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The prospectivity of Offshore Sierra Leone Using Newly Acquired 3D data

1- Introduction

Based on a previous 2D seismic survey in offshore Sierra Leone and Liberia revealing the exploration potential of the margin, a 3D long offset survey in deepwater Sierra Leone was acquired in 2008.

Only two exploratory wells were drilled in offshore Sierra Leone in shallow water in 1982 (Mobil A-1) and 1985 (Amoco A1-2), but they still provide information of petroleum systems (rich source rock, reservoir quality sands, presence of seal). Additionally, significant field analogues exist in other basins of the Gulf of Guinea (e.g. Cote d'Ivoire, Ghana). Across the region, Aptian to early Cenomanian sequences contain rich, oil-prone to mixed oil and gas-prone Type II or III source rock. In the Sierra Leone basin, the late Cretaceous interval thickens to more than 2000m and most likely includes mature Cenomanian to Turonian source beds, established as Type II throughout offshore West Africa.

This study assesses the prospectivity of block SL-4 and SL-5 by interpreting approximately 2700 km² of 3D migrated data, tied to the existing regional 2D lines. This evaluation of the hydrocarbon potential of these blocks, the discovery of the Jubilee field in 2007 by Tullow in deepwater Ghana, the similar proven petroleum systems in offshore Cote d'Ivoire and the growing interest from major oil companies in offshore Sierra Leone and Liberia, suggest that this area offers significant exploration potential in one of the few remaining unexplored deepwater basins in West Africa.

2- Regional geology

The geology of the Sierra Leone basin is related to the opening of the Atlantic Ocean. It has a common history with the basins of the Gulf of Guinea. Offshore Sierra Leone shelf to basin system is bounded by the Guinea transform system to the north and the Monrovia transform system to the south.

The structural evolution of the Sierra Leone transform margin can be divided in three main phases:

- The first phase is dominated by pre-rift/pre-transform block faulting throughout the Jurassic with associated volcanics.
- The second is a syn-rift/syn-transform phase, with sediments of early Cretaceous age. The boundary is marked by unconformities on both sides of the Atlantic and occurs at top Aptian and top middle Albian. NNW-SSE oriented extensional faulting reached a maximum during the middle to late Albian. A WNW-ESE oriented shear regime is related to the dextral transform fracture zone and basement uplifting. This caused strike slip flower structures and inversion of downthrown blocks along decollement zones, principally in the inner shelf and middle slope in water depths less than 2500m. More conventional tilted fault blocks are present in the lower slope in water depths greater than 2500m.
- The final phase is the post-rift/post-transform phase of late Cenomanian to present day and represents the passive margin.

3- Regional stratigraphy and seismic interpretation

The two shelfal wells do not provide a complete stratigraphic column of the basin and do not tie to the new 3D survey (fig. 1). Sequences are missing because of wrenching, shelf uplift and sediment bypass on the inner shelf. However, the stratigraphy of the deepwater Sierra Leone can be described by analogy with the Cote d'Ivoire offshore basin where a geological model is available. A generalised geo-seismic section of the Sierra Leone margin is presented in figure 2. Figure 3 shows a seismic section from the new 3D survey.

Pre-rift/Pre-transform: Palaeozoic to Jurassic

Palaeozoic series are limited in the Sierra Leone/Liberia basin area and are mainly marine clastics of Cambrian to Devonian age.

Syn-rift/Syn-transform: Late Jurassic to Mid Cretaceous

The rift phase started in late Jurassic, coincident with tectonic subsidence and stretching of the continental crust. Extensional block faulting is associated with extrusive igneous activity and continental siliclastic deposition took place in grabens. During Aptian and Albian times, intracontinental siliclastic sedimentation occurred in fluvial to lacustrine environments along the regional transform faults in strongly subsiding

basins. In middle-late Albian time, shallow marine incursions flooded subsiding parts of the rifted terrain. An intra Aptian-Albian horizon and a late Albian unconformity have been interpreted. Cenomanian to Turonian sedimentation deposited diachronously over the unconformity. Uplift occurred at the continent-ocean boundary along the transform where the continental crust was thicker whilst thermal subsidence related to stretching cool down took place in the basin. Fluvial-deltaic, shoreline to shallow marine sedimentation became largely marine siliclastic in the basin, whilst erosion affected the uplifted continental inner shelf. This erosional event can be seen as the mid Cretaceous unconformity (MCU) in the shallow section, reaching the slope during Santonian.

