Prospectivity and seismic expressions of pre- and post-salt plays along the conjugate margins of Brazil, Angola and Gabon.

M. Jameson., S. Wells J. Greenhalgh* and R. Borsato*
* Petroleum Geo-Services, Weybridge, UK

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Abstract

The conjugate margins of Brazil and West Africa represent a prolific hydrocarbon province with proven potential in a variety of plays. The application of conjugate margin reconstruction coupled with regional seismic datasets enables the characterization and identification of a range of new structural and stratigraphic plays. This discussion will focus upon the potential of pre-salt and post-salt Albian plays across the Santos, Campos, Kwanza, Congo and South Gabon basins.

Introduction

The hydrocarbon basins of offshore Brazil and West Africa represent a prolific region for hydrocarbon exploration and production (Fig. 1).

The Campos and Santos basins are two major hydrocarbon basins located along Brazil's Atlantic margin. In 1978, the Linguado Field was discovered in the pre-salt (Fig. 2) of the Campos Basin, representing one of the first successful pre-salt fields in Brazil. In 2006, the Tupi Field was discovered in the Santos Basin, the largest pre-salt discovery to date in the Brazilian margin (Fig. 3). The pre-salt had been an unattractive and difficult target, however following the success of Tupi, exploration and production of pre-salt plays has added an estimated 8 – 20 bboe to Brazilian offshore reserves (Chakhmakchev and Rushworth, 2010).

In contrast, pre-salt plays in West African basins of Gabon, Kwanza and Congo have been slow to develop. Despite proven hydrocarbon potential in the Kwanza and Gabon basins, pre-salt plays have not been fully exploited and developed. In 1992, the Falcão well penetrated the pre-salt, exposing ~ 600 metres of organic-rich lacustrine shale and encountering reservoir quality carbonates. In 1996, the Baleia well targeted the pre-salt and revealed an estimated 1 bboe in a dolomitic reservoir (Henry et al., 2010). In 1962, the Gombe Maria Beta well proved the potential of a petroleum system in the North Gabon basin, followed in 1998 by the Etame well which proved charged reservoir quality sands in the pre-salt of the South Gabon basin.

The conjugate margins of West Africa and Brazil share a broadly similar tectonic evolution from Early Cretaceous rifting to late Cretaceous drift. Despite the Brazilian and West African basins being separated by the South Atlantic spreading axis, similar syn-rift architecture and stratigraphic trends exist.

One of the key events affecting the development of syn-rift petroleum systems of the Campos (Fig. 4), Santos, Kwanza (Fig.5), Gabon and Congo basins, was the development of the Walvis Ridge. The Walvis Ridge is a large volcanic ridge that developed due to rifting and hotspot volcanism. The ridge influenced the depositional environment by permitting intermittent marine incursions from the proto-Atlantic into the West African and Brazilian basins.

The application of geophysical data from gravity and magnetics to GeoStreamer seismic has given a greater insight into the tectonic evolution of this area. Review of geophysical, petrophysical and geological evidence has enabled the characterization of syn-rift and pre-rift basins, opening up a range of new E&P opportunities.

Pre-salt petroleum systems

The onset of rifting in the Early Cretaceous (Berriasian) led to the development of a series of asymmetric horsts and grabens filled with fluvial and lacustrine sediments. As active rifting persisted, adjacent rift basins entered a sag phase. This phase was crucial in creating anoxic conditions favorable for source rock generation (Pasley et al., 1998).

Fluvial and lacustrine facies of the syn-rift are represented by the Kissenda, Melania, Dentale & Coniquet (Gabon), Cabiúnas & Lagoa Feia (Brazil) and Toca & Bucomazi (Angola) formations.

Proven potential for syn-rift source rocks exists in the conjugate basins with organic-rich lacustrine shales (~3 – 20 wt % TOC; Type I – II kerogens) recorded in the Lagoa Feia (Campos), Guaratiba (Santos) Kissenda – Melania (Gabon) and Bucomazi (Congo & Kwanza) Formations (Brownfield and Charpentier, 2006) (Fig. 2).

