Integrating regional 2D seismic mapping and 3D seismic spectral decomposition to understand the fairway evolution of offshore Benin

Pauline Rovira[1]* discusses how 2D and 3D mapping combined helps us to understand the differences in sediment input directions and faulting impact on the fairways of the Cretaceous, Paleogene and Miocene.

Abstract

Offshore Benin, and the wider Keta Basin, remains an underexplored area of the West Africa Transform Margin. The evolution of the different sediment fairways and their depocentres can be identified on structure maps from the mapping of a regional 2D seismic dataset. The 3D seismic offshore Benin supports the 2D interpretation but in addition, allows for a more complete evaluation through detailed seismic attribute analysis. The use of 3D spectral decomposition highlights the changes in fairway directions with clear imaging of the channel systems and their orientations, correlating with the thicknesses observed from regional 2D seismic mapping.

The transform faults strongly control the overall structuration of offshore Benin and the depositional style during the Cretaceous period. The onshore Togo and Benin river systems supply sediment directly to the basin in a north to south direction which is limited and directed by the transform movement and ridges outboard. Towards the end of the syn-transform deposition, the main fairway input changes from a directly northern source to a north eastern source in the Dahomey Embayment. Finally, in the Cenozoic, the Niger River system drainage increased leading to the Benin Ultra Deep area to form part of the Niger prodelta, with a predominant easterly sourced sediment input. The transform faults are no longer active and no

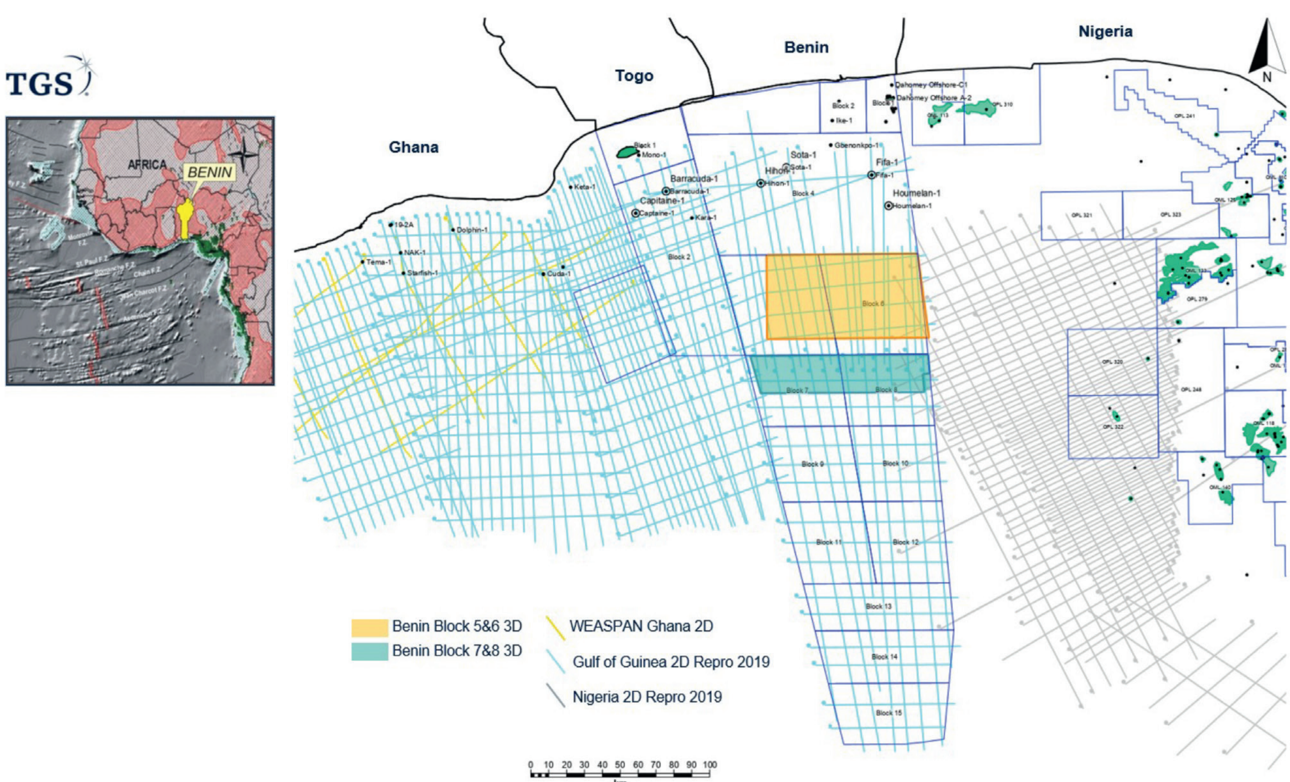

Figure 1 Map of the TGS seismic data library.