Post-transform: Late Cretaceous to recent

As sea floor spreading and thermal subsidence continued, a late Cretaceous transgression progressed shoreward over the Santonian unconformity. Mass transport clastics, channel fed fans and turbidites were accommodated on the steep slope. Marine clastics and carbonates were deposited by a renewed transgression in the Palaeocene. Interrupted by a global sea level fall in the Oligocene, marine deposition resumed in the Miocene and continued throughout the Neogene.

4- Petroleum systems of offshore Sierra Leone

There are two important petroleum systems in offshore Sierra Leone:

- Aptian-Albian lacustrine Type II and III source rock feeding Albian and Cenomanian reservoirs
- Cenomanian-Turonian marine Type II source rock feeding Albian, Cenomanian, Santonian and late Cretaceous reservoirs

4.1- Reservoirs

Reservoir potential in SL-4 and SL-5 is primarily in the syn-transform structures and the late Cretaceous turbidite sand-prone channels and fans.

In the Gulf of Guinea, mid Albian clastics in syn-transform series can be severely eroded. In Sierra Leone, the erosion mainly occurred on the upper shelf. More fluvial to shallow marine sands have been preserved in the syn-transform structures located from the upper to middle slope. Therefore reservoir quality should improve toward the basin. Late Albian - Cenomanian shallow marine to marine sediments fill the accommodation space of the late syn-transform structures and were deposited after the peak faulting of mid Albian as aggraded and stacked sands as well as possible carbonates.

During the late Cretaceous the margin configuration was similar to present. Santonian and Maastrichtian channel and fan sands supplied by rivers flowing from north - northwest fed the subsiding margin and deposited as fans in the deepwater areas. Figure 4 illustrates Campanian-Maastrichtian channel and fan fairways identified in SL-4 and SL-5. Producing analogues for these systems are seen in Cote d'Ivoire and Ghana.

4.2-Traps

The principal syn-rift/syn-transform play type is Albian syn-transform anticlines oriented NW-SE in the upper to middle slope section of the margin. Four-way closures, downthrown fault closures and hanging walls in flower structures are examples of trapping geometries. An analogue of a four-way closure anticline is found in the Baobab Field in Cote d'Ivoire.

Late Albian/Cenomanian stratigraphic and structural (roll-over anticlines) traps occur in the transtensive-transpressive accommodation basins.

The post-transform trapping mechanisms are associated with syn-transform structures and early post-transform large submarine fan systems. They represent one of the most attractive petroleum prospects. One of them, Savanna, is a Santonian lowstand fan, deposited over the north-west syn-transform structures of SL-5 and east structures of SL-4. Traps may be structural, draped over the paleo highs and ponded fan sands between highs or stratigraphic with shoreward pinchout and updip seal (fig. 5). These are often combined with late transform faulting in the shallower section. Amplitude mapping combined with AVO response is essential to mature these from lead to prospect status. A possible analogue for Savanna is found with the Jubilee field in Ghana. Other late Cretaceous stratigraphic traps, shoreward pinchout and post transform anticline are associated with sealed deepwater channel and fan complexes easily visible on the new 3D dataset (fig.6). One stacked channel system, Lion, shows a good correlation between RMS amplitude and AVO response over an area of at least 40km². Analogues of Lion are found in the Kudu and Ibex Fields in Cote d'Ivoire. It is our understanding that Lion was targeted in September 2009 by Anadarko and partners within SL-6 which lead to the Venus-B1 discovery.

4.3- Seals

Lateral facies change and late faulting are the predominant lateral seals in the Sierra Leone offshore basin. Top seal is provided by interbedded early Cretaceous shales and up dipping late Cretaceous deepwater shales.

