In Search of Deepwater Stratigraphic Traps Formed by Sand Rich Distributary Channels and Lobe Complexes in Miocene Sequences Offshore Niger Delta

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ABSTRACT

Deepwater stratigraphic trap plays have been the focus of exploration activities in the Circum-Atlantic passive margin basins following play opening discoveries in Tano and Sergipe basins in Ghana and Brazil respectively. These discoveries are found in slope environments with run-up-dip gradients that lack any obvious structural features. Prospects associated with this play are developed through local avulsion cycles that progress through sand deposition, avulsion node switching and creation of up-dip seal. Recent updates in process stratigraphy indicates that majority of deep-water stratigraphic trap plays are dominated by distributive systems formed through unique flow hydraulics that are triggered by local gradient change and subsequent deposition and avulsion. Recognition criteria for these deposits include reservoir facies, bedforms and geometries associated with such sediment gravity flow regimes. Exploration targets in Miocene deep-water sediments in Niger Delta have largely been focused on the channelized fairways of turbidite systems supported by shale tectonics resulting in structural and combination traps. Observations of deep-water deposits associated with varying local accommodation and gradient changes in the Niger Delta have shown that favourable geologic conditions for the development of stratigraphic traps may exist, and may open up new exploration horizons. This hypothesis is also supported by observations on high-resolution seismic data in Quaternary systems, outcrop studies and physical experiments. We propose that exploration for deep-water stratigraphic traps in Niger Delta can yield positive results through a genetic understanding of the predictable auto-cyclic processes necessary for the development of sand rich distributive fans that have potential for stratigraphic trap formation. From a strictly geologic perspective, deep water stratigraphic traps share similar play elements risk as other type except for trap seal (specifically dip seal); however low industry economic success rate results from a lack of understanding of the genetic parameters controlling deep-water stratigraphic trap formation. Successful deep-water stratigraphic traps have driven country entry opportunities and creation of new ventures.

Keywords: Stratigraphic traps, Niger Delta, Deepwater, Gradient, Turbidites, Process stratigraphy.

INTRODUCTION

Submarine distributary channels and lobe complexes have been recognized as important clastics reservoirs for hydrocarbon deposits in the deepwater slope environment (Posamentier and Kolla, 2003; Reading and Richards, 1994). The individual architectural elements that make up these systems are usually arranged in complex but predictable stacking pattern, Hamilton *et al.,* (2017). Knowledge of the autogenic depositional evolution of deepwater distributary reservoirs can inform derisking of reservoir, trap and seal play elements in exploration and development. Following the deepwater stratigraphic trap play opening discoveries in the Circum-Atlantic Tano (Ghana) and Sergipe (Brazil) basins (figure 1), there has been renewed exploration interests deepwater

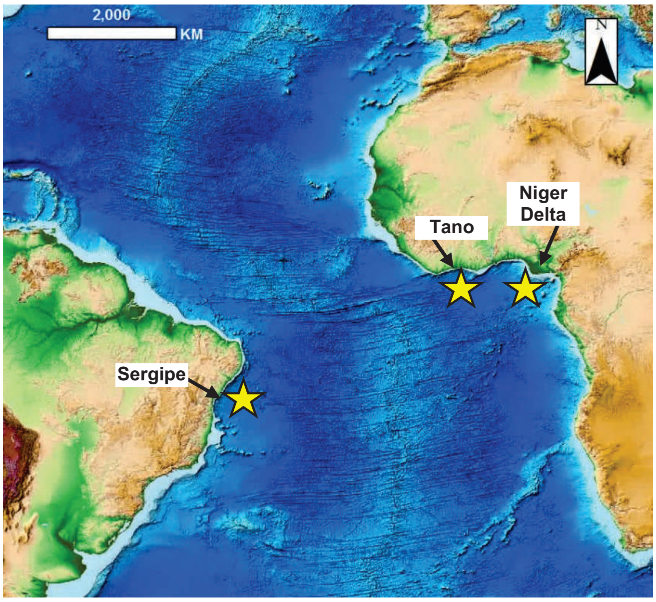

Figure 1: The Circum-Atlantic passive margin showing the Tano, Sergipe and Niger Delta basins.