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Survey	2D Line km	3D area km²	Acquisition Year	Reprocessing Year	Record Length ms
GoG 2D Repro	25,725	-	2009	2019	14,000
Benin Block 5&6 3D	-	4,078	2011	-	13,000
Benin Block 7&8 3D	-	1,983	2013	-	13,100

Table 1 2D and 3D survey specs used in this study.

longer control sediment distribution, leading to an unconfined channelised system.

Introduction

Offshore Benin is located within the Gulf of Guinea, forming part of the West Africa Transform Margin, and borders Togo to the west and the prolific Nigerian Delta province to the east. Since exploration began in the late 1960s, 18 exploration wells have been drilled offshore but success has been limited with the discovery of only the Seme North and Seme South fields to date. The majority of the wells have been drilled within the shelf-slope setting and the deep basin remains unexplored. The dataset used for this study comprises regional 2D (reprocessed in 2019) spanning the length of the basin extending from Ghana to Nigeria, as well as two high-quality 3D surveys located offshore Benin (Figure 1 and Table 1).

The 2D data has been used to map and understand the key mega-sequences from a regional, large-scale perspective, tying into the wells where available. Following on from the regional interpretation, structure and isopach maps were produced to gain initial insight of the main depocentres and how that extends in the outboard and basinal setting of offshore Benin, away from well control. The 3D data was then utilised to garner more specific detail on the depositional systems of each mega-sequence. The 3D results show strong support for the 2D evidence but also allow for infilling of knowledge gaps in terms of fairway style and possible reservoir sweet-spots. Spectral decomposition images from the Block 5&6 3D are shown but other attribute workflows are being developed to further characterise the fairways.

Geological setting

The Benin Basin marks the eastern continuation of Ghana's Keta Basin, bound to the north by the distal end of the Romanche Fracture Zone and to the south by the Chain Fracture Zone and the Charcot Fracture Zone. These faults are major dextral-slip transform faults that have accommodated movement during the opening of the Central Atlantic throughout the Cretaceous. Rifting is initiated in the Lower Cretaceous, with rapid infilling of these newly formed pull-apart basins by continental and lacustrine clastics (Brownfield & Charpentier, 2006). Further outboard, a more restricted marine setting is developed. The Mid-Albian unconformity is clearly visible regionally, and marks the end of the main rifting event. However, transform movement on the faults continues into the Upper Cretaceous. The basin fill becomes fully marine in the Late Cretaceous. The onset of the passive margin occurs in the Palaeocene once transform faulting movement ends, driven by thermal subsidence (Kjemperud et al, 1992). The key seismic sequences were interpreted across the regional 2D in the first instance, tying into the wells where possible. A lack of well penetrations in the deeper parts of the basin make the exact age correlation of horizons difficult from shelf to basin. However, the combination of published reports and good quality seismic data extending and connecting Ghana, Togo, Benin and Nigeria allows for a stratigraphic framework of some confidence.

Clastic reservoir intervals are found throughout the stratigraphy, from Mid-Albian fluvio-deltaic rift sediments to Miocene deepwater turbiditic channels and fans. The main source rocks, that have been proven are the Neocomian and Aptian-Albian lacustrine and marginal marine source rocks. There is a risk of over-maturity for these where the greatest sedimentary cover occurs. However, for much of the basin, based on simple basin modelling, these source rocks are located within a present-day oil-gas window, assuming a base case geothermal gradient of 35 °C/km. The Cenomanian and Palaeocene source rocks, proven by the Capitaine-1 and Barracuda-1 wells, and Palaeocene source rocks, would be within the early to main oil window at present-day. Structural traps are mainly present within the rift and transform sequences, and stratigraphic traps being the primary closure mechanism for the passive margin plays.

