The Kwanza-Campos conjugate pair: mirror twins? Revisiting and exploring new frontiers

Matthew Plummer[1*] and Jeff Tilton[1] reveal the similarities between two basins that can advance the identification of additional exploration potential on both sides of the South Atlantic.

Introduction

Along the conjugate margins of the South Atlantic, some of the world's most prolific hydrocarbon provinces can be found which are dominated by Cretaceous petroleum systems. The Kwanza Basin offshore Angola and its conjugate equivalent offshore Brazil, the Campos Basin, are exploration hotspots based on their drilling successes and the remaining running room for yet-to-find resources. During the 1980s to mid-1990s the Campos Basin experienced a surge in exploration activities, triggered by significant hydrocarbon discoveries within Cretaceous post-salt turbidite systems. The conjugate offshore equivalent of the Kwanza Basin started its most active exploration period in the early 2010s with the emerging pre-salt play. Roll forward to 2021, and these conjugates are due to become exploration hotspots once again with modern seismic data being acquired and upcoming licensing rounds in both basins. In this article conjugate basin characteristics and petroleum system elements are identified and compared, illustrating the potential that exists on each side of the South Atlantic and establishing whether the basins really are mirror twins.

Exploration history

Kwanza Basin

Exploratory drilling in the offshore Kwanza Basin commenced in the late 1960s, following on from more than 50 years of exploration in the onshore part of the basin. The first sustained period of exploration occurred in the 1980s with 15 prospects tested through the drill bit. Four of these were successful in finding hydrocarbons in the shelfal region, with the Kwanza's first offshore discovery made in the pre-salt at Denden-1 in 1983. Three pay zones were identified in the post-salt section of Cegonha-1, Mubafo-1, and Pakubalu-1.

In pursuit of success that had been made in the deep-water Lower Congo Basin to the north, several exploration wells were drilled in the 1990s making discoveries in both shelfal and deep-water settings (Figure 1). In the early 2000s there was a continued effort in the deep-water acreage with a further 11 wells drilled primarily on post-salt targets with Exxon Mobil making the Semba-1 oil discovery in the Benguela sub-basin. A hiatus in drilling in the offshore Kwanza basin occurred in the 2006-2009 period, before significant acreage was licensed in the early 2010s to target pre-salt prospectivity in response

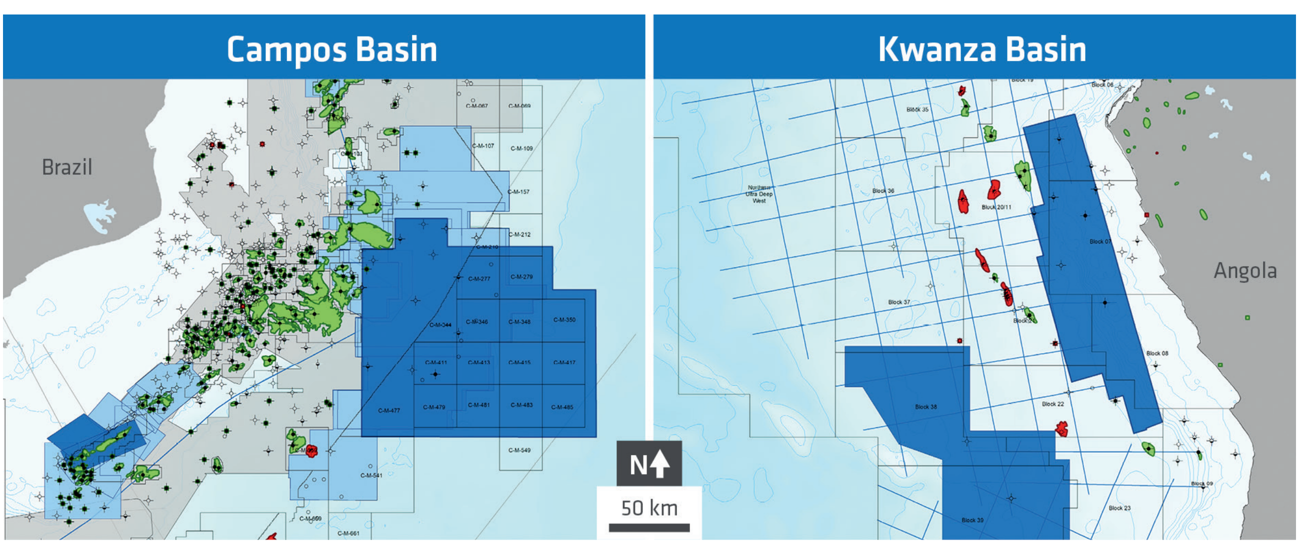

Figure 1 Wells, fields, bathymetry and seismic databases (a) Campos Basin (new field wildcat wells only) and (b) Kwanza Basin. Well information modified from IHS Markit. Fields and blocks from IHS Markit.

[1] PGS
[*] Corresponding author, E-mail: matthew.plummer@pgs.com
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to the success in the equivalent section of the Santos Basin of Brazil.

Maersk was the first company to strike oil in the deep-water pre-salt of the Kwanza Basin in 2011 with the Azul-1 discovery, closely followed by Cobalt at Cameia-1. A campaign of exploration drilling on predominantly pre-salt targets continued throughout the first half of the 2010s, resulting in 13 pre-salt discoveries.