A range of proven and potential reservoirs exist within pre-salt syn-rift of the conjugate basins. In the Campos Basin potential reservoirs exist in the lacustrine coquinas of the Barremian – Aptian Lagoa Feia Formation (porosity (ϕ) 15 – 20 and permeability (K) of ~ 1000 mD). In the Santos Basin the Guarujá (Guaratiba) Formation represents a time-equivalent unit and is the reservoir for the Tupi Field. Additional potential reservoirs include

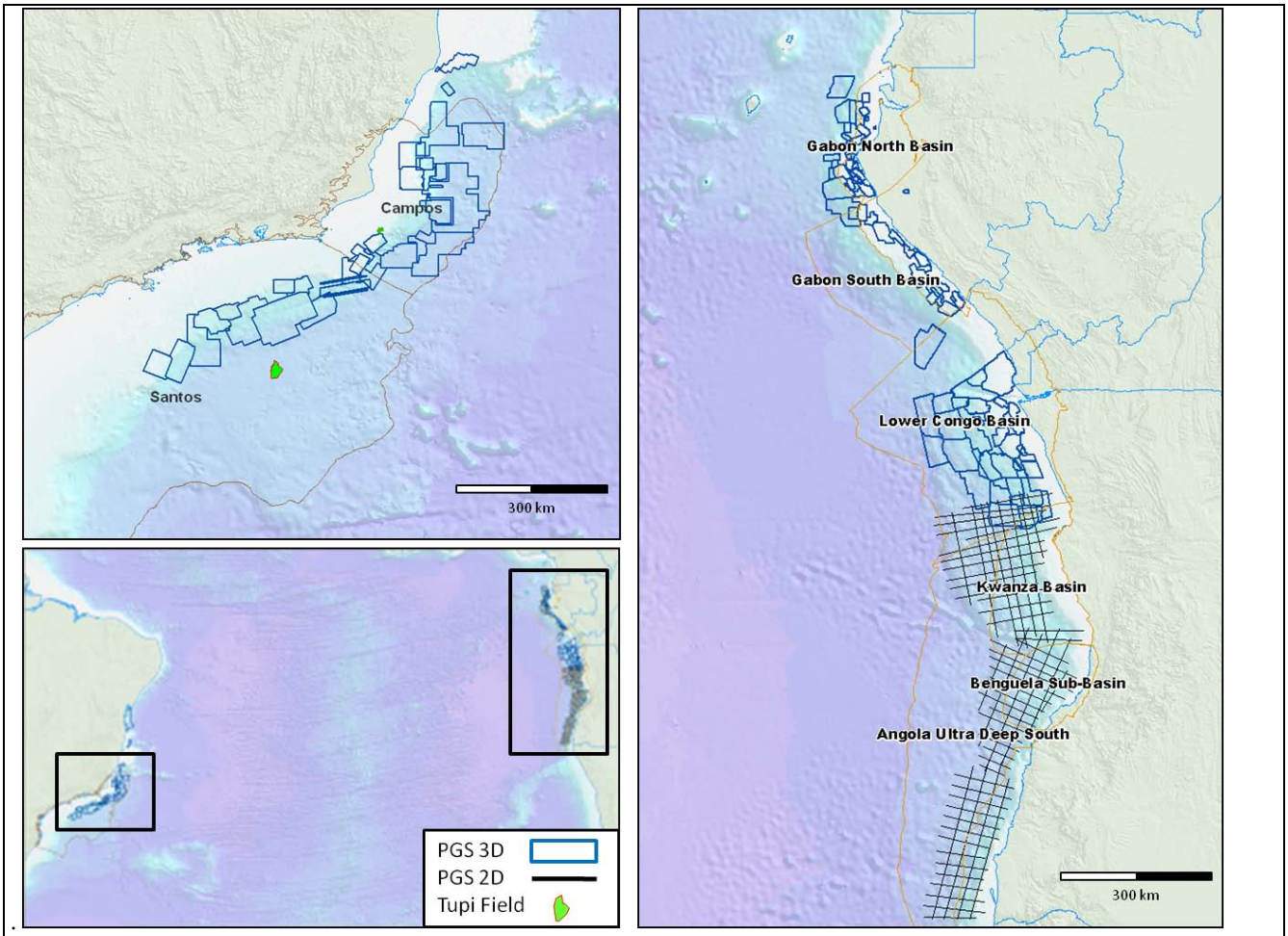

Figure 1: *Location map illustrating the Kwanza, Congo, South & North Gabon, Campos and Santos basins, Tupi Field and Regional dataset coverage*