Seismic stratigraphy

Figure 2 shows a number of faulted rift basins within the continental crust domain in the present day shelf-slope setting. The Upper Cretaceous shows limited extent beyond the Chain Transform Fault Zone (CTFZ) and is primarily confined to the basin inboard. The Upper Cretaceous seismic package is composed of high reflectivity, bright amplitudes and a channelised facies. Across the regional 2D dataset, this sequence shows a mixed turbidite and contourite system with stacked and laterally migrating channels and associated basin floor fans. The 'Paleocene Wedge' sequence denotes a localised package to this basin that pinches out westwards in the Ghanaian portion of the Keta Basin and northwards against the Upper Cretaceous slope. This turbiditic wedge marks the first substantial post-rift deposition beyond the CTFZ.

A seismically unreflective package of Eocene-Paleocene age, the Imo Shale Formation (Brownfield, 2016), is mappable regionally and appears to correlate with Nigeria's Akata Formation. Another local sequence to the Benin Basin develops in the Oligo-Miocene, but conversely to the Paleocene Wedge, the Dahomey Wedge pinches out southwards, onlapping onto the Oligocene unconformity, and is restricted to the inboard part of the basin. The final mega-sequence of note is the Miocene channelised package, which has a similar response seismically to the Upper Cretaceous. The sequence is dominated by bright reflectivity and local erosive surfaces and forms the deepwater equivalent to the Agbada Formation of the Niger Delta.

Fairway evolution

Upper Cretaceous

A general deepening trend is noted from the inboard to the outboard of the Benin Basin. From the structure, and in particular the thickness map (Figure 3a), it is clear that faulting is having a large impact on deposition of the Upper Cretaceous, with progressive thinning of the package to the south and minimal Upper Cretaceous is deposited beyond the CTFZ. The main rifting event is over by the time of Upper Cretaceous sedimentation. However, transform movement along the E-W faults continues and strongly controls the thickness variations observed with generally a thicker depocentre in the hangingwall area of the faults where ponding is occurring. From this 2D overview, it can already be determined that input to the basin is coming from immediately to the north of the Benin Basin. The 3D data on the other hand shows a similar story, but the additional detail highlights that more minor splay faults to the transform faults are also impacting Upper Cretaceous deposition (Figure 3b) and localised thinning is noted over horst structures.

Spectral decomposition carried out on slices within the megasequence shows dominant north to south fairways, particularly in the east of the Block 5&6 3D that highlihts a long-lived channel belt (Figure 4). Sediment wave fields can be seen inbetween the main channel belts, which may be associated levee type deposits or contourite/sand wave systems.

Paleogene

The Palaeocene sequence, like the Cretaceous, continues to show influence from faulting on deposition. The Palaeocene Wedge thickness (Figure 5) reveals a greater input from the Niger Delta area with a depocentre thick being developed in the east of Benin and the CTFZ causing funnelling of the deposition parallel to the fault. From the 3D attribute analysis, a chaotic facies is noted near the pinch-out edge, likely to be the result of local slope instability,