Campos Basin

Offshore exploration in the Campos Basin began in the early 1970s. The first successful well (1-RJS-9A) was drilled by Petrobras in 1974, discovering the post-salt Garoupa Field in Albian carbonate reservoirs. Additional post-salt discoveries (Namorado, Enchova, Cherne, Bonito, Linguado and Corvina) were made soon after in the remaining years of the decade.

After this initial success in the shelfal region, exploration moved quickly to deep- and ultra-deep waters in the mid-1980s. The discovery of the Albacora and Marimba fields in 1984 opened the post-salt play, and success continued there throughout the late 1980s to early 2000s with the discovery of fields including Marlim, Albacora Leste, Barracuda, Caratinga, Roncador, Jubarte and Cachalote (Bruhn et al., 2003).

Exploration returned to many of the deep-water post-salt fields in the 2008-2011 period, testing underlying deeper targets

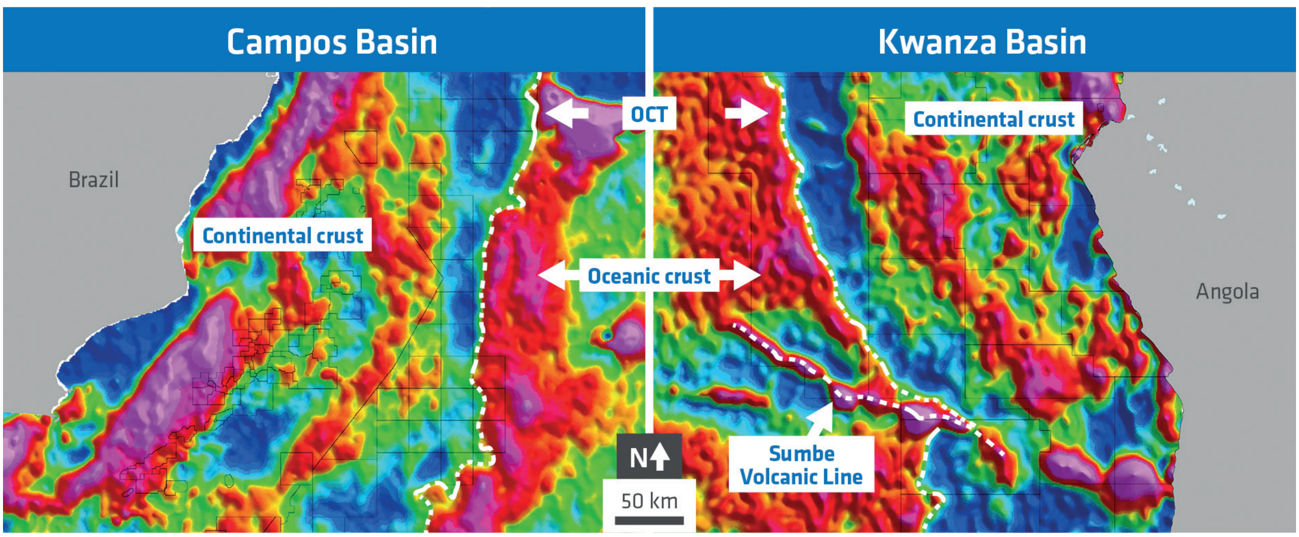

Figure 2 Bouguer anomaly gravity maps (HP 300km filter) displaying key regional features in (a) Campos Basin and (b) Kwanza Basin (data after Sandwell et al 2014, Becker et al 2009). Pink = gravity high, Blue = gravity low. OCT = Ocean Continent Transition.