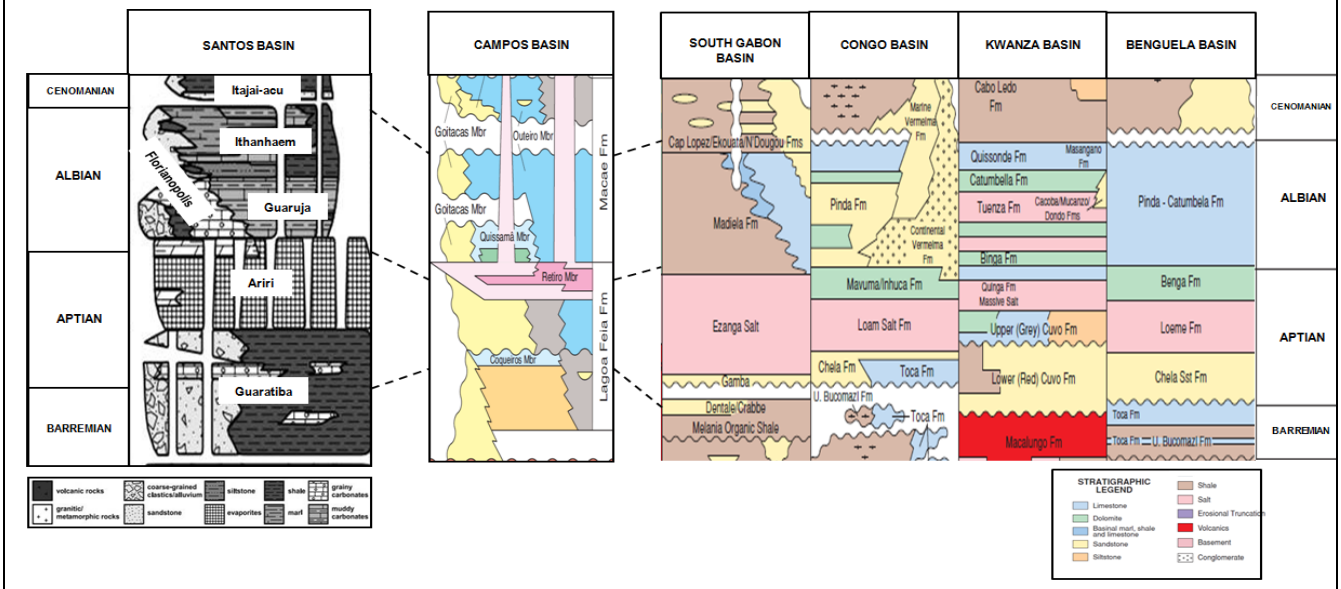

Figure 2. *Barremian, Aptian and Albian stratigraphy of the Santos, Campos, South Gabon, Congo, Kwanza and Benguela Basin (Santos Stratigraphy from: Pereira & Feijo 1994)*

Neocomian basalts of the Cabiúnas Formation (no available ϕ or k data).

On the West African margin, potential analogous reservoirs have been intercepted in the Congo Basin. The Toca Formation represents a time-equivalent, lacustrine carbonate, which is the productive reservoir for the Kambala and Takuka fields. Two units have been identified within the Toca Formation. The lower unit consists of calciturbidites (ϕ 5 - 12 and variable K of ~ 1 - 100 mD). The upper unit represents a carbonate platform system with shallow and deep carbonate facies recorded (ϕ 16 - 20 and K of ~ 600 mD). The best reservoir zones are represented by pelecypod coquinas and carbonate grainstones that have enhanced porosities and permeabilities due to dissolution, diagenesis and fracture (Bassant *et al*., 2005; Harris *et al.,* 2000; Scheevel *et al*., 2004). Additional reservoir potential exists in the syn-rift Neocomian sandstones of the Lucula sandstone.

In Gabon, pre-salt carbonates have not been identified; however pre-salt plays have exploited the Gamba-Dentale sandstone play. The Gamba sands represent a transgressive sequence of fluvial and lacustrine sandstone (ϕ 25 - 30 and K of 100 – 5000 mD) (Teisserenc and Villemin, 1990). The absence of significant pre-salt carbonate development in Gabon may be due to the local structure of rifting, creating isolated basins. Subsequent basin tilting may have introduced a greater volume of clastics, preventing carbonate formation. However, the presence of Aptian carbonates cannot be discounted around rift highs isolated from clastic input.

The pre-salt Petroleum system is sealed by Aptian salt, with extensive salt deposition recorded in offshore Gabon (Ezanga ~500m), Angola (Loeme ~800m) and Brazil (Alagoas & Guaratiba ~2000m).