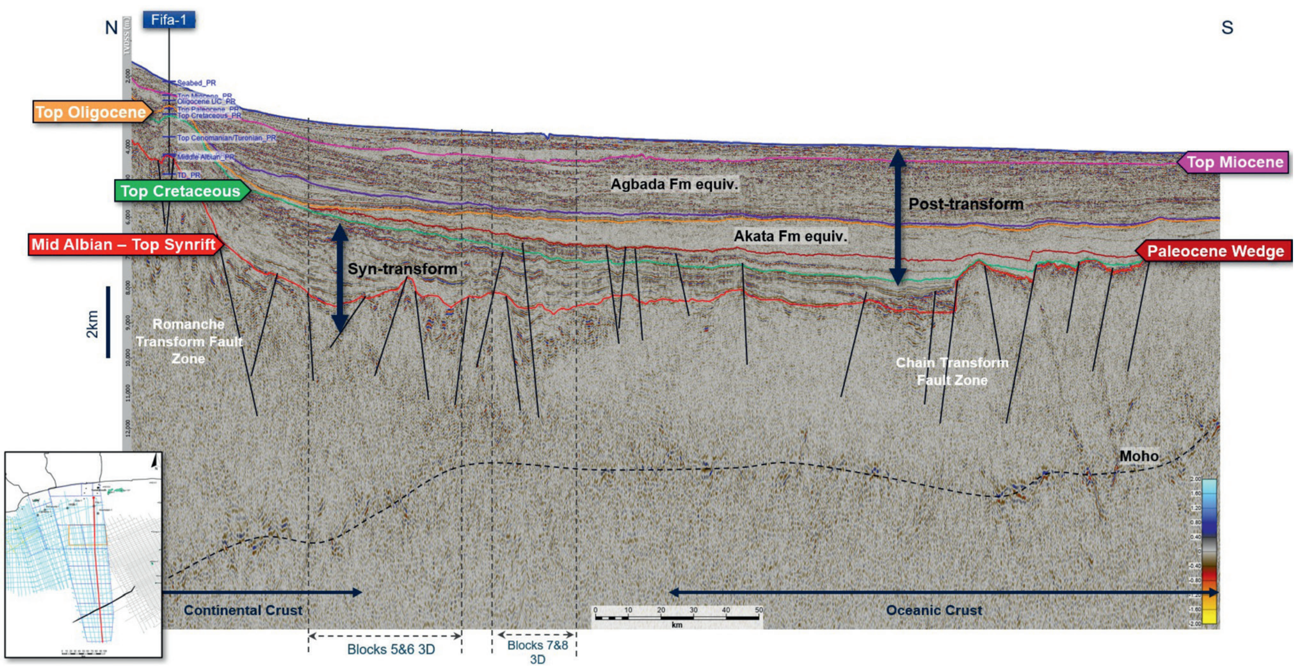

Figure 2 Regional 2D transect (N-S) offshore Benin highlighting the type geology and key mega-sequences.

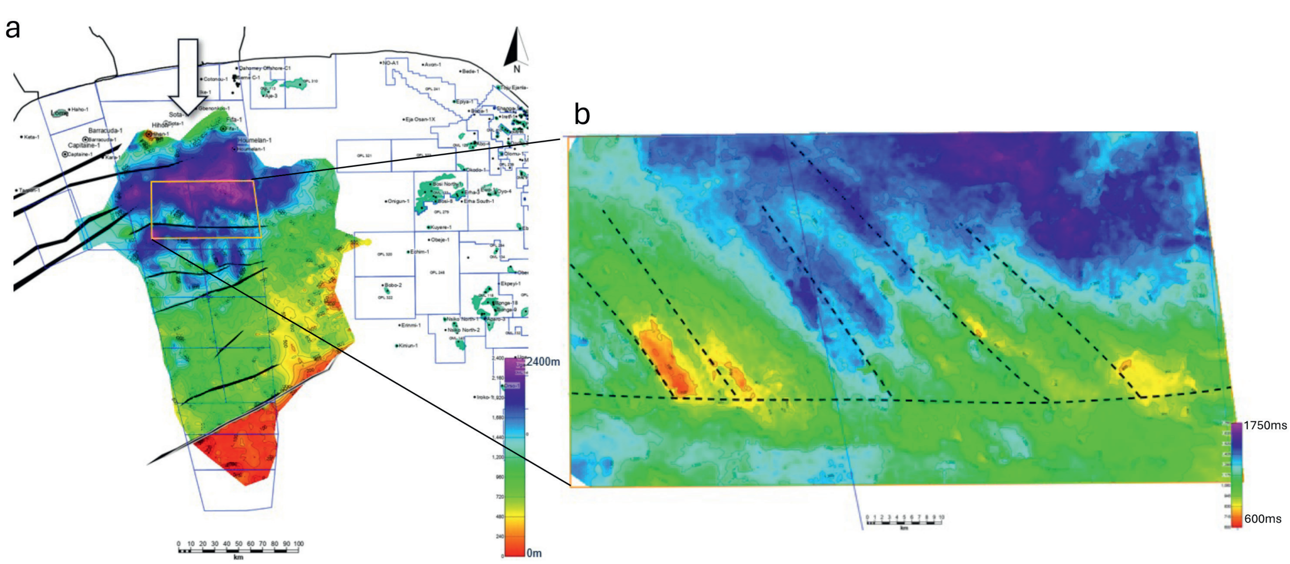

Figure 3 a) Isopach map for the Upper Cretaceous megasequence (Top Cretaceous to Mid-Albian Unconformity) from 2D interpretation. b) Isochron map for the Upper Cretaceous megasequence from 3D interpretation.

