt basins north of the Rio Grande Rise–Walvis Ridge system, containing up to 1–2 km-thick salt layer (Jackson et al., 2000) (Fig. 1);
4) abnormal velocity layers below the shelf and/or the thinned crust in the Angolan margin (Blaich et al., 2011; Contrucci et al., 2004), and seaward dipping reflectors (SDRs) in the Santos and Campos basins (Mohriak et al., 2008; Torsvik et al., 2009).

The main tectonostratigraphic episodes represented by cycles of basin evolution or stratigraphic megasequences identified in the studied basins are: pre-rift, syn-rift, transitional, and post-rift (Fig. 2a–b) (e.g., Anka et al., 2010; Mohriak et al., 2008, Paton et al., 2008; Vayssaire et al., 2007). Our study is focused within the syn- to post-rift cycles, whose main characteristics are (Figs. 2, 3) the following:

2.1. The syn-rift cycle (Late Jurassic to Early Cretaceous)

In the Campos, Lower Congo, Colorado and Orange basins this cycle is represented by lacustrine black-shales and continental shoaling up prograding deltaic and fluvial sediments (Bushnell et al., 2000; Cobbold et al., 2001; Cole et al., 2000; Contreras et al., 2010; Da Costa et al., 2001; Davison, 2007; Guardado et al., 2000; Mello et al., 1989; Paton et al., 2008). Basins offshore the Argentinean margin, as the Colorado Basin, also contain marine shallow water and alluvial sand deposits with possible reservoir potential ("syn-rift" reservoirs, Fig. 2) (Vayssaire et al., 2007). Offshore western South Africa, in the Orange Basin, syn-rift siliciclastic and lacustrine sediments, usually mixed with volcanic layers, fill half grabens (Paton et al., 2008; Vayssaire et al., 2007). The reported syn-rift SRs correspond to calcareous shales of the Lagoa Feia Formation in the Campos Basin (Guardado et al., 2000), bituminous shales of the Bucomazi Formation in the Lower Congo Basin (Cole et al., 2000), and the generic so-called "syn-rift" for the Colorado and Orange basins (Fig. 2).

2.2. The transitional basin cycle (Barremian to Early Albian & Barremian to Maastrichtian)

It is represented by the cessation of crustal stretching and most of basement-involved fault activity although regional subsidence prevailed (Mohriak et al., 2008). A "sag" basin phase is proposed in the Campos and Colorado basins (Figs. 2, 3) (Contreras et al., 2010; Kingston et al., 1983; Vayssaire et al., 2007). The transitional megasequence overlies the "break-up unconformity" (BU), which resulted from erosional peneplanation (Davison, 1999). In both studied segments on both sides of the South Atlantic this sequence comprises deepening-up siliciclastics, from fluvial red beds to deltaic deposits (Burwood, 1999; Bushnell et al., 2000; Contreras et al., 2010; Mohriak et al., 1990c; Paton et al., 2008; Stoakes et al., 1991). In the Colorado