Post-salt petroleum systems

In the Albian, permanent marine incursion of the proto-Atlantic led to widespread development of shallow marine carbonates and siliciclastics above the Aptian salt. In the Campos and Santos basins, three third-order sequences have been identified (Zarpelon, 2008), directly affecting facies and reservoir quality of the Macaé carbonates. These third order sequences can be correlated to the Pinda carbonates of Angola (Eichenseer *et al*., 1999) and Madiela carbonates of Gabon (Brownfield and Charpentier, 2006). The three sequences comprise, 1) a post-salt shallow marine carbonate platform that has been pervasively dolomitized, 2) an intermediate carbonate sequence with better intergranular porosity and localised dolomitisation and 3) an upper sequence with shallow facies restricted to the shelf and structural highs (Spadini, 2008).

The upper sequence has been the main target in the Campos and Santos basins with ϕ of 15 - 30 %, variable K (~100's mD) and production rates of up to 43,600 bopd (Coward *et al.,* 1999). Similar sequences in the Kwanza and Gabon basins revealϕ 5 - 30 %, K of 0.5 - 199 mD and production rates of ~50,000 bopd. In all the basins, shoaling upward trends are the most productive facies, associated with grainstone intervals. The influence of salt-driven raft tectonics within all the basins has affected the distribution of upper carbonate sequences and localized dolomitisation.

The Macaé, Guarujá , Pinda and Madiela formations also include siliciclastic components. In the Campos Basin, the Namorado Sandstone Member of the Macaé Formation (Ciro *et al*., 1998) represents a key play (ϕ 17 - 30 and K of 0.1 – 1600 mD). Calcite cements sourced from underlying carbonates represent a key parameter controlling reservoir quality. In the Santos Basin, siliciclastics have not been recorded in the Guarujá Formation; however there is good potential for reworked calciturbidites and conglomeratic-carbonate debris.

In the Kwanza and Congo basins, the Pinda Formation siliciclastic reservoirs represent a nearshore environment, with basinward potential for deeper marine turbidite facies (ϕ 10 - 35 and K of ~150 mD) (Dale *et al*., 1992). The thickest clastic reservoirs have been recorded on the eastern part of the shelf where coarser, nearshore clastics accumulated (Spaw and Koehler, 1981)

Lower Cretaceous Prospectivity of Offshore Brazil, Angola and Gabon

Pre-salt plays have great potential in the Brazil and West African margin, however the greatest challenges are imaging beneath what can be extensive ~2000 m salt. The advantage of GeoStreamer data is clear in the pre-salt, with improved imaging through dual-sensor acquisition and pre-salt oriented processing. Regional seismic datasets also contribute to defining pre-salt plays by enabling the generation of regional structure depth and isopach maps. The end result is a regional expression of prospectivity

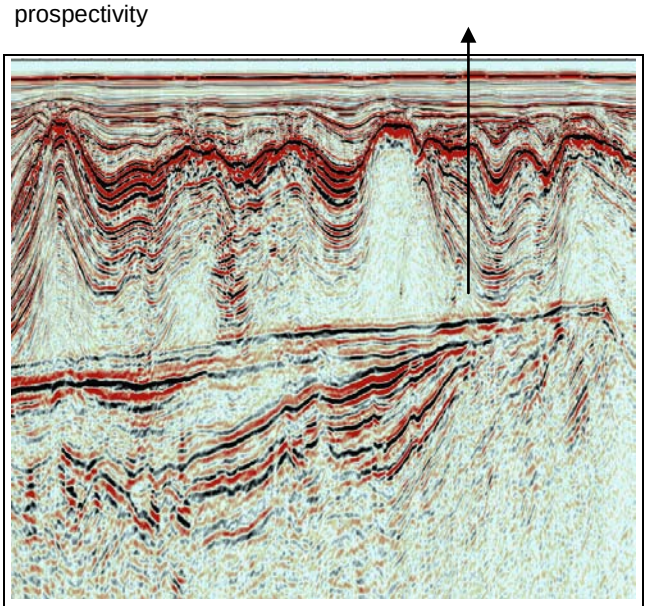

Figure 3. *An example of GeoStreamer data across with the Tupi discover well labeled, the section reveals extensive syn-rift and sag sequences within the Santos Basin.*

Conclusions

The conjugate margins of Brazil and West Africa remain an attractive area for exploration and production. Regional datasets enable the interpretation of conjugate margins and the characterization and identification of analogue plays and prospects. World class discoveries such as the Tupi Field have highlighted the importance of pre-salt plays across the Brazilian and West African basins. The pre-salt petroleum system has been proven in Gabon and Angola, with many explorers and operators beginning to target the pre-salt.

