Understanding tectonic development and the implications for prospectivity offshore Côte d'Ivoire and Ghana

Avril Burrell[1]* presents the influence of transform tectonics during the development of the Côte d'Ivoire and Tano basins and discusses the underexplored potential in the deepwater area.

Introduction

The Côte d'Ivoire and Tano basins form a prolific hydrocarbon-producing province with several large, high-profile discoveries made in recent decades including the discovery of the Jubilee (Kosmos, 2007) and TEN (Tullow, 2009) fields in Ghana, and the play-opening discovery and subsequent expansion of the Baleine structure (Eni, 2021/2022) offshore Côte d'Ivoire. The basins are located within the Gulf of Guinea transform margin and bounded by two transform fracture zones: the Saint Paul's Fracture Zone to the north west and the Romanche Fracture Zone in the south east. The area formed during the opening of the Atlantic and this comparatively structurally quiescent location between two fracture zones has led to the consistent spatial-temporal deposition of marine clastic sediments. Using regionally extensive 3D seismic data, observations can be made on the influence transform tectonic development has had on the structural architecture of the basin and the inherent implications for prospectivity. Through these insights, remaining underexplored potential in the deep water can be highlighted drawing on analogues from the southern Atlantic.

Exploration history

Hydrocarbon exploration in the shallow offshore of the Tano Basin began in the 1970s, with two main international operators leading drilling efforts: Esso and Phillips. During this period, the majority of discoveries were made offshore Côte d'Ivoire (Lion, Panthere and Belier), with a smaller number of discoveries found offshore Ghana (Tano South and Cape Three Points) (Figure 1). These discoveries highlighted the mixed oil and gas potential in structural traps in the Cretaceous section on the shelf.

Exploration efforts continued in Côte d'Ivoire in the 1980s with the discovery of large fields in Albian plays such as Espoir (189 MMboe recoverable) and Foxtrot (146MMboe recoverable) (S&P Global Basin Monitor Report, 2024). By 1986, after limited drilling success, all companies in Ghana had relinquished their licences. In the 1990s there was no exploration offshore Ghana. In the 1990s there was, with only one new field wildcat well (West Cape Three Points 1) drilled by Hunt Oil towards the end of the decade in 1997. Similarly, in the late 1990s there was a lack of discoveries in the shallow waters of Côte d'Ivoire.

The early 2000s kick-started the push into deepwater exploration with a focus on Upper Cretaceous turbidite channel systems in combination structural/stratigraphic traps. The largest discovery in Ivorian waters was made with the drilling of Baobab in 2001 (230MMboe recoverable), rapidly followed by Paon (213MMboe recoverable) (S&P Global Basin Monitor Report, 2024). The discovery of the Jubilee Field in 2007 (Kosmos) and the TEN fields (Tullow) in 2009 in Ghana lead to a revival of activity in the region, marking the basin as a global hotspot and inspiring the hunt for analogue plays across the margin.

Recent success in Cote d'Ivoire with the discovery of the Baleine Field (Eni, 2021) has expanded the Upper Cretaceous play to include carbonate shelf edge reservoirs. In Ghana, the

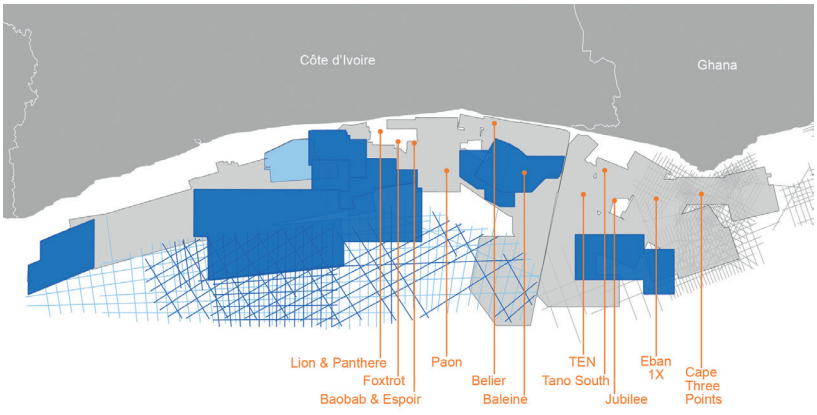

Figure 1 Map showing the PGS multi-client data library in the Gulf of Guinea used in this work, with key discoveries mentioned in the text indicated.