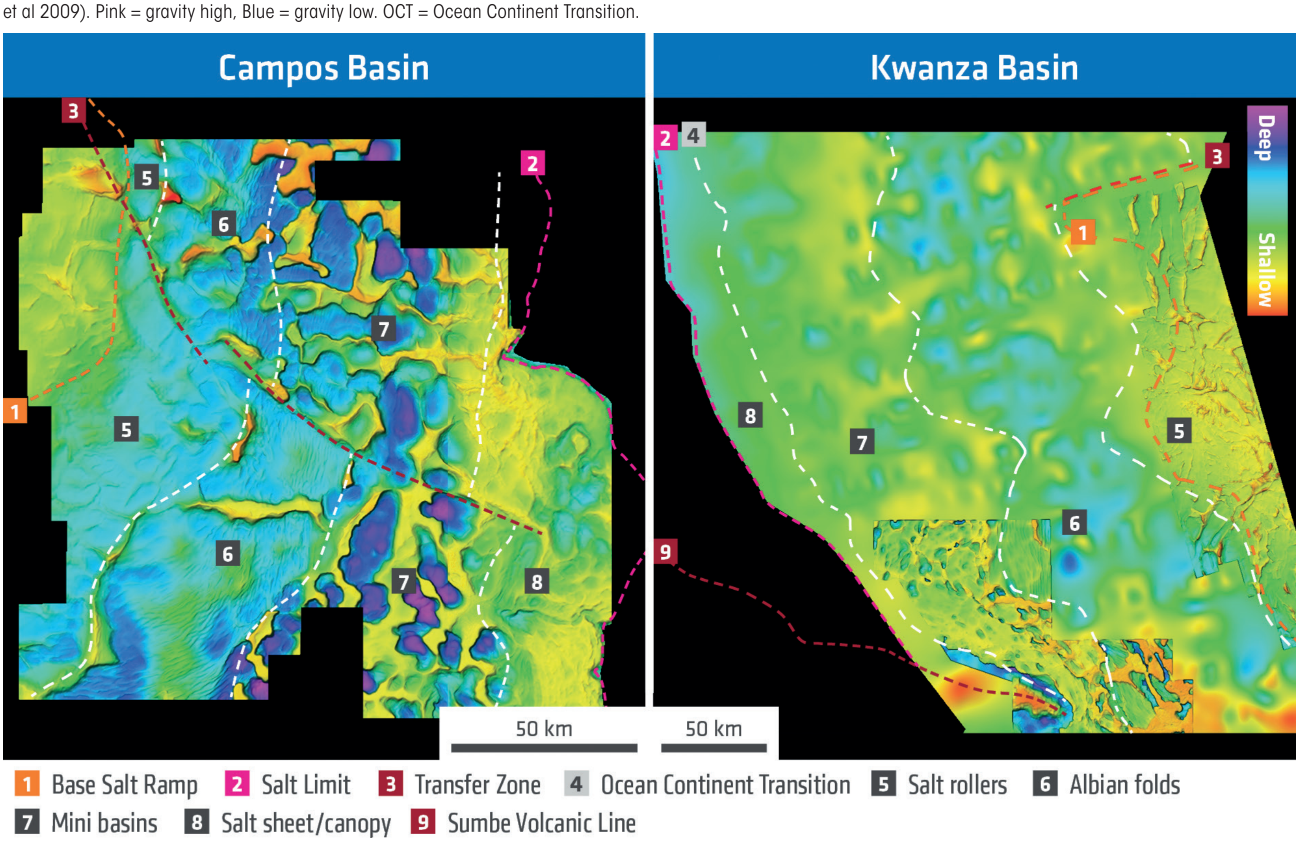

Figure 3 Top salt structural domains in (a) Campos Basin and (b) Kwanza Basin.

in the pre-salt and proving significant volumes at Jubarte, Marlim and Albacora. In parallel with this phase of renewed near-field exploration, the Seat, Gávea and Pão de Açucar pre-salt discoveries were made in the deep-water Campos by Repsol, Sinopec and partners.

Since 2017 a number of licensing rounds have been held in the Campos Basin, with acreage outboard of the Agência Nacional do Petróleo, Gás Natural e Biocombustíveis (ANP) defined pre-salt polygon awarded in each. Exploration drilling has commenced on these blocks testing pre-salt targets, most recently yielding the 1-BRSA-1377-RJS Urissane oil discovery.

Basin architecture and geological domains of the conjugate basins

It has long been identified that South Atlantic conjugate basins have typically shown asymmetric style (Unternehr et al. 2010, Reston 2010). Whilst this asymmetry is evident in cases such as the Santos-Namibe pairing (Moulin et al. 2013), the Kwanza-Campos salt basin conjugates show remarkable symmetry in structural style and scale, in the rift architecture as well as in the post-salt passive margin sequences. Figure 2 demonstrates that a distinct gravity low bounds the interpreted Ocean-Continent Transition (OCT) in both basins around 200 km from the present-day coastlines. Inboard, within the continental crust domain of both basins, the gravity data shows a series of highs (pink) and lows (blue). Here, the signature appears to reflect in part the presence of salt rather than basement structure, especially in the inboard Kwanza Basin. Outboard of the OCT, the gravity data transitions to a more consistent signature beyond the limit of the salt basins.

The Campos-Kwanza conjugate basins can each be divided into four separate domains (salt rollers, Albian folds, mini basins, and salt sheet/canopy) based on salt geometry and architectural style of post-salt sediments (Figure 3).

Starting inboard, the salt rollers domain is characterized by extension of the mid and late Cretaceous sequence on top of a thin layer of Aptian salt (Figure 4). Each basin also has a prominent ramp at the base of the salt (Hudec and Jackson 2002), formed by the uplift and partial erosion of a large, rotated fault block. Sag-phase sediments onlap this structure above and below but are missing along the ramp and itself. In the Campos Basin large-scale extension occurred at the end of the Albian (rafted blocks) followed by a lesser period in the Late Cretaceous (minor growth faults). In the Kwanza Basin the base salt step rotates WSW-ESE in the north, possibly influenced by the Luanda Transfer Zone. Mini basins also show