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stratigraphic trap play exploration. In the Niger Delta, however, exploration companies have not shown much desire to drill for deepwater stratigraphic traps. Exploration drilling in the deepwater sub-basins / domains of the Niger Delta have focused mainly on other trap type plays – combination, faulted and 4-way closure traps. The reason for this exploration trend can be two-fold. First, it appears that the Niger Delta tectonostratigraphic framework is dominated by structure / combination traps. Secondly, exploration companies may view deepwater stratigraphic traps as being more risky in terms of geologic success rate. While the former is mostly true based on exploration observations, data from upstream industry vendor analysts demonstrate that the latter is largely a perception of risk and not backed by global exploration data.

Deepwater stratigraphic traps are not inherently more risky than structural and / or combination traps with a global technical success base rate of about 49% and 54% respectively (Westwood Energy Report, 2017).

We define deepwater stratigraphic traps as slope deposits where the updip reservoir / seal pair does not benefit from structural support for the hydrocarbon accumulation to exist. In other words, if we can demonstrate that we have a subsurface container to fit a minimum threshold volume for geologic success, then the trap can be classified stratigraphic when the stratigraphic components of the trapping mechanism are the most important for defining the accumulation (figure 2).

Deepwater stratigraphic trap discoveries in the Circum-Atlantic passive margin basins have been mostly associated with distributive systems deposited in the upper and mid slope environments. These lobe dominated distributary sandy reservoirs are usually deposited during the early sediment fill of the basin post rifting. Paleo-depositional slopes and paleo-water depths provides the right terrain for sediments gravity flows driven by the characteristic flow hydraulics that enables the deposition of small radius sandy fans with potential for updip avulsion in the Cretaceous slope environments. This autocyclic process follows a self-organizing mechanism in deepwater process stratigraphy and thus can be predictable.

This paper presents how knowledge of the hydraulic characteristics of deepwater sediment gravity flows deposits can be used for interpretation and prediction of stratigraphic trap potential in the Niger Delta basin.

Niger Delta Geologic Setting and Exploration

The Niger Delta Basin is a mature hydrocarbon province with approximately >800 fields developed and multiple play systems identified and delineated based on age (Tertiary Paleogene vs Neogene), trap type (structural, combination, stratigraphic) and environment of deposition (shallow water vs deepwater slope deposits). The Basin is located on the central part of the Gulf of Guinea on the West Coast of Africa (figure 3) and comprises of regressive sequence of clastics sedimentation from Paleocene / Eocene to Pleistocene covering both onshore and offshore with approximate areal extent of 75,000 sq. km (Doust and Omatsola, 1989, Evamy *et al.,* 1984) that prograded over passive continental margin sequence of mainly Cretaceous sediments. Three diachronous lithostratigraphic formations are recognized as products of the continuous delta progradation and they include the Akata Formation (over-pressured marine muds), Agbada Formation (interbedded sands and mudstones) and Benin Formation (continental sands) respectively (Doust and Omatsola, 1989).

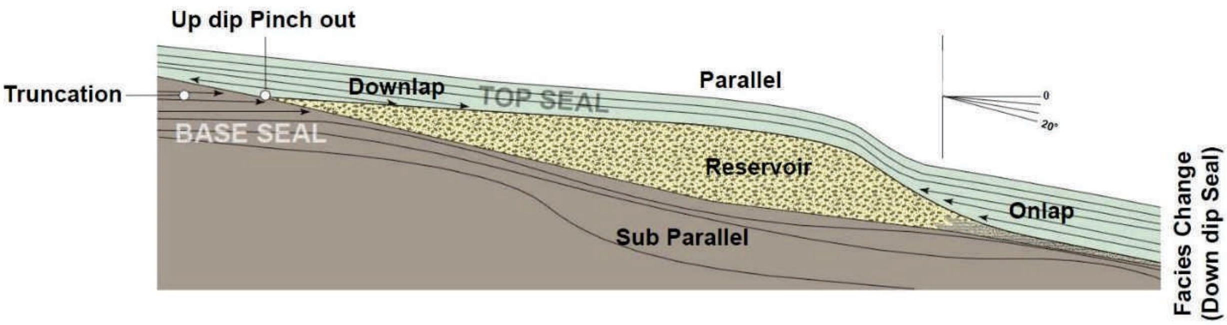

Figure 2: Sketch of deepwater stratigraphic trap showing reservoir and seal pair geometric relation.

Exploration in the Niger Delta Basin commenced in the 1950s while deepwater slope reservoir deposits and plays became prominent in the 1990s to early 2000s.