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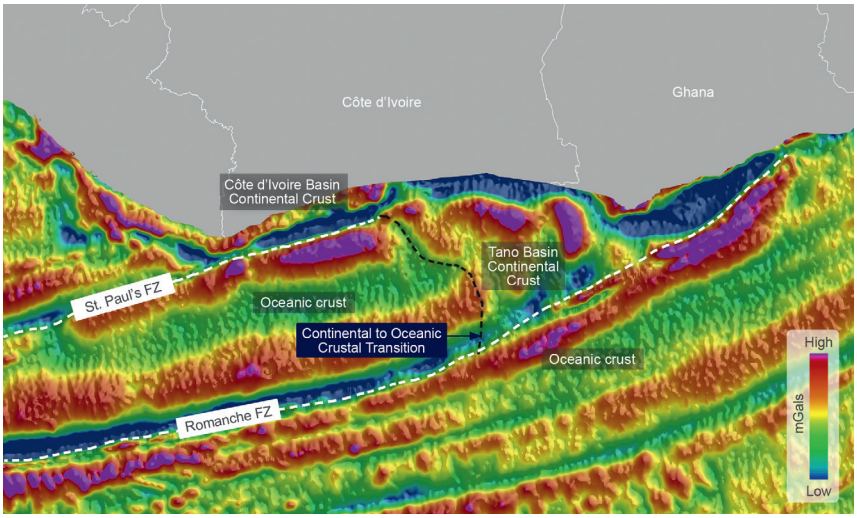

Figure 2 Bouguer corrected gravity anomaly map (200km HP filter) (Sandwell et al. 2014) displaying the key tectonic lineaments along the Gulf of Guinea margin. The Saint Paul's and Romanche Fracture Zones are highlighted, along with the Continental to Oceanic Crustal Boundary (COB).

Eni Eban-1X discovery is reported to have found light oil in an 80m-thick section of Cenomanian sandstones. These large accumulations show that significant volumes of hydrocarbons are found in Cretaceous-aged plays over continental crust in this well-explored basin.

Understanding tectonic history

The Tano and Côte d'Ivoire basins developed during the opening of the Atlantic, with transform rifting beginning in the Late Jurassic to Early Cretaceous periods and finishing at the end of the Albian with the formation of oceanic crust (Brownfield and Charpentier, 2006). By the Late Albian to Early Cenomanian periods Brazil and West Africa had fully broken apart ending the major phase of tectonic development along the Gulf of Guinea margin (Antobreh et al., 2009). Intrusive volcanics are observed around the syn-transform regional unconformity from the Albian to Cenomanian-Turonian levels on 3D seismic near the Romanche Fracture Zone, but are unlikely to have significant effects on source rock maturity due to their limited extent.

The Tano Basin developed in an area of relative tectonic quiescence between the Saint Paul's and Romanche Fracture Zones, resulting in pull-apart grabens with a thick clastic fill. The St Paul's transform fault terminates into a curved coastal fault in the eastern Ivorian offshore and evolves into a horsetail splay structure at the connection with the Romanch Fracture Zone, offshore Ghana (Basile et al. 2005). Generally, this has created a broad shelf to deepwater profile in much of the basin, underpinned by thick continental crust, gradually thinning towards the continental to oceanic crustal transition (Figure 2). The continental to oceanic crustal transition between the St Paul's and Romanche Fracture Zones in the western Tano Basin is not clearly defined by the Bouguer-corrected gravity data (Antobreh et al., 2009) but has been interpreted using PGS regional 3D seismic coverage.

In comparison, the Côte d'Ivoire Basin to the west has a narrow shelf to deep-water profile, characterised by transform faulting and initial graben development orientated sub-parallel to the present-day coastline. The continental to oceanic crustal transition is also more abrupt here and visible on the Bouguer-corrected gravity data. This is due to the underlying Saint Paul's Fracture Zone creating a significant gravity contrast between thick, high-density continental crust to the north and low-density oceanic crust immediately to the south.

The stratigraphic section of both areas can be divided into the pre-, syn- and post-transform tectonic phases, each with a distinct depositional history and related petroleum systems. The pre-transform succession outcrops onshore in Ghana and is composed of Precambrian to Triassic-aged strata. Within the Tano Basin, pre-transform Jurassic-aged conglomerates and shales deposited in a continental setting have been tested by drilling and are likely to have been sourced from the erosion of uplifted shoulders along the basin margins (Basile et al., 2005).