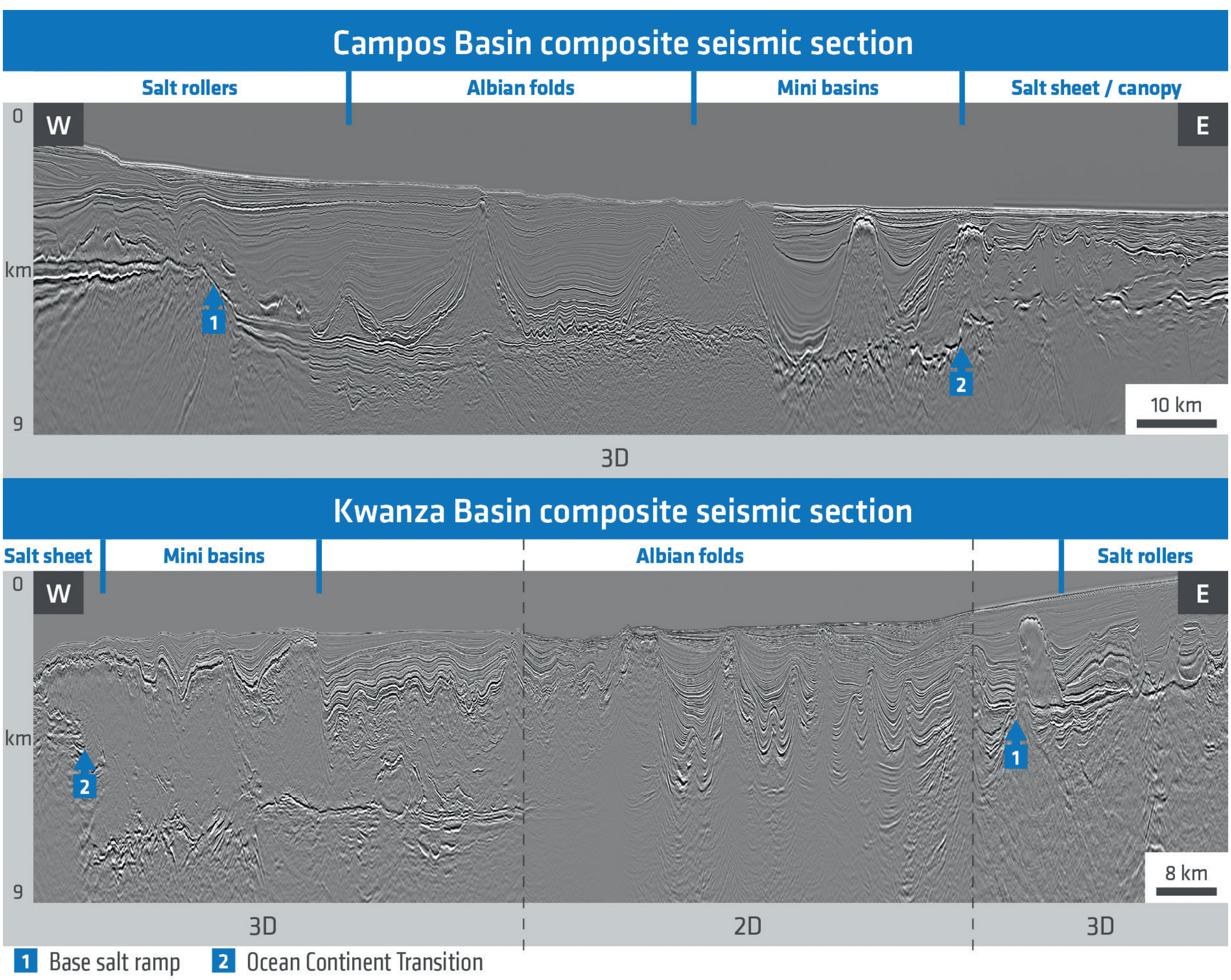

Figure 4 Composite seismic sections (a) Campos Basin 3D and (b) Kwanza Basin 2D/3D.

large-scale extension occurring at the end of the Albian period and persisting throughout the end of the Cretaceous. As salt is displaced further into the basin the post-salt section begins to touchdown or weld to the pre-salt section trapping remnant salt in rollers behind normal faults.

The Albian folds domain is next, characterized by salt cored anticlines formed due to ductile deformation of Albian carbonates. The Campos Basin has high frequency salt cored folds of the early Albian (Quissama Formation) which was deposited as a nearly isopachous unit on top of the Aptian salt then abruptly shortened. The remnant salt has primarily formed salt pillows with an occasional diapir. This domain varies in width in the Kwanza Basin and the folds are higher amplitude, encompassing the entire Albian sequence with deformation continuing into the early Tertiary.

The mini basins domain is characterized by inflation of the layered evaporite system (LES) and subsequent down building of sediment basins of all stages of development. The majority of mini basins in Campos are welded (grounded) at the base of the LES, and as down building occurs convex mega-flaps of Albian carbonates form along the salt flanks. The ends of these carbonate mega-flaps usually display well defined truncations from initial extension during the formation of reactive diapirs. Mini basins within the Kwanza Basin show a distinct change in orientation with those near the Sumbe Volcanic Line becoming elongated and sub-parallel to the feature. These mini basins are less likely to be welded at the base of the LES, though the presence of Albian carbonate mega-flaps with well-defined truncation are still observed.

The final domain, the salt sheet/canopy, is characterized by the inflation and flow of a salt sheet over oceanic crust and subsequent climbing over younger strata. A pre-salt step related to the transition from continental to oceanic crust marks the beginning of this domain. Reflections within the LES show evidence of internal thrusting as the salt flows basinward up and over the fault step. In the Campos Basin there is evidence to suggest salt was deposited onto oceanic crust. This thin veneer of salt inflates as salt is displaced from the inner basin, lifting the Albian cover sequence which forms an outer fold and thrust belt. The salt sheet becomes allochthonous at the beginning of the Late Cretaceous period as it climbs onto younger strata.