Deepwater slope reservoirs have been identified in the basin within Miocene to Pliocene intervals and they constitute important play elements in the basin. The most common trapping configuration of deepwater reservoirs in the basin are related to faults and anticlinal structures produced by mudstone tectonism forming mostly structural and combination traps respectively.

Deepwater exploration in the Niger Delta has been focused mostly on the structural and combination trap plays. Exploration for deepwater stratigraphic traps have not attracted much attention in the basin due to their perceived risk profile or lack of well-established knowledge base defining the geologic framework for the development of these trap types in the Niger Delta.

As the opportunity space in structural / combination trap exploration plays continue to reduce and easy targets become scarcer, there is the urgent need to grow our technical knowledge base towards understanding the geologic controlling variables (factors) that support development of deepwater stratigraphic traps.

Most of the ideas presented here were developed with examples from offshore passive margins, but can also be applied in the exploration for deepwater stratigraphic traps in the Niger Delta.

We present two examples of potential deepwater stratigraphic trap in the Niger Delta offshore to demonstrate key geologic parameters or variable that may be necessary for the development of deep-water stratigraphic traps.

Circum-Atlantic Passive Margin Stratigraphic Trap Exploration

Activity related to deepwater stratigraphic trap exploration in the Circum-Atlantic passive margin increased with the play opening discoveries of the Jubilee Field in the Tano Basin (Ghana) in 2007 and the Barra Field in the Sergipe Basin (Brazil) in 2010. These significant discoveries (figure 4) opened up the potential for new deepwater stratigraphic trap plays in the Cretaceous sequences on both margins of the Atlantic passive margin basins.

Subsequently exploration companies drilled >200 wells

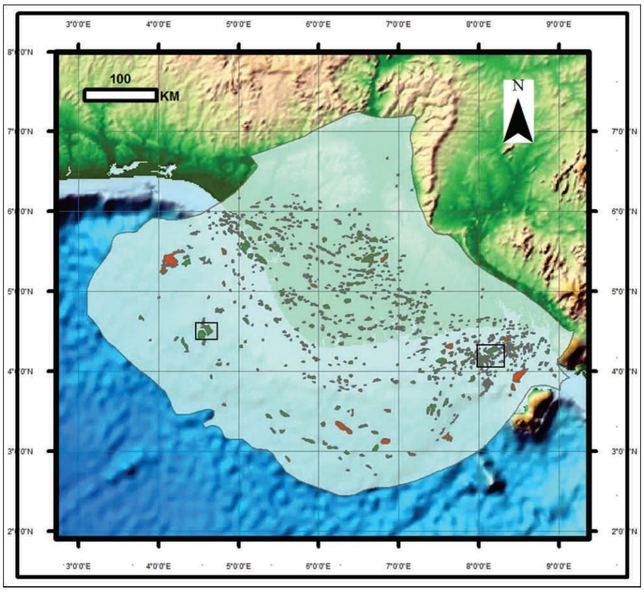

Figure 3: Outline of the Niger Delta Basin showing the basin showing discovered field polygons.

targeting similar deepwater stratigraphic trap plays across the South and Central Atlantic basins with mixed results owing in part to a lack of process stratigraphic understanding of deepwater distributary reservoir deposits . Majority of the targeted leads where amplitude anomalies that are characterized as Jubilee “look alike”. These exploration operations were not backed by a process understanding of deepwater sediment gravity flow deposition that is tied to a sub-regional tectonostratigraphic knowledge of the genetic basin evolution.

A Westwood Energy Report in 2017 puts the average technical success rate (TSR) for deepwater stratigraphic traps drilled globally from 2008 to 2017 at 49%. Average commercial success rate (CSR) for the same time period