The syn-transform phase of transtensional opening in the Gulf of Guinea began around the Berriasian and ceased at the end of the Albian. A thick section of continental to marginal marine clastics was deposited during this period, providing potential reservoir units in the form of fluvial to marginal marine sandstones. (Brownfield and Charpentier, 2006). Source rocks transition from deeper Aptian lacustrine shales to shallower Mid-Albian marginal marine shales through the stratigraphic section as rifting progressed.

Extensional opening of the transform margin basins ceased at the end of the Albian and was followed by wide-spread deposition of Cenomanian-Turonian marine shales (MacGregor et al. 2003). The area formed a continuous anoxic seaway from the late Albian to Turonian (Tissot et al. 1980) in which a number of high total organic carbon content (TOC) oil prone source rocks developed.

Exploring the petroleum systems

Two main plays have been the focus for exploration in the Ivorian and Ghanian offshore, the syn-transform Lower Cretaceous and the post-transform Upper Cretaceous (Figure 3). The Lower Cretaceous play dominates the area around the shelf edge in the Tano Basin. A contributeng factor in this inboard dominance is the source rock maturation history. Berriasian to Albian source rocks sit within the gas maturity window around the shelf due to a relatively thinner overburden, whereas they are likely to be over-mature in more distal syn-transform basins where depth of burial is greater. These source rocks are paired with Albian-aged fluvial to shallow marine syn-transform sandstones, as proven in the Baobab Field (CNR, 2001).

The Upper Cretaceous system is most successful around and outboard of the present-day shelf edge due to the thick clastic section allowing for sufficient burial of shallower Cenomanian-Turonian-aged source rocks. These type II source rocks have mixed oil and gas potential (Tissot et al. 1980). Complementing this widespread source kitchen are Albian to Santonian-aged shallow to deep marine sandstone reservoirs deposited as turbidite channel and fan systems. The largest discovery in the Upper Cretaceous system is contained within the Baleine shelf-edge structure which is reported by Eni to contain 2.5 billion barrels of oil and 3.3 trillion cubic feet (TCF) of associated gas over two main reservoir levels. This discovery has also expanded the play to include carbonate shelf edge reservoirs. This inferred carbonate build-up is observed on seismic as a high amplitude, parallel layered sequence which developed on an isolated shelf-edge terrace. The Paon (Anadarko, 2012) discovery has proven that the Upper Cretaceous play extends into the deepwater Tano Basin, with the Saphir-1X well (TotalEnergies, 2014) illustrating that the play extends to the west in the Côte d'Ivoire Basin.

Tectonic segment styles and sediment Input

Four main tectonic segments are identified as being present within a classic transform margin as classified by Cronin et al. 2023:

1. the transform margin *sensu stricto*,
2. local pull-apart segment on the transform margin,
3. narrow horsetail segment splaying off from the transform and
4. the extensional end at the horsetail structure.

Each of these segments shows distinctive sediment routing characteristics owing to key differences between the shelfal staging widths, deep-water slope gradient and seabed topography across the four classifications. Due to the presence of two fracture zones and the well-preserved record of structural architecture, seismic sections from three of these segments will be shown from the Côte d'Ivoire and Tano basins (Figures 5-7). The locations of the sections are indicated on a seabed depth surface generated from PGS

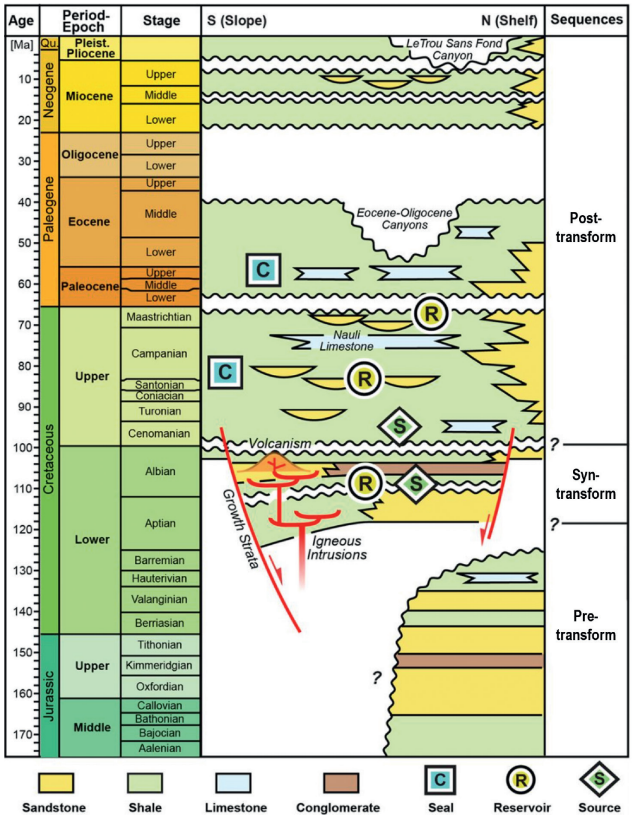

Figure 3 Tectono-stratigraphic column for the Ivorian Tano Basin (modified from Scarselli et al. 2019). Key reservoir, source and seals are highlighted across the syn- and post-transform stratigraphy.