Rich oil-prone source rocks and high-performing reservoirs

With a spread of well penetrations in both deepwater and shelfal areas, along with onshore outcrops, numerous play elements have been proven for the Kwanza and Campos basins (Figure 5).

Source rocks

Source rocks are widespread and range in age from the Barremian pre-salt Cuvo/Lagoa Feia formations through to the Turonian Ubatuba Formation in Campos, and Upper Senonian N'Golome Formation in the Kwanza Basin.

The pre-salt section of the shelfal Kwanza area has proven itself to be generative for hydrocarbons with the Denden-1 well flowing pre-salt lacustrine sourced oil to surface. In addition to the hydrocarbons recovered in Denden-1, pre-salt petroleum systems have been proven through the discovery and recovery of

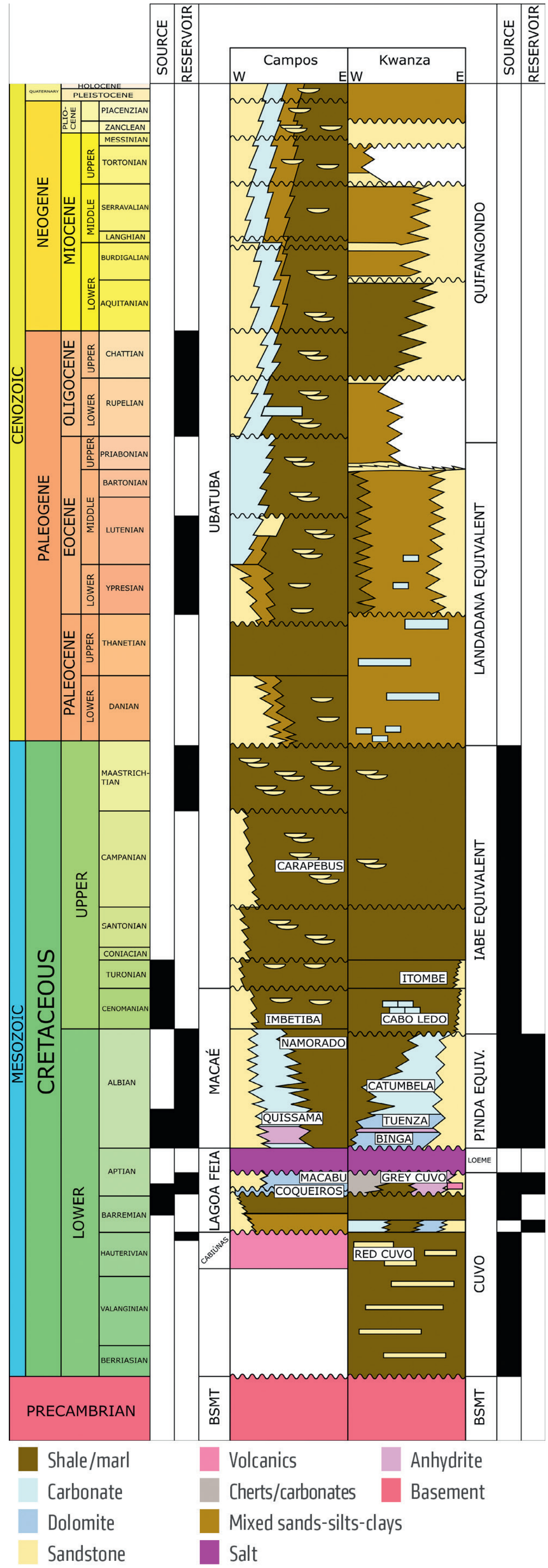

Figure 5 Schematic stratigraphy and play elements comparison of Kwanza and Campos Basins (modified from ANPG, Saller et al. 2016, Winter et al. 2007 and Katz and Mello 2000).

oil in the Quiteta-1 and Ametista-1 wells along with oil shows in Voluta-1, all typed to a pre-salt origin. Properties of the Quiteta and Ametista oils indicate that they are derived from organic matter found in the immediate pre-salt Grey Cuvo unit, deposited in a marginal marine/saline lacustrine environment.

Deep-water well penetrations have also proven the presence of pre-salt source rocks, being dolomitic to calcareous to clay-rich mudstones, comprising amorphous kerogen with Total Organic Carbon (TOC) content up to 10% and high Hydrogen Indices (HI), typical of lacustrine deposition (Saller et al. 2016).

On the conjugate, the highly generative Lagoa Feia Formation (Barremian age) in the Campos Basin comprises rich calcareous black shales ranging from 100 to 300-m thick and typically with TOC of 2-6%, but this has been seen to reach as high as 9% (Guardardo et al 2000; Katz and Mello 1994, Mello et al 1994). Calcium carbonate content reaches 19% (Mello et al 1994) and HI as high as 900 mg HC/g TOC (Guardardo et al 2000), with deposition of this type I kerogen source rock occurring under brackish to saline, lacustrine conditions (Guardardo et al 2000, Katz and Mello 1994, Mohriak et al 1990), comparable to the environment of deposition of the Cuvo Formation in Kwanza. Analysis of geochemical data has proven the Lagoa Feia/Cuvo system to be the dominant source of hydrocarbons in the Campos and Kwanza Basins.