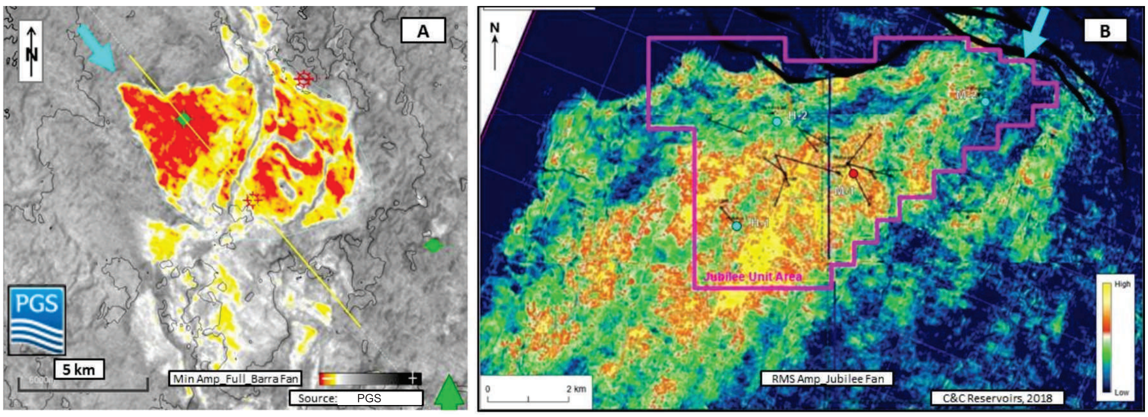

Figure 4: Seismic amplitude extractions showing (A) the Barra Field, Offshore Brazil South America and (B) the Jubilee Field, Offshore Ghana West Africa. The dominant reservoir environment of deposition in these two fields are mostly slope distributary lobe complex and trapping configuration is dominantly stratigraphic. Arrow shows sediment feeder direction.

was 27%. Both the TSR and CSR were approximately 5 percentage points lower than the average success rate for all the other trap types (combination, 4-way dip, Faulted). Based on this analysis, it is plausible to state that deepwater stratigraphic traps are not inherently more risky compared to other trap types but requires a process stratigraphic knowledge of the development of distributive / channelized slope deposits and genetic basin evolution.

Process Stratigraphy Development of Sand Rich Deepwater Distributary Reservoirs

All deepwater reservoirs are products of unique hydraulics associated with the sediment gravity flow responsible for the deposit. Thus, physics based relations can be used to characterize deepwater deposits through analysis of the fluid mechanics, sediment transport mechanism and unique bedform associated with the deposit. An adequately delineated dimensionless constant using layer-averaged process known as the Densimetric Froude Number (Frd) have been used to describe the hydraulic state of deepwater distributary lobe deposits (Hoyal and Sheets 2009).

$$Fr_d = \frac{V}{\sqrt{g \frac{\Delta\rho}{\rho} h}}$$

Where V is the layer-averaged turbidity current velocity, g is the layer-averaged gravitational acceleration, $\Delta\rho/\rho$ is the vertical density stratification of the flow and h is the height or flow thickness.

The hydraulic Froude number exerts an important control in the way in which distributary channels interact with their terminal deposits (Hamilton *et al.,* 2017). Flows with Densimetric Froude numbers > 1 are described as supercritical flows and will lead to dominantly lobe (distributive) deposits while flows with Densimetric Froude numbers < 1 are described as subcritical flows.

Supercritical distributary deposits are common in steep paleo-depositional gradients with higher flow velocities increasing the potential for up-dip sediment bypass (net non-deposition). Supercritical sediment gravity flows are typically bedload dominated and result in the deposition of short-radius sand rich lobe complexes especially when deposited early during filling up of local deepwater basin accommodation and close to sediment input source. This has been validated by direct monitoring of modern sediment gravity flows deposits using high resolution bathymetric (figure 5) data (D. Vendettuoli *et al.,* 2019).

Hoyal and Sheets 2009 had earlier demonstrated this observation at experimental scale using tank experiments and further defined the autocyclic process of distributary fan development through avulsion cycle mechanism. The avulsion cycle process is internal (autogenic) to the deepwater sediment gravity flow domain and comprises three self-organizing stages that are predictable based on observed bedforms and architectural element geometries associated with the distributary channels and lobe deposit. Autogenic avulsion is common in bedload dominated supercritical sediment gravity flows on steep paleo-depositional slopes and consists of the following cycles: (1) distributary-channel formation and basinward extension (2) lobe element (mouth-bar) deposition and aggradation (3) back-stepping of channel-lobe transition and up-dip avulsion (figure 6).