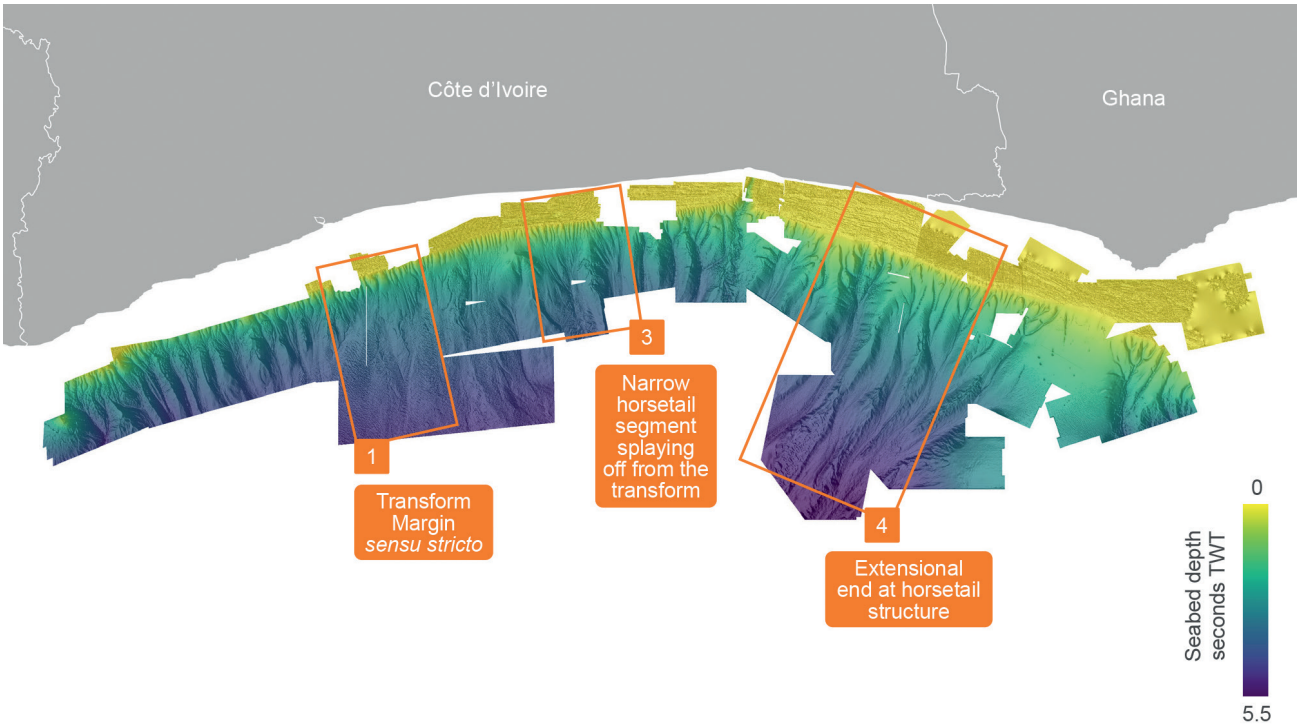

Figure 4 Seabed depth horizon (seconds, TWT) from PGS multi-client merged 3D seismic data highlighting three of the tectonic segment styles present offshore Côte d'Ivoire and Ghana as classified by Cronin et al. 2023. The approximate location of the three seismic lines in Figures 5-7 are indicated by the orange polygons 1, 3 and 4.

merged 3D seismic coverage in Figure 4. As stated by Cronin et al. (2023), the authors were limited in their ability to share seismic examples throughout their work due to confidentiality restrictions; PGS multi-client data will be used to show direct examples.