4.5- Source rock maturity, migration and timing

Basin modelling, using interpreted seismic, crustal heat generation, basin stretching history and thermal simulation appropriate for frontier offshore basins, has been conducted to determine the timing of oil expulsion and reservoir temperatures. Source rocks include terrestrial to shallow marine Type II/III in the early Cretaceous and richer deep marine Cenomanian and Turonian Type II (anoxic) source rocks.

Expulsion peaks are seen in the late Cretaceous/early Palaeogene and again in the late Tertiary due to increased burial. The work demonstrates the following

- Most identified reservoirs from Albian to Maastrichtian should have received a late charge which should not have been biodegraded.
- Shallower reservoirs, which were cooler during the early phase charging, may have experienced biodegradation, resulting in heavy oil and mixed phases of oil.
- Mid depth reservoirs should mostly contain light oil.
- Deepest reservoirs are most likely overpressured and gas prone.

5- Conclusion

The tectonic history of offshore Sierra Leone is related to the opening of the Atlantic Ocean and has a geological history and petroleum systems common to the other basins of the Gulf of Guinea. Key factors that determine the prospectivity in this area are:

- Occurrence of at least two important source rocks: the Albian lacustrine shale (Type II/III) and the regional Cenomanian-Turonian marine shale (Type II).
- The possibility of numerous reservoirs related to fluvial-deltaic and marine sands of mid to late Cretaceous age.
- Numerous play concepts including combination of syn-transform structural and stratigraphic trap, ponded fan sands, shoreward pinchouts and early post-transform anticlines along the north-west transform fracture zone and large sealed channel fed fan complexes.
- Migration pathways via fault plane conduits and permeable formations.
- Presence of side and top seals identified on 3D seismic.

On the basis of the seismic stratigraphy interpreted in SL-4 and SL-5 and by analogy with the Cote d'Ivoire basin and petroleum systems identified in the region, several significant leads have been identified in the syn-transform and early post-transform sequences. Late Cretaceous sand channels are evident from 3D seismic which, with further amplitude analysis, may develop into drillable prospects.

Most of the leads will receive and entrap oil expelled in late Cretaceous and late Tertiary, although there is a risk of biodegradation for the shallowest reservoirs. The quality of reservoirs remains a significant uncertainty in the area as currently it can only be assessed by analogy with distant oil and gas fields.

In summary, this interpretation of 3D data suggests that deepwater offshore Sierra Leone offers excellent exploration potential.