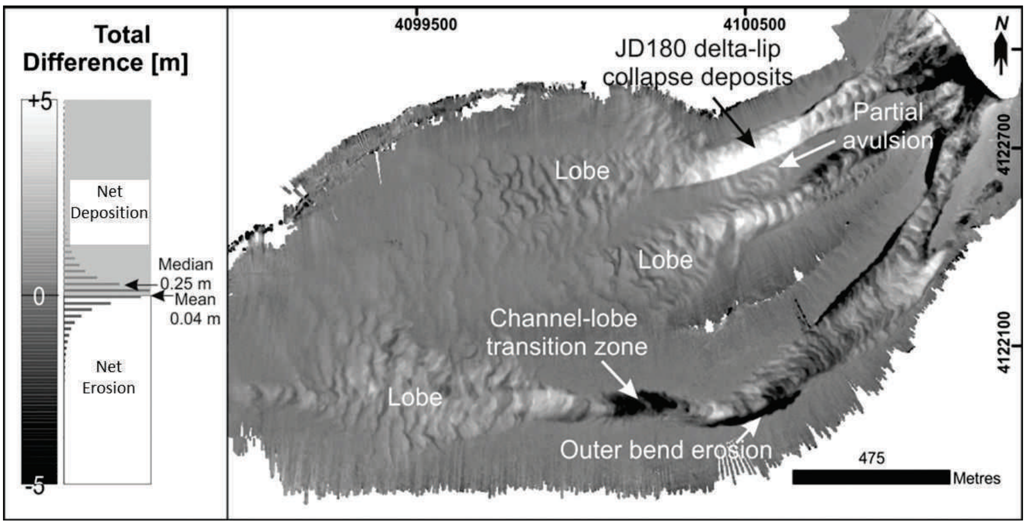

Figure 5: High resolution bathymetric data of modern sea-floor showing net bypass and net deposition associated with a distributary supercritical turbidity current deposit (from D. Vendettuoli et al. 2019). The channel-lobe transition zone characterized by net erosion (bypass) increases the potential for dip-seal leading to stratigraphic trap development.

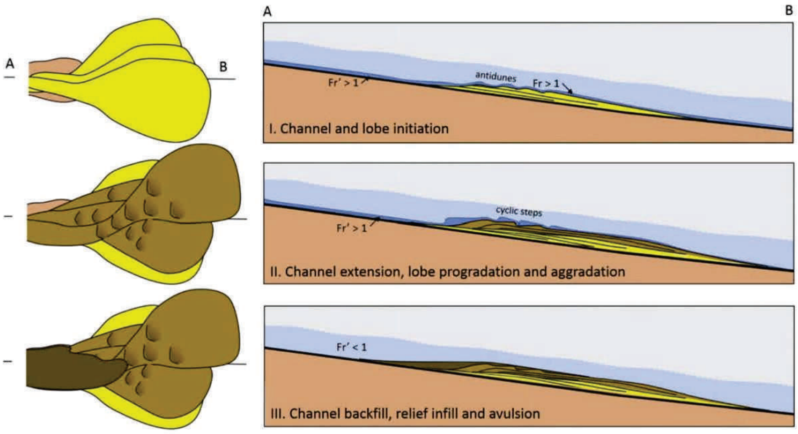

Figure 6: Autogenic avulsion cycle (from Postma et al. 2018). This process potentially leads to the development of dip-seal associated with deepwater distributary reservoirs deposited on steep slopes through by supercritical sediment gravity flows.

Application in Deepwater Stratigraphic Trap Exploration in Niger Delta

Process based stratigraphic knowledge of deepwater distributary reservoir development presented in the preceding sections shows that the following factors: (1) depositional gradient, (2) flow hydraulics and (3) sediment supply, exerts a fundamental control on the depositional style and reservoir characteristics of deepwater deposits. For the most part depositional gradient tends to control the other factors to a large extent.

Applying the knowledge of the role these 3 factors play in deepwater reservoir deposition tied to an understanding of the genetic evolution of the deepwater sub-basin (figure . 7) provides the platform for deepwater stratigraphic trap exploration in the Niger Delta.