Regional 3D seismic data coverage has been used to demonstrate the evolution in tectonic segment styles across the Côte d'Ivoire and Tano basins, highlighting the implications for reservoir distribution along the margin. Figure 5 shows a full-stack 3D seismic line from the Côte d'Ivoire Basin, where the St Paul's Fracture Zone immediately underlies the section. The narrow, sand prone shelfal staging width, high deep-water slope gradient and steep seabed topography from the first classification of segment styles (transform margin *sensu stricto*) are clearly observed. The transform margin *sensu stricto* results in bypass-dominated clastic depositional systems due to the steep, single-faulted margin where sediments bypass the slope through deep shelf-edge canyon systems (as evidenced on the seabed depth image in Figure 4). Sediments are sourced from the high-margin plateau and pond in deep water on the basin floor over a relatively short sediment transport distance due to lack of intra-basin terraces (Cronin et al., 2023).

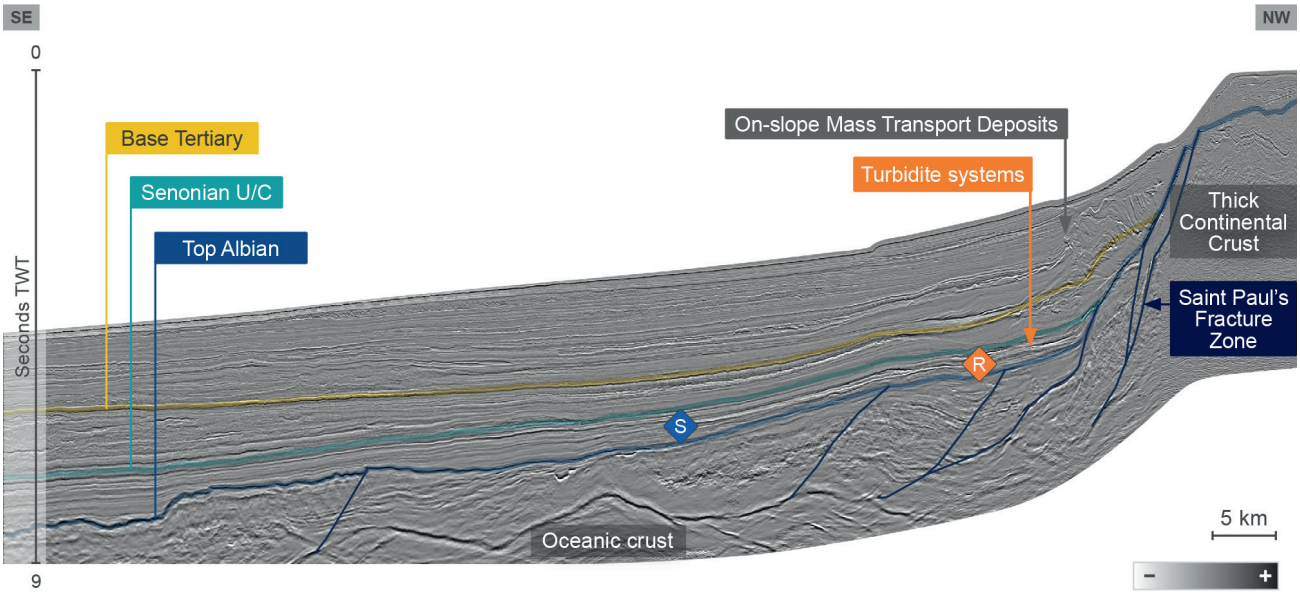

Figure 5 Merged 3D full-stack prestack time migrated (PSTM) seismic dip line across tectonic segment classification 1: transform margin sensu stricto (approx. line location indicated by polygon 1 on Figure 4). This line shows the abrupt lateral change from thick continental crust in the northwest to oceanic crust in the southeast across the single faulted margin of the St Paul's Fracture Zone.