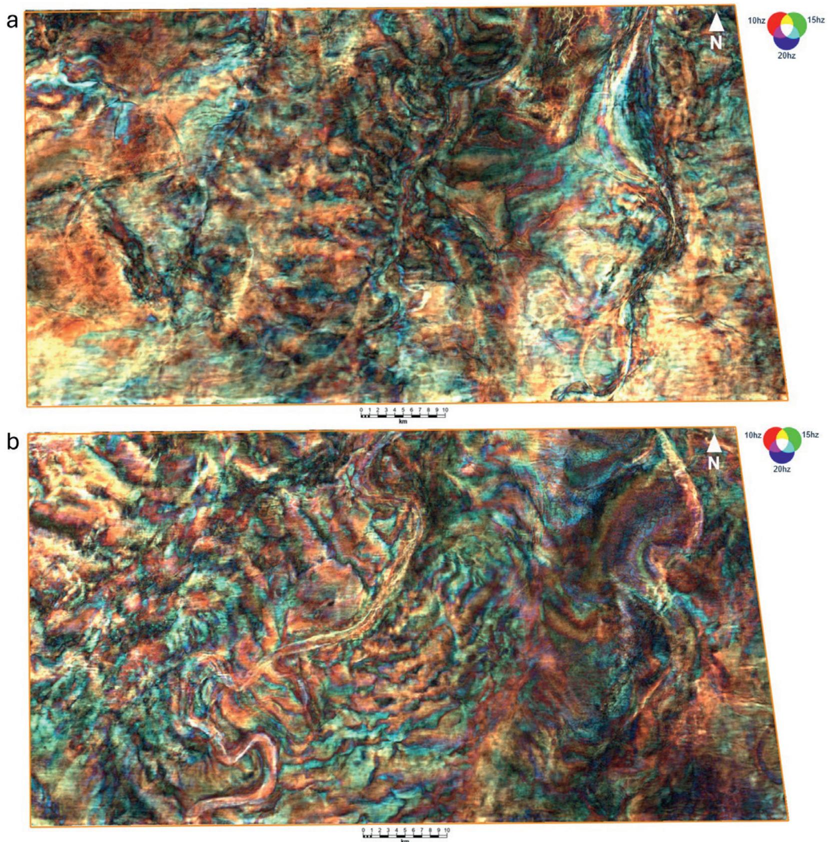

Figure 4 Spectral decomposition images (RGB blended) of two slices within the Upper Cretaceous, syn-transform package. a) slice through approx. Cenomanian level. b) slice through approx. Santonian level.