The key to successful exploration targeted at the pre-salt level is the application of advanced technologies such as GeoStreamer, pre-salt oriented processing techniques and regional understanding of the structural framework.

In contrast, post-salt, Albian plays offer an alternative exploration target in the conjugate basins. Historically post-salt plays have been a major target following on from the success of the Pinda Formation, however the potential for alternative reservoirs such as the Madiela carbonates and clastics offer new exploration opportunities and prospects.

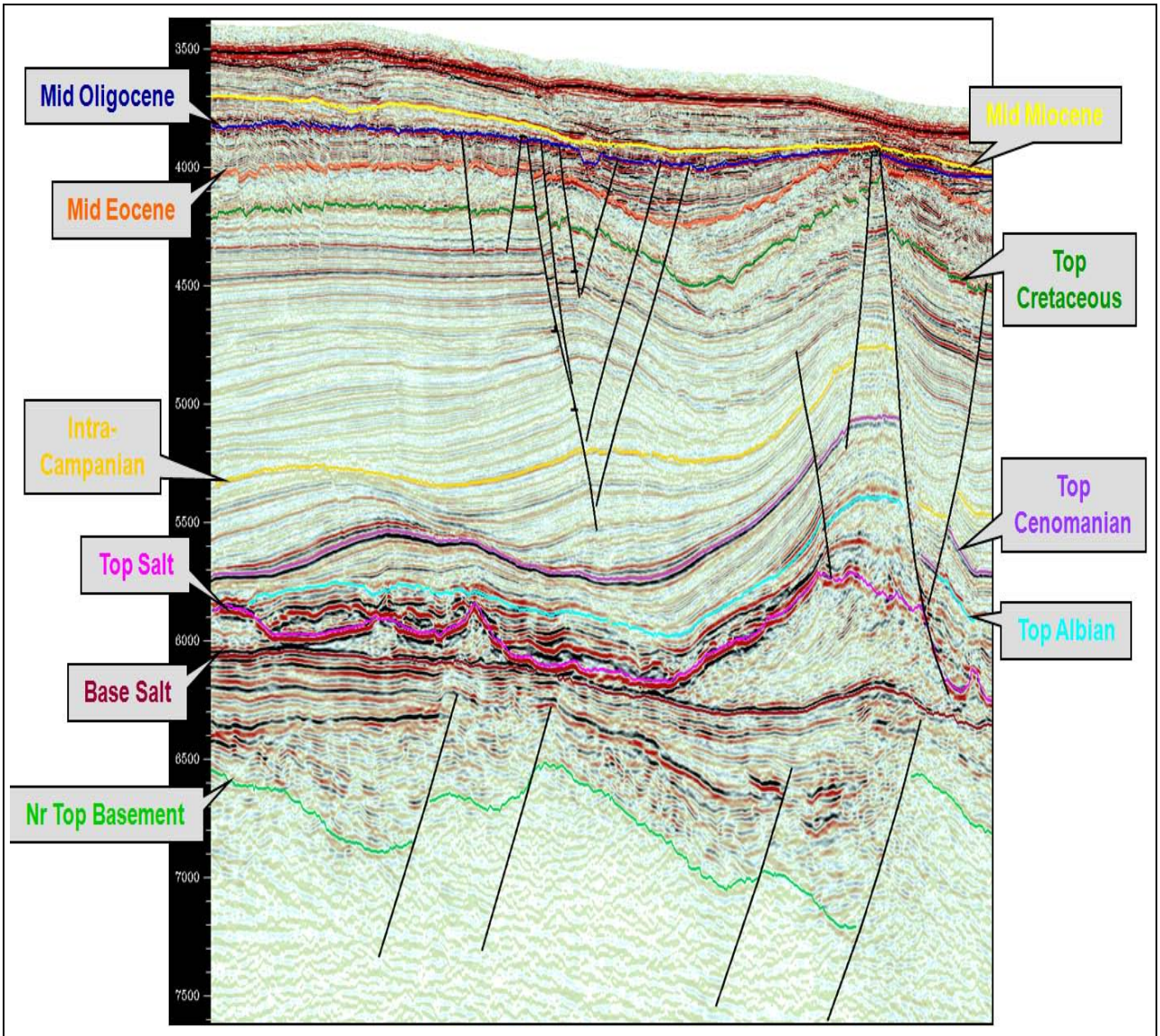

Figure 4. *An example of 3D seismic line across the Campos basin, Brazil. The excellent sub-salt imaging reveals a number of high amplitude events and clearly reveals the structure of the syn and post-rift sequences. Faults are marked in black and various horizons are represented in a variety of colours*