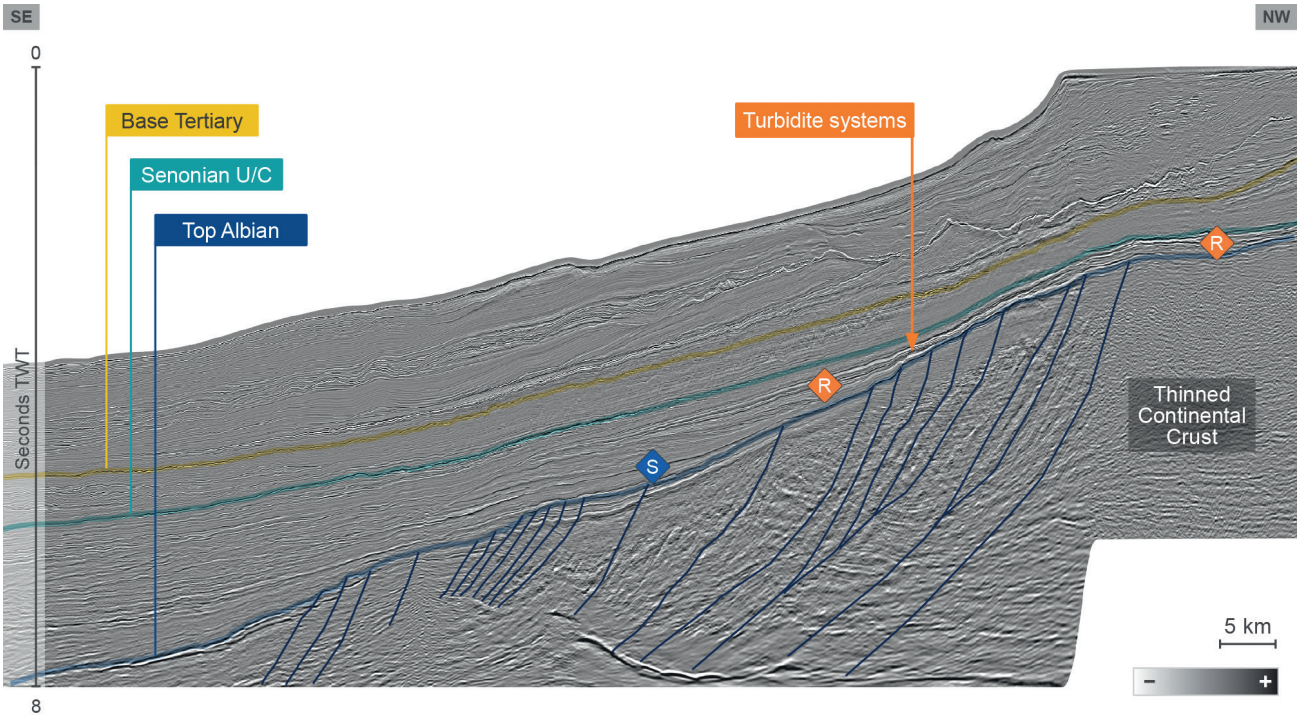

Figure 6 Merged 3D full-stack PSTM seismic dip line across tectonic segment 3: narrow horsetail segment (approx. line location indicated by polygon 3 on Figure 4). This line shows the change in style from the single faulted margin in Figure 5 to the extension dominated tectonics of the narrow horsetail resulting in ramp-terrace profile.