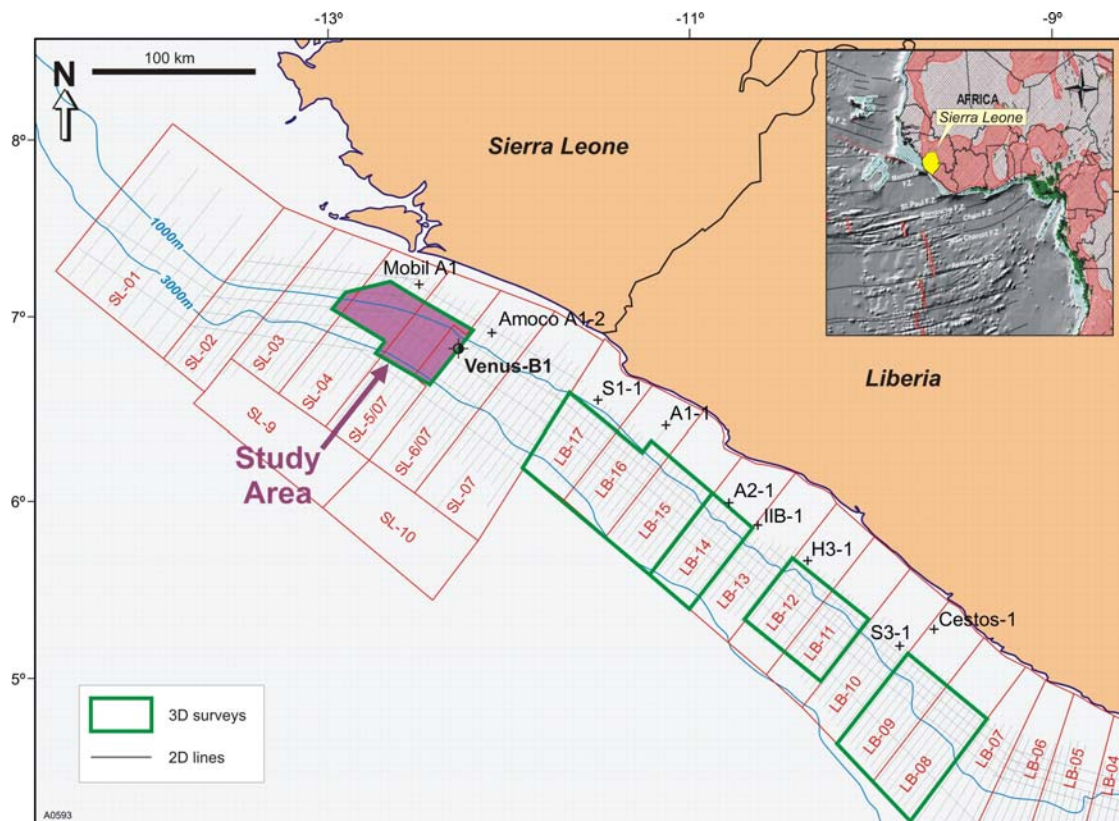


Figure 1: Basemap of current blocks offshore Sierra Leone and Liberia, locating well data and TGS seismic data.