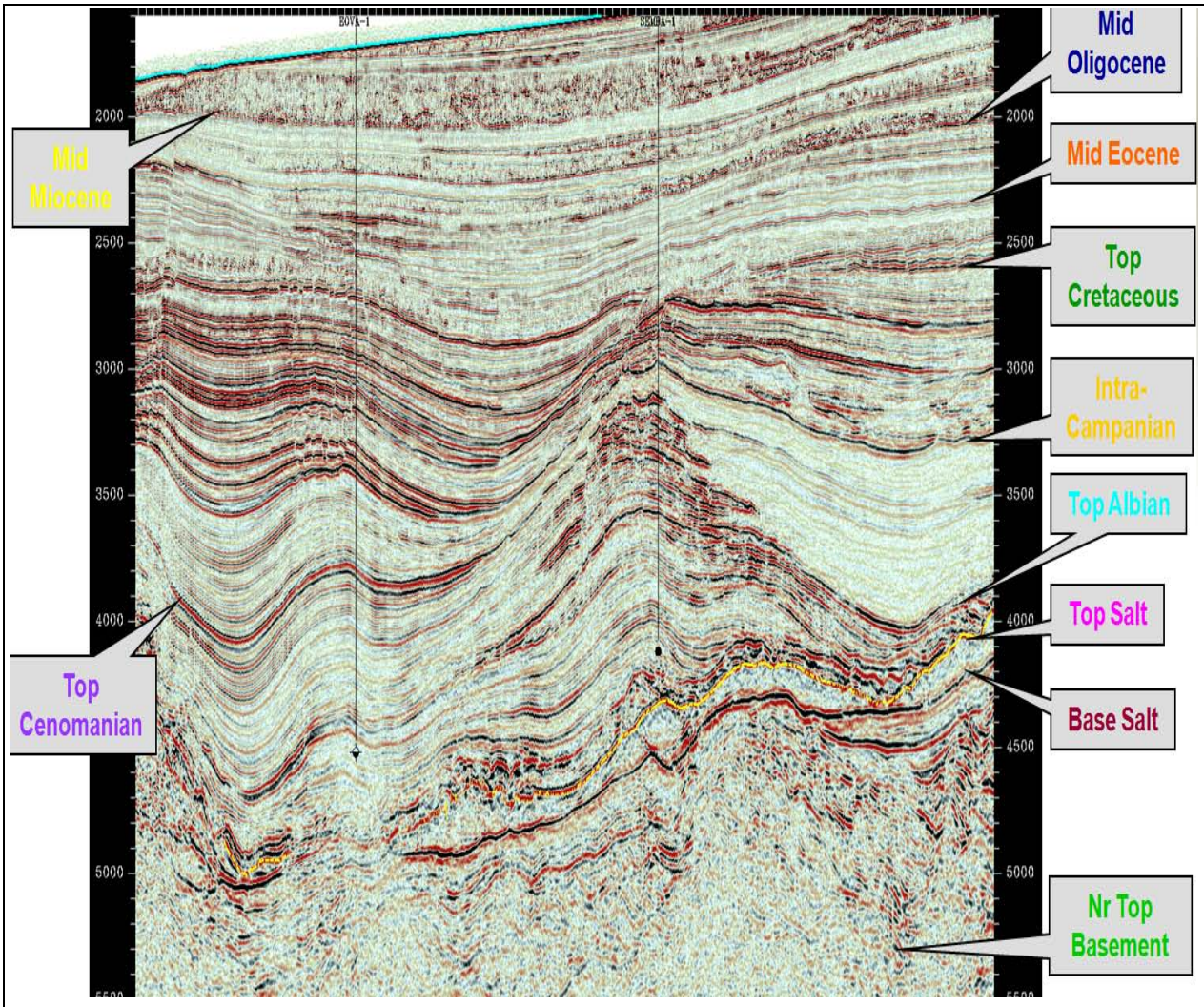

Figure 5: *An example of a 3D seismic line across the Kwanza basin, Angola. Note the syn-rift structure and faulted reflectors at depth, beneath the Loeme salts. The overlying Pinda formation has been affected by raft tectonics, leading to the development of relatively shallow faults. The potential of thick syn-rift grabens gives good potential for source rock generation, with a range of high amplitude features and anomalies visible on the seismic line.*