The Niger Delta basin is dominated largely by deltaic / deepwater depositional processes genetically related to gravity driven extensional and shale diapirism tectonics in proximal domain. The distal domain of the deepwater environment shows mostly compressional tectonics. In addition, local collapse events triggered by high rates of sediment loading also create accommodation that is subsequently filled by deepwater deposits. These unique tectonostratigraphic framework of the Niger Delta provide potential for the application of process

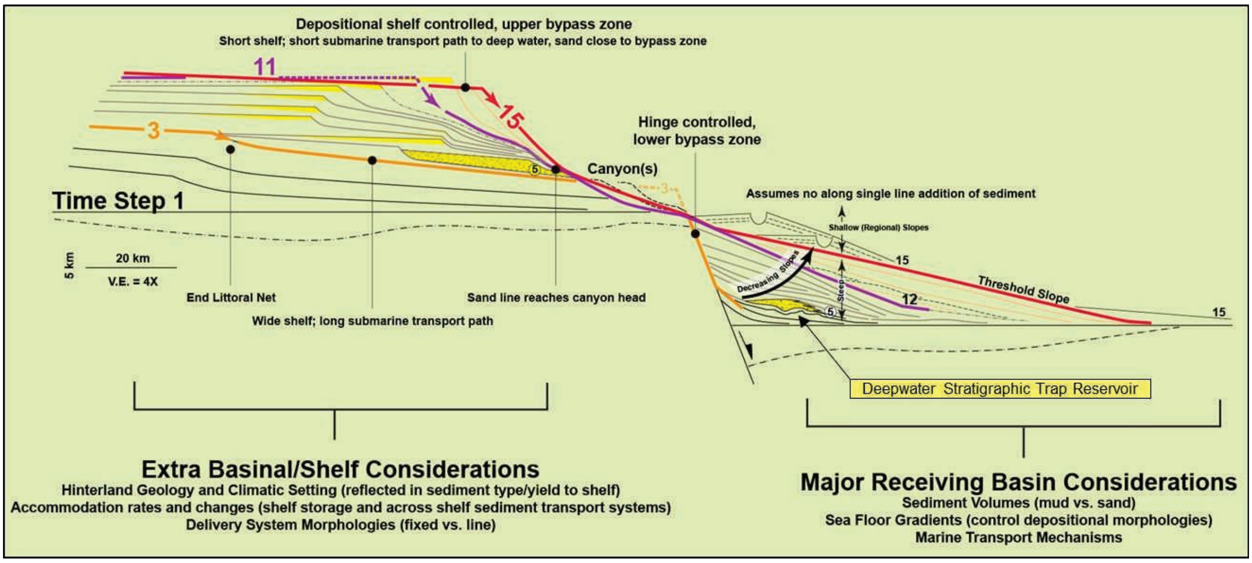

Figure 7: Section showing control of paleo depositional slope on style of deepwater reservoir considering the genetic evolution of the basin. Down to basin faults create accommodation and initial steep depositional slope which is filled passively by sediment gravity flows. Early part of the basin fill characterized by steep paleo-depositional slopes is dominated by sand rich supercritical fans with potential for updip bypass creating stratigraphic traps.

stratigraphy knowledge to explore for deepwater stratigraphic trap deposits – considering the fact that the factors mentioned can be observed in predictable autogenic geologic processes that lead to development deepwater stratigraphic trap reservoirs.

Two examples are shown below to demonstrate how these factors can be applied in a process stratigraphic sense to support exploration of sand rich distributary deposits that have the potential to form stratigraphic traps.

Application Related to Local Accommodation by Faulting

This example is derived from the Tortonian Sequences in the Eastern Niger Delta. Down to the basin growth faults create large accommodation that is subsequently filled by deepwater slope channel fairways derived via sediment feeders in the up-dip shelf slope break. These regional faults create the steep depositional slopes required for triggering supercritical flow hydraulics in sediment gravity flows leading to the potential for sandy distributary fan deposits in the basin (figure 8). These type of exploration targets are common with older sequences deposited basinward of the paleo-shelf slope break and associated with a sub-regional fault system that creates local accommodation with steep sediment input fairways.