In the post-salt, greater source potential has so far been identified in Kwanza compared to Campos. Onshore, rich but immature Albian through to Maastrichtian marine carbonate prone facies show oil-producing potential with properties ranging to more than 6% TOC and with HI of more than 600 mg HC/g TOC (PGS/ANPG/SonaStream unpubl. results).

In the shelfal area, at least five post-salt units demonstrate oil potential with TOC to 6.3% and HI to around 830. Previously, considerable risk has been assigned to the maturation of these post-salt source rocks (Burwood 1999). However, biomarker studies performed on shows and bitumens indicate proven charge from post-salt kitchens. In the deep-water Kwanza, post-salt marine source rocks have also been identified in the Cenomanian and Turonian-aged Cabo Ledo and Itombe formations.

At present in the post-salt of the Campos Basin, source potential has only been identified in marine shales of the Cenomanian-Turonian Imbetiba/Namorado and Ubatuba formations. The Late Cenomanian-Early Turonian time period experienced anoxic conditions in the Campos Basin, with shales displaying high TOC and source potential of 40 kg HC/ton rock (Guardardo et al 1989).

Reservoirs

Whereas source rocks are more widespread throughout geological time in the Kwanza Basin than in the Campos, the reverse is the case when considering proven reservoirs. In the Campos Basin, oilfields produce from a variety of reservoirs including post-salt turbidites and carbonates, pre-salt microbiolites and coquinas, and pre-salt fractured basalts. Exploration in the Kwanza Basin has so far proven reservoirs in post-salt carbonates and pre-salt carbonates/cherts.

The youngest productive reservoirs of the Campos Basin are Oligocene and Oligo-Miocene turbidite facies. In the Marlim and Albacora fields (2.9 Bbbl and 1.5 Bbbl respectively), these comprise both channel levee and lobe complexes, along with non-channelized lobes (Liro and Dawson 2000). Reservoir properties are of high quality, with porosities ranging from 27 to 32% and permeabilities of 1000 to 2500 md reported (Bruhn 2001).

Turbidite facies are also important reservoirs in the Paleocene-Eocene and Maastrichtian sections of Campos, providing the highly effective reservoirs of the deep-water Barracuda (870 MMbbl) and Roncador (2.9 Bbbl) fields (Rangel et al 2003). Extensive channelized and amalgamated deposits of fine-coarse sandstones with porosities in the 26-30% range and permeabilities of more than 400 md have made these highly attractive targets.

Further production from the Campos Basin in present-day shelfal fields (Bonito, Garoupa and Linguado) is provided by Albian-aged oolitic and oncolytic limestone reservoirs (Macaé Formation) (Liro and Dawson 2000). Porosities in these reservoirs range from 18 to 30% and permeabilities reach to more than 2000 md with an average of 200 md. Pore types include moldic, vuggy and solution-enhanced interparticle (Carozzi and Falkenhein 1985).

In the shelfal post-salt section of the Kwanza Basin, the equivalent Albian Catumbela, Dolomitic Tuenza and Binga formations have been penetrated. Well data show the Catumbela Formation to comprise well-developed oolitic shoals, deposited in a mid-ramp environment. The Dolomitic Tuenza and Binga formations of inner ramp platform setting, demonstrate in places near complete dissolution and dolomitization, with dominantly moldic porosity in addition to minor intercrystalline porosity. Matrix permeability is reported as fair to good. The Tuenza Formation can also display significant fractures, providing high permeability systems, as evidenced by mud losses whilst drilling.

Albian-aged oolitic grainstones and dolomites have also been penetrated in the deep-water Kwanza, with proven good-to-excellent interparticle and intercrystalline porosities, enhanced by high levels of vuggy and moldic porosity, along with open fractures.

In addition to the pre-salt Chela/Grey Cuvo dolomite reservoirs proven in Denden-1, pre-salt sag phase mounds have so far been the dominant primary target in the deep-water Kwanza setting. Proven reservoirs in this Aptian-aged section comprise microbial chert build-ups found on isolated structural highs, and shrubby boundstones that accumulated on platform tops in shallow water, both with primary vuggy porosity (Saller et al. 2016).

Analogous to the pre-salt Barra Velha Formation of the Santos Basin of Brazil (Wright and Barnett 2015, Wright and Tosca 2016, Tosca and Wright 2018, Gomes et al. 2020), a common facies observed in the sag section of both the deep-water Kwanza and Campos comprises stevensite with calcitic spherulites and dolomite (Muniz and Bosence 2015). Similarly to the Santos Basin, the Kwanza units are also interpreted to have undergone varying degrees of diagenetic processes from minor (Saller et al. 2016) to cases of near complete silica replacement, and the associated generation of secondary vuggy pores connected by fractures (Poros et al. 2017). In the Campos Basin, the sag section Macabú Formation shows significant chert content with observed partial-to-full replacement of pre-existing constituents

(Lima et al 2019), along with Macabú Formation microbialite build-ups (Liro and Dawson 2000).