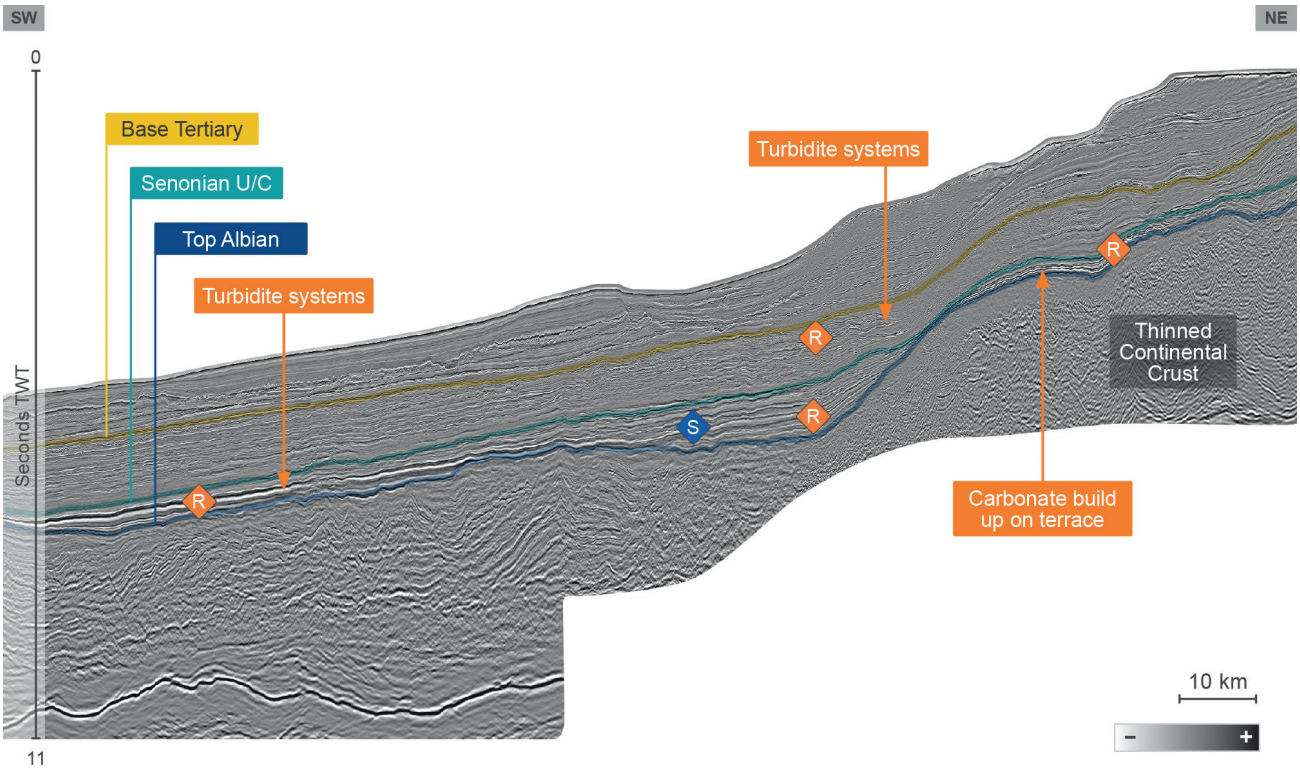

Figure 7 Merged 3D full-stack PSTM seismic dip line across tectonic segment 4: extensional end at horsetail segment (approx. line location indicated by polygon 4 on Figure 4). This line shows the extended lateral change from thin continental crust in the northeast to oceanic crust in the southwest with multiple ramp-terrace structures occurring along the shelf to deep water profile.

Further to the east in Figure 6 is a typical profile from type three of the tectonic segment classifications: the narrow horsetail segment splaying off from the transform margin. Here we observe a relatively wider shelfal staging width, lower deepwater slope gradient and a gentler seabed topography. The extensional block faulting in this style of segment results in more terrace and ramp style paleo-bathymetry which has significant implications for ponding of clastic sediments on the terraces. Continental crust is thinned here through extension related to the horsetail structure, with a system of oblique-slip faults stretching continental crust away from the transform margin sensu stricto (Cronin et al., 2023).

In the centre of the Tano Basin, in Figure 7, is a typical profile from type three of the segment styles: the local pull-apart segment on the transform margin. Here we observe a relatively wide shelfal staging width, extended deep-water slope gradient and a gentler seabed topography. The extensional block faulting in this style of segment results in numerous alternating ramps and terraces with sand sequestration occurring along the slope profile within stacked frontal splays. Levee-confined slope channel complexes are also common (Cronin et al., 2023).

Implications for prospectivity

Due to the close relationship between transform segment style and clastic deposition patterns in a region dominated by combination stratigraphic/structural traps, there are clear implications for prospectivity from west to east across the Côte d'Ivoire and Tano Basins. To demonstrate this relationship, sediment distribution can be illustrated using an RMS amplitude extraction from the Upper Cretaceous as shown in Figure 8. This has been created from merged full-stack PSTM 3D datasets.

In the east of the Tano Basin, the area of transform segment style four: the extensional end at the horsetail segment dominates and we can observe the influence that the ramp-terrace style has on shelf to deep-water sand distribution. Sands are segregated within terraces as frontal splay complexes or sheet sands before bypassing the subsequent down-slope ramp and then being ponded in the next terrace. This low gradient, extended paleo-bathymetry over thinned continental crust allows for development of combination stratigraphic/structural traps at multiple levels on the shelf slope. This depositional pattern is more entrenched at segment four in the Tano Basin and becomes less prevalent to the west as the structural extension of the horse-tail splay decreases towards the transform margin *sensu stricto.*

To the west, in areas along the Saint Paul's Fracture Zone the steep single-faulted margin of the transform margin *sensu stricto* results in clastic sediment bypassing the slope and being deposited in the deepwater basin floor. As demonstrated by the Bouguer-corrected gravity anomaly map in Figure 3 and the seismic interpretation in Figure 5, sediments here are deposited directly over oceanic crust. This deep-water area in both the Côte d'Ivoire and Tano basins is relatively underexplored although basin floor fans are clearly observed to be widely present along the margin (Figure 7). This lack of exploration may be attributed to a perceived absence of trap development where existing up-slope discoveries rely upon faults from the ramp/terrace structures to form the up-dip trap for Upper Cretaceous plays.