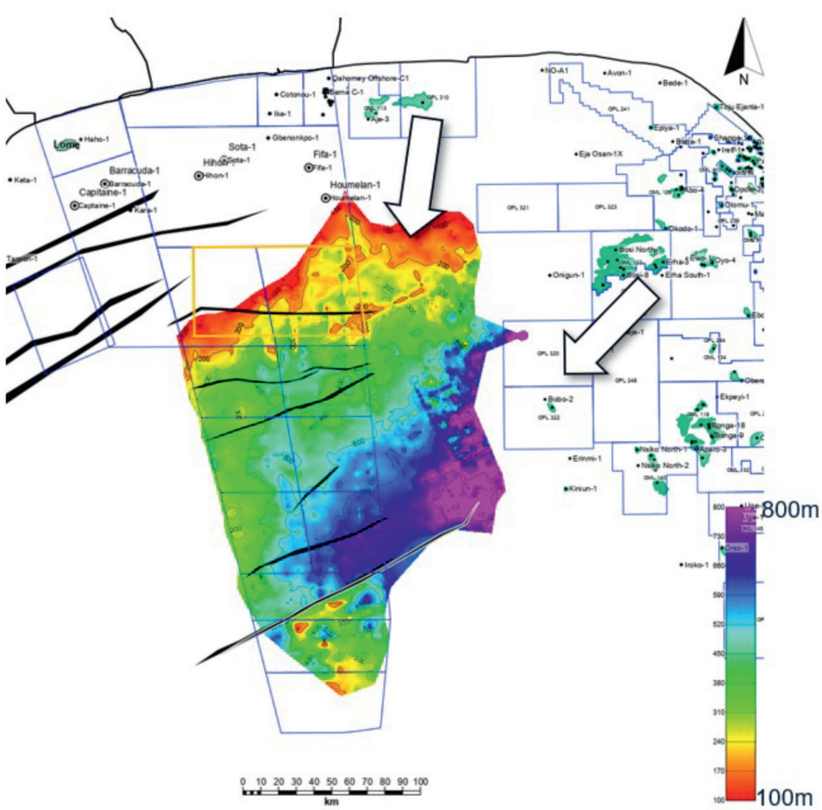

Figure 5 Isopach map for the Palaeocene Wedge sequence from 2D interpretation.

but away from the edge in the relative depocentre (the 3D survey is located up-dip of the main package thick for this sequence), a NE-SW fairway trend is observed suggesting additional increased input from the Dahomey Embayment in the NW (Figure 6a). The Eo-Oligocene package shows little seismic reflectivity and distinct channel features are not discernible from the spectral decomposition slices. Mass transport complexes (MTCs) are prevalent within this likely non-reservoir interval due to uplift in the Oligocene resulting in slope instability. However, a general NW-SE depositional trend remains (Figure 6b) and this also correlates with the interpretation from the regional 2D dataset. Away from the slope, the very bland seismic response suggests a very shale prone section and regionally this shale is well developed. This section forms the Benin Basin equivalent to the Niger Delta's Akata Formation, and is expected also to be a good-quality seal.

Miocene

The regional 2D thickness reveals two dominant depositional trends. In the nearshore, there is still a strong influence from a northerly input on the western side of Benin, but basinward, an easterly influence from the Niger delta area becomes much more prominent, with a much thicker package in the deepwater domain (Figure 7a). The transform faults are no longer expressed in the depositional fabric, with the area being in a passive margin setting by the Miocene time. The 3D is located north of the main eastern and basinal depocentre. However, the isochron (Figure 7b) supplements the 2D overview and shows the general thickening outboard as well as further highlighting a potential western fairway.

The seismic data shows that the Miocene mega-sequence is composed of bright and reflective turbidite-type facies encased in a low-reflectivity shale prone facies. The spectral decomposition images showcase these deepwater systems adding detail to the