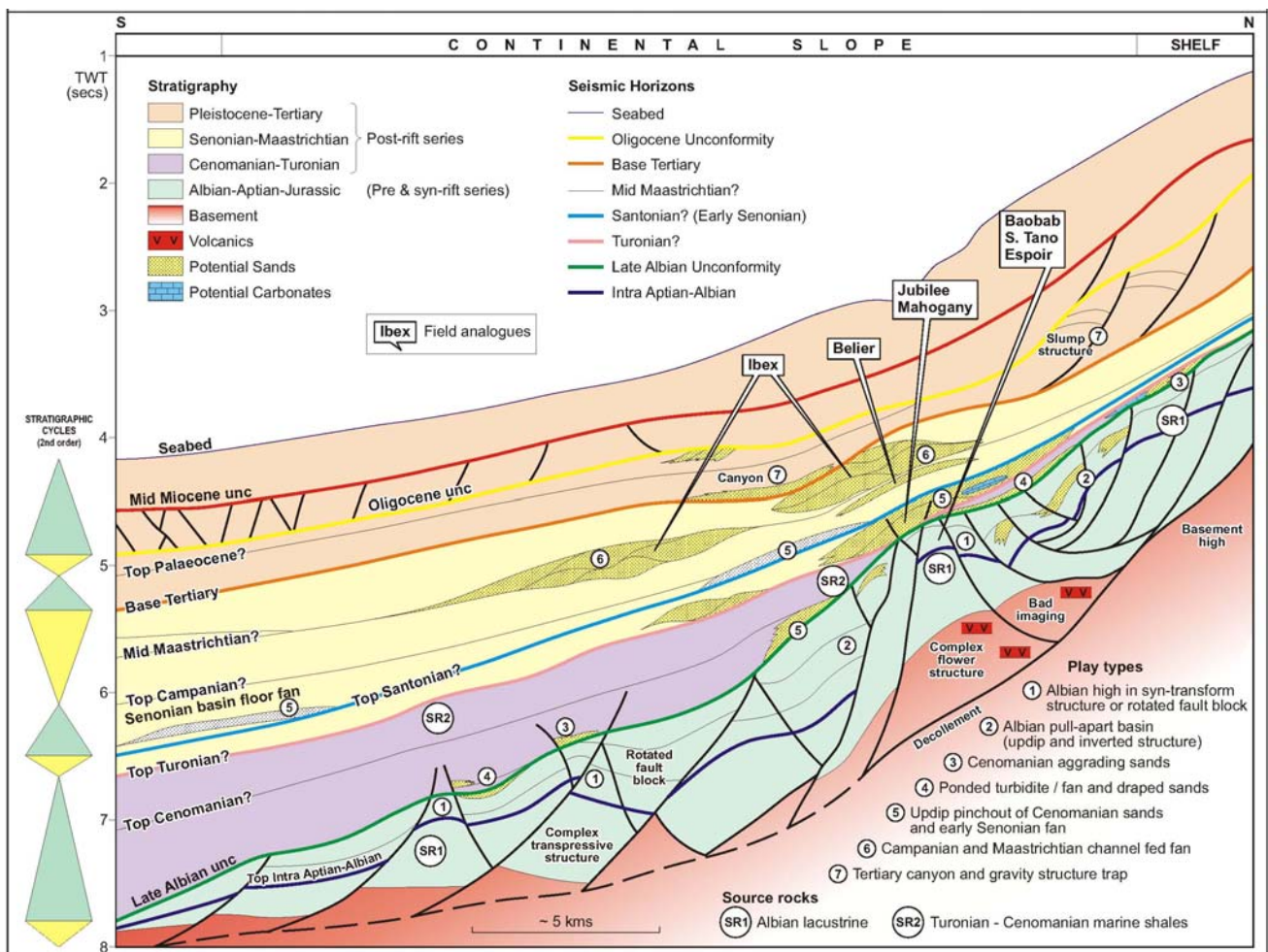


Figure 2: Generalised geo-seismic section of offshore Sierra Leone margin (Age dating by analogy with the Cote d'Ivoire offshore basin).