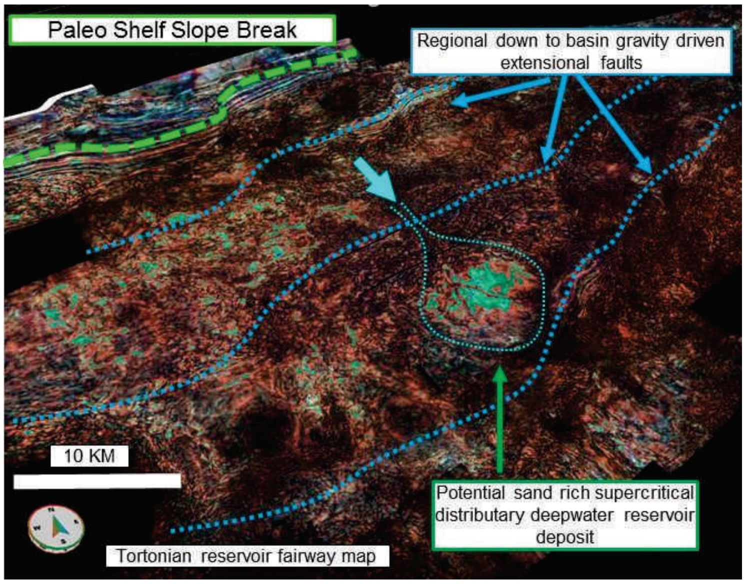

Figure 8: Tortonian distributary fan deposit. Local steep gradients created by basinward faults can support development of supercritical flow hydraulics leading to deposition of sandy lobe complexes with updip feeder bypass.

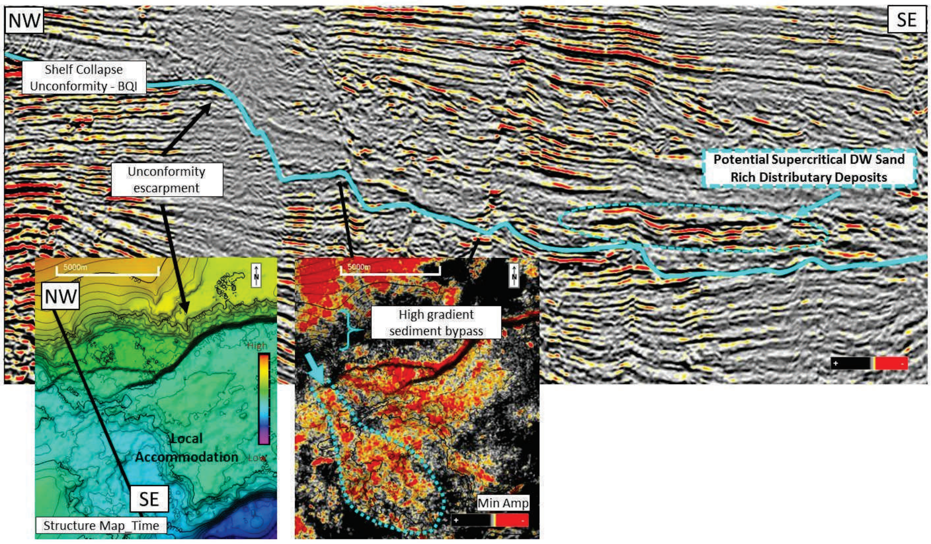

Figure 9: Potential deepwater stratigraphic trap plays associated with accommodation created by shelf collapse events in the Niger Delta.

Application Related to Accommodation Created by Shelf Collapse

Shelf and delta front collapse events are common within the Niger Delta basin. These events are responsible instantaneous accommodation creation that is subsequently filled by deepwater sediment gravity flow deposits. One of such collapse event in the eastern Niger Delta within ExxonMobil JV acreage is responsible for the development of deepwater confined channels plays. Deepwater stratigraphic trap plays can also be predicted within local accommodation created by this shelf collapse event (figure 9).

In other parts of the Niger Delta or older collapse events this can be an important play system that can unlock significant volumes of hydrocarbon deposits.

CONCLUSION

Exploration interests in deepwater stratigraphic trap leads have increased in the last decades following play opening discoveries in Tano and Sergipe Basins in Ghana and Brazil respectively.

Dominant trap types drilled as exploration prospects in the Niger Delta have been structural and combination traps, due in part to perceived risk profile and lack of a process stratigraphic understanding of deepwater reservoir development that can inform prospecting for stratigraphic traps in the deepwater environment. An analysis of industry drilled deepwater stratigraphic trap plays in the Circum-Atlantic passive margin basins reveals that stratigraphic traps in the slope environment are not significantly more risky compared to other trap types but require an understanding of the genetic evolution of the basin from a tectonostratigraphic perspective and how this controls sediment routing and consequent hydraulics of sediment gravity flow deposits.

Better prediction of deepwater clastic reservoir play element through a process-based understanding of the hydraulics of sediment gravity flows will support the departure of industry-driven focus on structure / combination trap plays and build confidence and knowledge to explore for deepwater stratigraphic trap plays

Two examples potential leads presented in this paper shows that we can apply process stratigraphy knowledge toward maturation of exploration leads in the Niger Delta for deepwater stratigraphic trap play system.

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