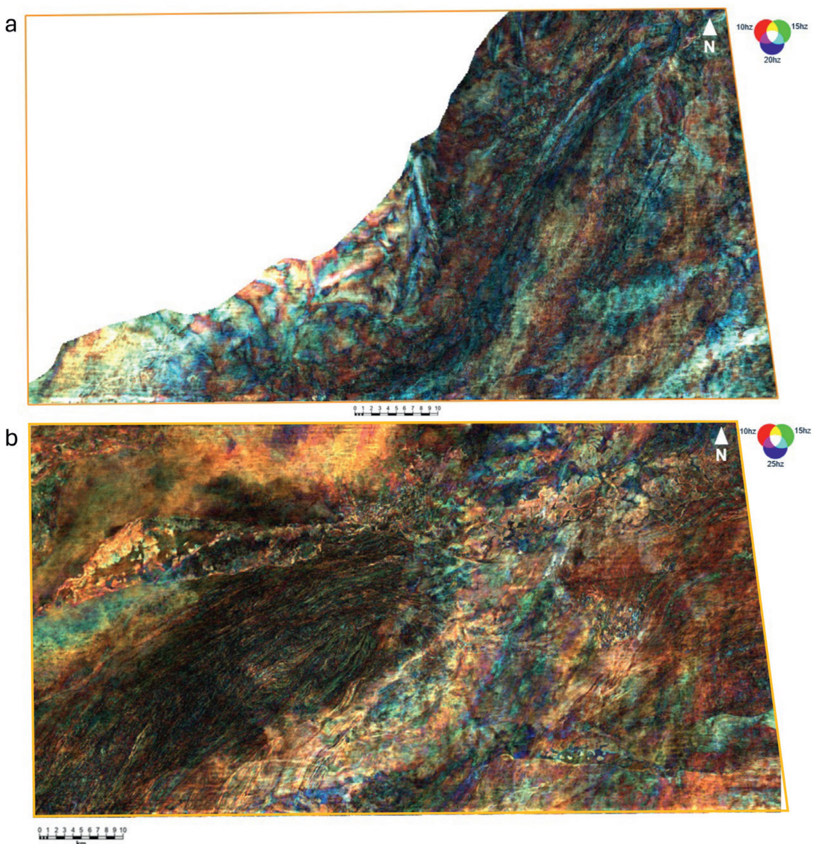

Figure 6 Spectral decomposition images (RGB blends) of two slices within the Paleogene mega-sequence. a) slice through the Palaeocene Wedge. b) slice through the Eo-Oligocene MTC.

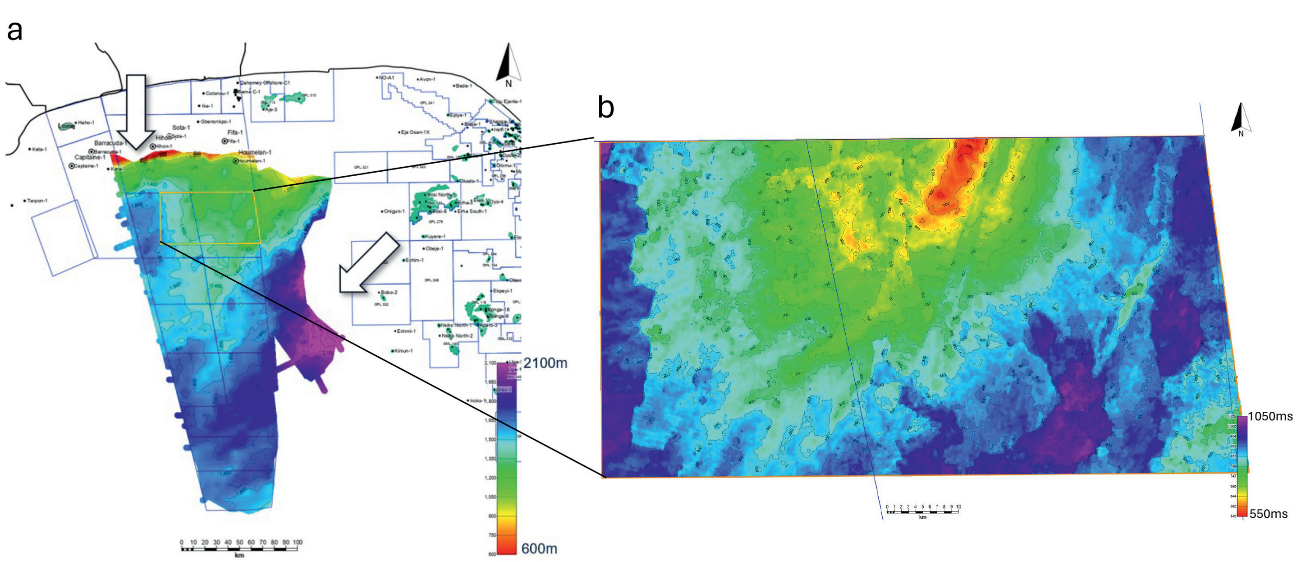

Figure 7 a) Isopach map for the Miocene megasequence (Top Miocene to Top Dahomey Wedge) from 2D interpretation. b) Isochron map for the Miocene megasequence from 3D interpretation.