The syn-rift Barremian section of the Kwanza and Campos deep water contains mainly limestones including mollusc packstones and grainstones (coquinas), with some dolomitic mudstones and silicified ooid packstones/grainstones (Saller et al. 2016, Lima et al 2019). In the Kwanza Basin syn-rift penetrations, diagenetic effects are seen to a consistently higher level than in the Aptian sag packages, with replacement by chert being common (Saller et al. 2016, Poros et al. 2017), more akin to the Campos Basin where significant silicification is restricted to the sag phase (Lima et al 2019).

Present and future exploration hotspots

New modern 3D data acquisition and upcoming licensing rounds (Figure 6) show the Kwanza and Campos Basins once again becoming global exploration hotspots. Historical shelfal exploration in the Kwanza Basin focused on the post-salt section, with secondary targets in the pre-salt. The wells drilled in the 1980s were all drilled on 2D seismic data which struggled to clearly image the pre-salt section. Despite this, both pre- and post-salt discoveries were made, and several hydrocarbon system elements were proven. The revisiting of these proven hydrocarbon systems with new modern broadband seismic data has enabled improved pre-salt imaging, basin framework definition and further identification of exploration potential.

The improved imaging of basement structure, syn-rift and sag phase megasequences in conjunction with a review of the well results and analogous systems from the Campos Basin, has enabled the petroleum potential of the Kwanza shelf area to be reassessed. A play concepts diagram is presented in Figure 7, illustrating the key petroleum system elements in their seismic setting. The identification of proven charge from pre- and post-salt source rocks to well locations on the Kwanza shelf has significantly reduced the risk of source rock presence/maturity and hydrocarbon migration in the area. In the deeper section, basement structural highs are evident, acting as likely migration foci for charge from syn-rift and sag phase source kitchens, and the potential for reservoirs in these same megasequences has been observed. In the post-salt, Albian raft structures show potential in dolomitized and oolitic grainstone reservoirs, analogous to proven fields in the Campos Basin, whilst also benefiting from charge from both pre- and post-salt source rocks as already proven. As established in the Campos Basin, Tertiary-aged clastic reservoirs are highly productive and potential targets within these plays in the Kwanza Basin have also been identified.

Exploration success in the Campos Basin is well established and is now moving to further emerging and frontier areas in the deep water, in the search for extensions to the proven plays. To date in the basin, the dominant reservoirs are turbidites found in the post-salt section. Pre-salt reservoirs have primarily been drilled in shallow waters, though the success of deep-water pre-salt carbonate reservoirs in the Santos Basin show the potential for further exploration. In the deep-water Campos, sag and syn-rift reservoir potential is seen in base-salt and fault-related traps, with access to the Lagoa Feia Aptian source kitchens (Figure 8), as proven in the conjugate deep-water Kwanza. The upcoming ANP 17th bid round offers pre-salt opportunities in deeper waters, and although details of the play elements are at present unconfirmed, the recent 1-BRSA-1377-RJS Urissane pre-salt oil discovery made by Petrobras and partners in block C-M-411 (ANP Round 14) provides further encouragement for the play extending into the deep-water Campos Basin.