However, recent 2022 exploration success offshore Namibia with TotalEnergies' Venus-1 discovery has suggested that Upper Cretaceous turbidite reservoirs at the base of slope can prove successful by utilising outer highs and counter-regional dip to

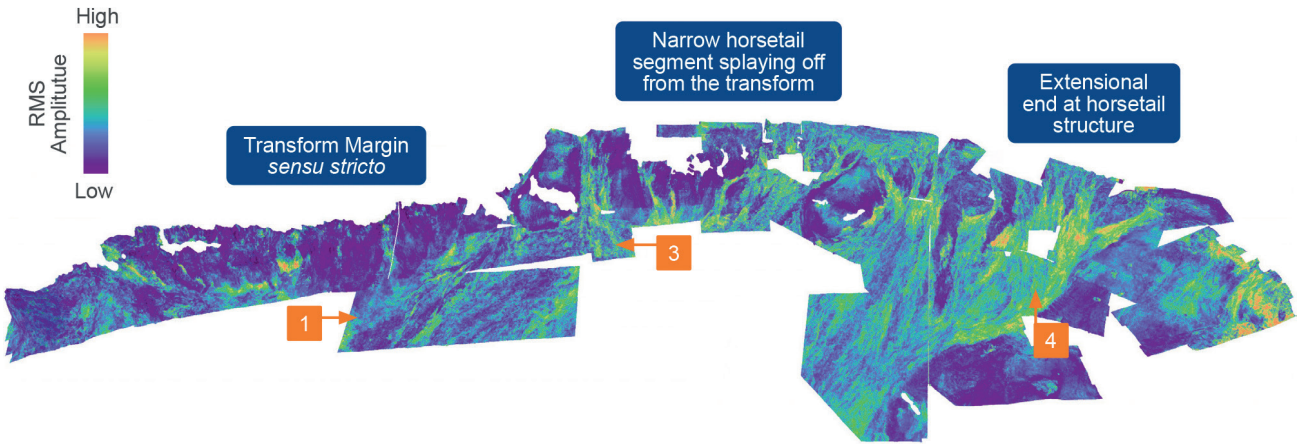

Figure 8 RMS amplitude extraction from the Upper Cretaceous created using PGS merged 3D full stack pre and post stack time migrated seismic data. The location of the three transform segment styles is highlighted showing the implications for sediment distribution across the margin. From left to right; segment style 1: steep shelf gradient and sediment bypass to deepwater over oceanic crust. Segment style 3: moderate deepwater slope gradient and wider shelf staging area: intra-slope terraces with deposition on shelf slope. Segment style 4: lowest slope gradient and widest shelf staging area: extensive intra-slope ramp/terraces and sediment ponding. Note the spatial/temporal focus of sediments at the base of slope across the figure.

provide trapping mechanisms. Similar concepts can be applied to the outboard area of the Côte d'Ivoire and Tano Basins where deepwater sediments are observed to drape over oceanic crustal highs in four-way dip closures.

Drawing further on the Namibia play analogues, Cretaceous-aged source rocks deposited over transitional-to-oceanic crust in the deep-water Orange Basin are oil mature in outboard areas. The concept for hydrocarbon generation and expulsion from source rocks subjected to increased heat flux from the mantle (Doran et al. 2017) may also be applied to the deep-water offshore of Côte d'Ivoire and Ghana, expanding prospectivity beyond the area underpinned by continental crust. Cenomanian-Turonian aged shales are a proven source rock offshore Côte d'Ivoire containing high TOCs and are characterised by their low amplitude, planar response typical of deepwater shale deposits, as highlighted in Figure 5.

This regional scale understanding of petroleum systems highlights the exciting opportunities remaining over oceanic crust in the Côte d'Ivoire and Tano Basins, allowing exploration potential to be extended from analogs and existing in-basin discoveries into underexplored areas.

Conclusions

The shelf and slope areas of the eastern Côte d'Ivoire and Tano Basins are well explored with large, play opening hydrocarbon discoveries being made since the early 2000s with continued success as the plays have emerged. The region's success can be directly attributed to the influence of transform tectonics. This location between the Saint Paul's and Romanche Fracture Zones has produced favourable conditions for the two main Cretaceous-aged plays to develop resulting in the region becoming an exploration hotspot. Through extensive seismic data coverage, key authors from international operators have developed new insights into the influence transform tectonics have had on developing the basin architecture resulting in four classifications of transform segment styles. These have direct implications for prospectivity due to the way reservoir sands are developed and distributed across the shelf to deep-water profile in relation to the segment style. Through these insights, analysis of regionally extensive PGS seismic data and by building on analogues from offshore Namibia, remaining underexplored potential in the deep water can be revealed.

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