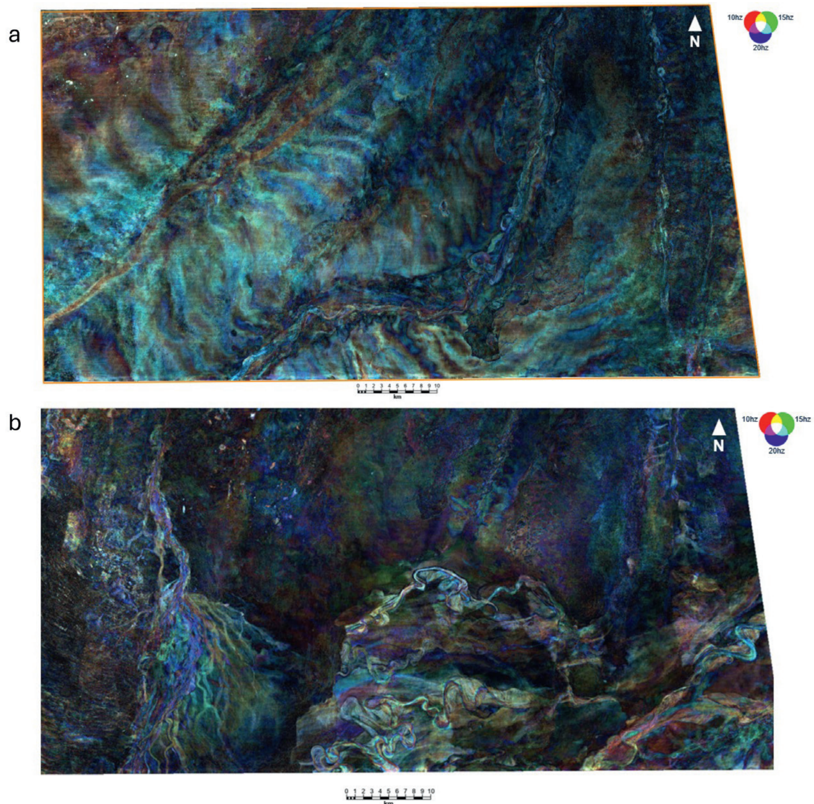

Figure 8 Spectral decomposition images (RGB blends) of two slices within the Miocene mega-sequence. a) slice through the Tortonian. b) slice through the Messinian. Termination of the E-W system is likely to be owing to faulting and/or potential down-cutting from an overlying MTC.

thickness interpretations. Interestingly, the slices taken through the older parts of the sequence reveal a dominant NE-SW channel belt, continuing the trend observed from the Paleogene of a primary clastic input from the Dahomey Embayment (Figure 8a). Meandering channel belts are observed, with individual tortuous channels within these belts discernable. Clear associated levee systems are present and potentially some reworked sand waves in between the turbidite belts.

The younger Upper Miocene slices on the other hand show this combined E-W fairway, with input from the Niger Delta, and the N-S fairway, with input from onshore Benin (Figure 8b) as noted from the 2D and 3D thicknesses. These Miocene systems are unconfined, and eroding into the older NE-SW system. Not depicted in Figure 8, but additional attribute work shows that throughout the Upper Miocene the N-S fairway eventually dwindles whereas the Niger Delta input continues to increase leading to an even stronger E-W fairway system.

Imaging these channel belts allows for identification of reservoir sweet-spots and although untested in offshore Benin, these Cenozoic clastics have the potential to be viable, good quality reservoirs, with some of the Nigeria fields having up to 30% porosity, e.g. Bosi North and South Fields, Hatch Field. Additionally, the N-S Benin-sourced system results in potential reservoirs with a much shorter transport distance than the Nigeria fed turbidites.

Conclusions

From the Cretaceous through to the Miocene, sediment input progressively moves from a dominant northern source, to a northeastern source, to an eastern source. Transform faulting strongly influences fairway orientation throughout the majority of the Cretaceous. The northern input along with E-W oriented faults leads to a confined and mixed system with depocentres confined by the transform faults. The passive margin stage that follows results in an unconfined channelised system that is first fed from the Dahomey Embayment area to the north east and then more recently from the east as part of the Niger prodelta. Interestingly, a Benin-sourced input is still recognised in the Miocene, even if less dominant that the input coming from the Niger Delta. This leads to a north to south channel fairway with a shorter transport distance than the easterly sourced turbidites. The combination of regional 2D mapping along with more detailed observations and interpretations of the fairway type and distribution from 3D attributes allows for an improved understanding of Benin's depositional systems.

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