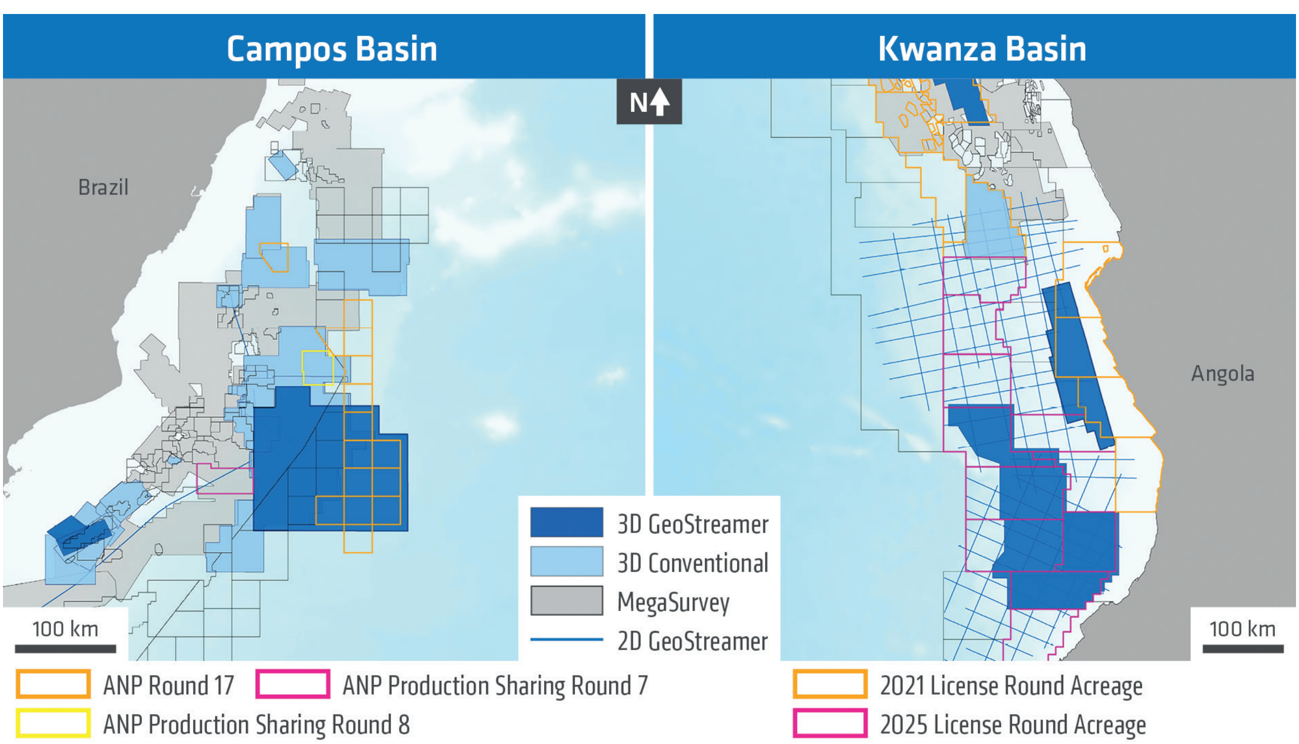

Figure 6 Upcoming licensing round blocks (a) Campos Basin and (b) Kwanza Basin. Fields and blocks from IHS Markit.

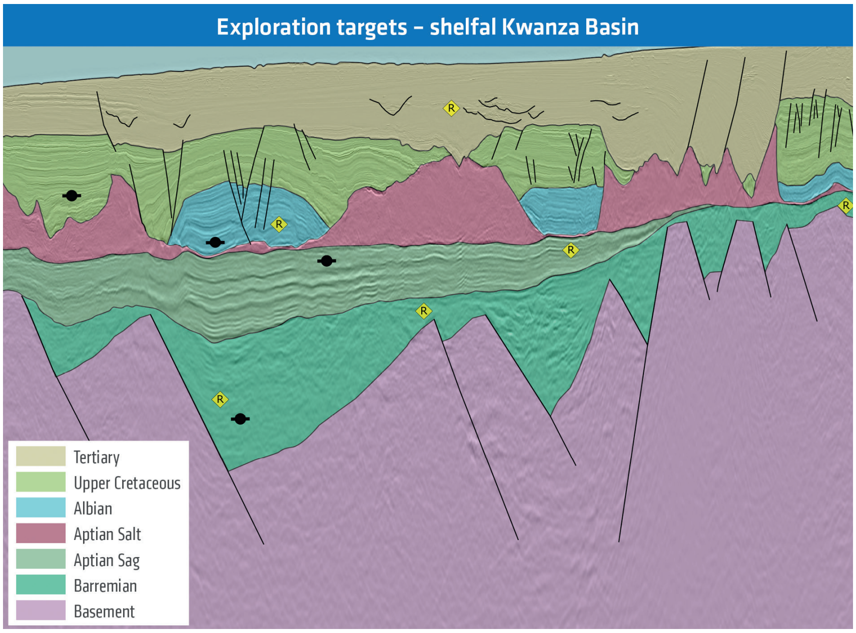

Figure 7 Shelfal Kwanza Basin exploration targets.

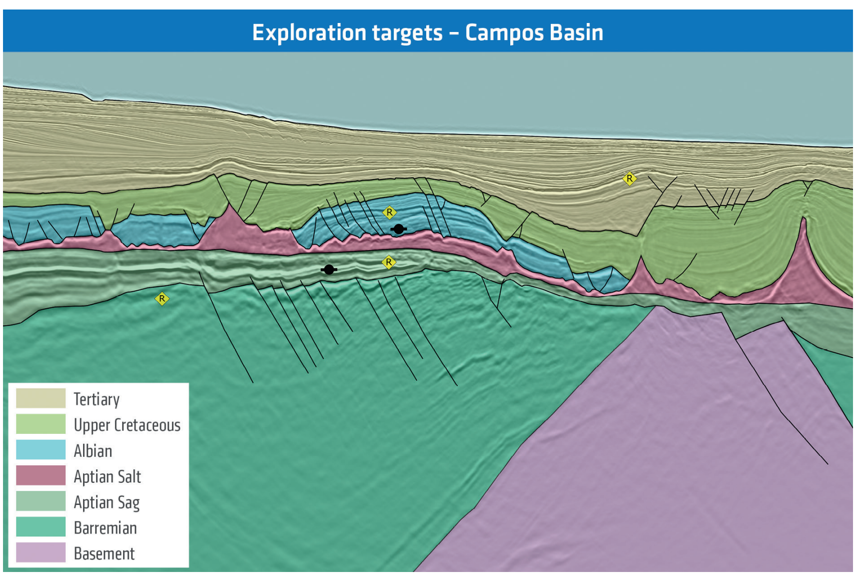

Figure 8 Campos Basin exploration targets.

Conclusions

An overview of the Kwanza and Campos conjugate pair has been presented that shows common characteristics including structural configuration and petroleum system elements. The basins display remarkable symmetry in architecture from the highly prospective rift and sag geometries of the pre-salt, to the salt geometry domains and associated post-salt deformation. They exhibit near mirror images of highly effective proven source and reservoir systems at least through until Cenomanian-Turonian times, when fully separated basin conditions were established. Despite this difference, the impact of the common underlying geology can be applied in a similar manner to reservoir systems in the latest Cretaceous and Tertiary sections.

This part of the prolific South Atlantic hydrocarbon province is undoubtedly an area where analogies and learnings can be translated between the conjugate basins, fuelling opportunities in these mirror twin exploration hotspots.

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