References

Appi, C.J., L.A.F. Trinadade., F.T.T. Goncalves and R.P. Bedregal. 1998. Albacora Oil Field: an example of the Lagoa Feia-Carapebus (!) Petroleum System, Camops Basin, Brazil, AAPG Rio abtract.

Bassant, P., P.S. Brown., R. Preece., M. Fernandes and A.J. Lomando. 2005. Reservoir Development and Distribution of a Dolomitized Lacustrine Carbonate: The Toca Formation, Offshore Cabinda, Angola. AAPG Calgary.

Brownfield, M.E., and R.R. Charpentier, 2006, Geology and total petroleum systems of the West-Central Coastal Province (7203), West Africa: U.S. Geological Survey Bulletin 2207-B, 52 p.

Chakhmakchev, A. and P. Rushworth. 2010. Global overview of recent exploration investment in deepwater – new discoveries, plays and exploration potential. Search and Discovery Article #40656. AAPG Calgary Convention, 2010, pp 1 – 23.

Dale, C.T., J.R. Lopes and S. Abilio. 1992. Takula Oil Field and the Greater Takula Area, Cabina, Angola: Chapter 13 in C.T. Dale., J.R. Lopes and S. Abilion, eds. Volume M 54: Giant Oil and Gas Fields of the Decade 1978 – 1988, pp 197 – 215.

Eichenseer, H.T, F.R. Walgenwitz and P.J. Biondi. 1999. Stratigraphic control on facies and diagenesis of dolomitized oolitic siliciclastic ramp sequences (Pinda Group, Albian, Offshore Angola). AAPG Bulletin, vol. 83, pp 1729 - 1758,

Elias, V.L.G. and D.E. Steagall. 1996. The impact of the values of cementation factor and saturation exponent in the calculation of water saturation for the Macaé Formation, Campos Basin. SCA Conference Paper, No. 9611, pp 1 - 9.

Harris, N.B. 2000. Toca Carbonate, Congo Basin: response to an evolving rift lake in: M.R. Mello and B.J. Katz, eds. Petroleum systems of South Atlantic margins; AAPG Memoir 73, p 341 – 360.

Henry, S.G., S. Lumen., K. Naresh., S. Adriano. And V. Sujata. 2010. Tupi's Conjugate: New Pre-saslt Plays in the Angolan offshore. AAPG Search and Discovery Article #90104.

Pasley, M.A., E.N. Wilson., V.S. Abreu., M.G.O. Brandao and A.S. Telles. 1998. Lower Cretaceous Stratigraphy and Source Rock Distribution in Pre-salt Basins of the South Atlantic: Comparison and Angola and Southern Brazil.

Pereira, M.J. and F.J. Feijo. 1994. Bacia de Santos, Boletim Geocienias Petrobras, v. 8 (1), p 219 - 234

Scheevel, J., F. Domingos., J. Nogueira., M. Fernandes., L. Skander., L. Costa., A. Lomando and V. Kienast. 2004. Analysis and Modeling of Fracture-enhanced Production in Lacustrine Carbonate Reservoirs at Kambala Field, Cabinda Province, Angola, West Africa. Hedberg conference

Spadini, A. 2008. Carbonate reservoirs in Brazilian sedimentary basins. 19th World Petroleum Congress, Spain: Forum 6, Carbonate Reservoirs, pp 1 - 16.

Teisserenc, P., and Villemin, J., 1990, Sedimentary basin of Gabon—Geology and oil systems, *in* Edwards, J.D., and Santogrossi, P.A., eds., Divergent/passive margin basins: American Association of Petroleum Geologists Memoir 48, p. 117–199.

Zarpelon, P.R., A.R. Spadini and A. Biassussi. 2008. Albian carbonates from southeastern Brazil: stratigraphy and retreat of a platform in response to halokinesis (abs), in AAPG International Conference Exhibition, Cape Town, South Africa.