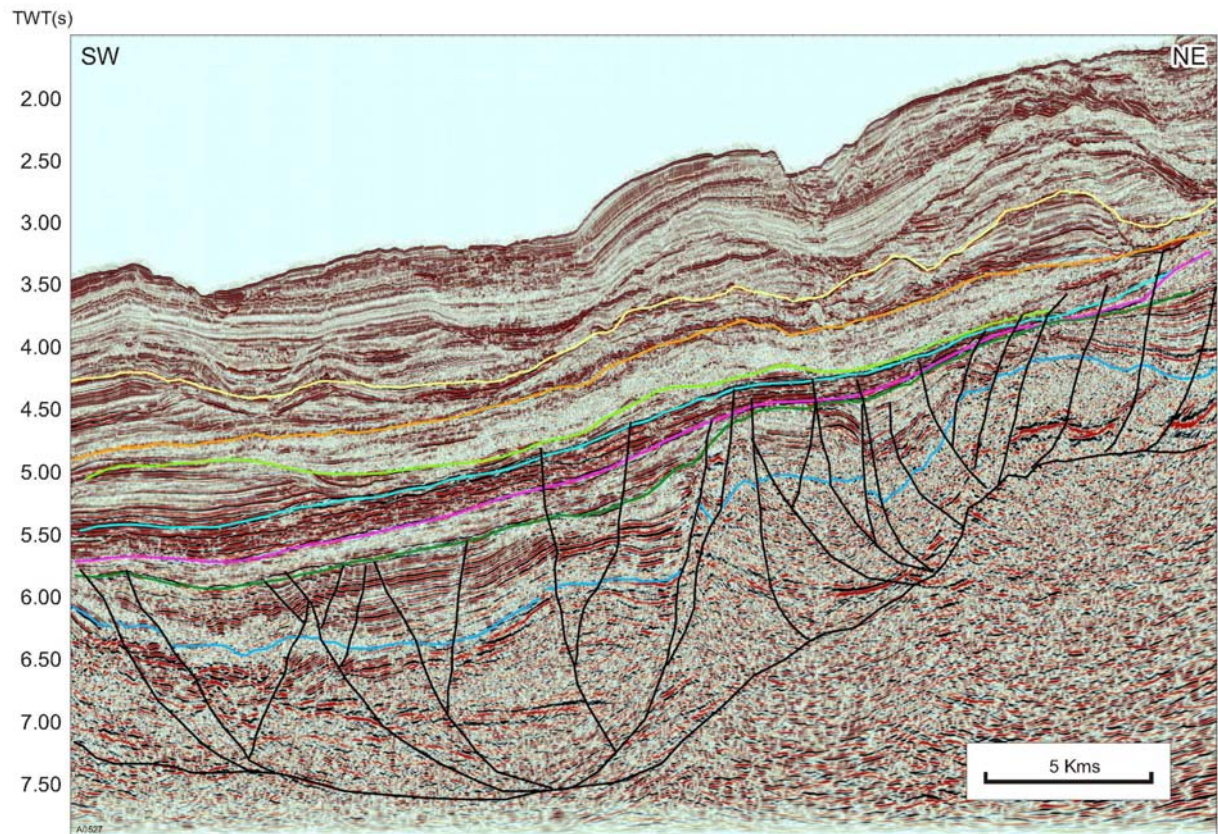


Figure 3: Example of arbitrary seismic line (full stack) across SL-5 block, showing interpreted horizons (see fig. 2 for horizon names).

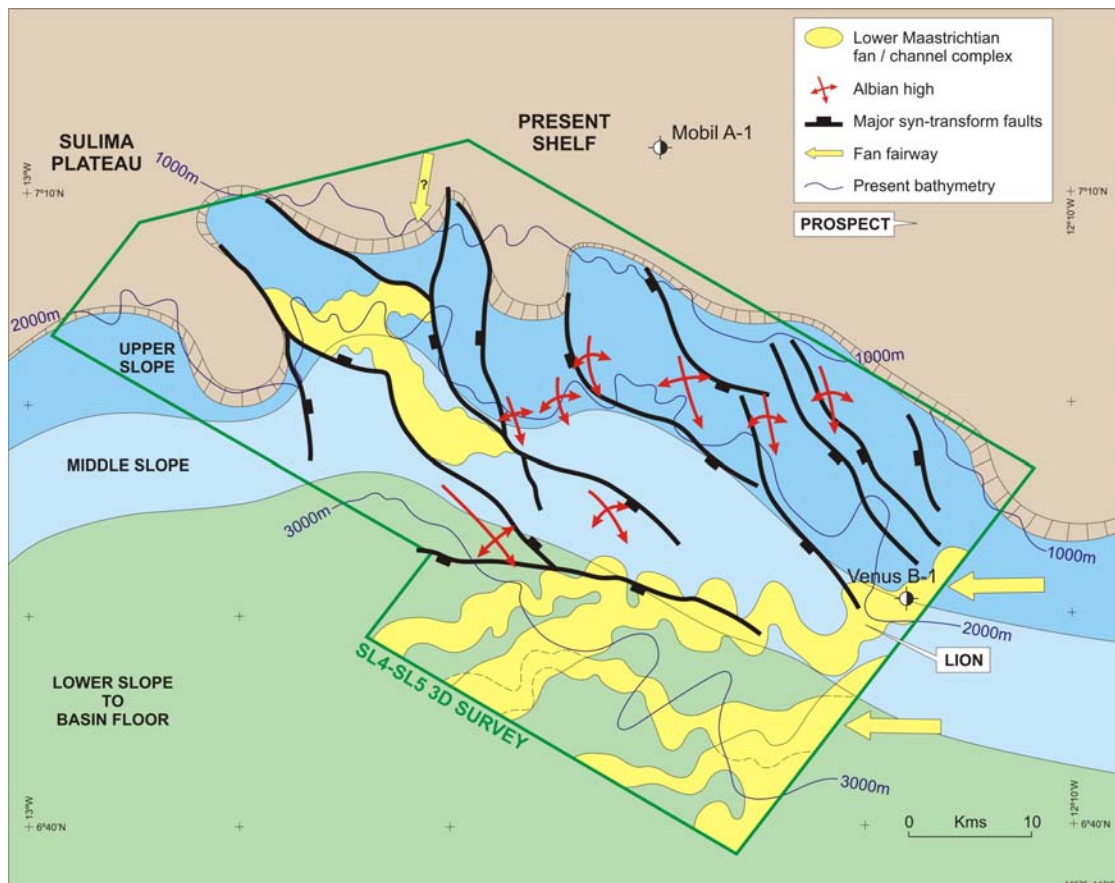


Figure 4: Schematic map showing syn-transform structures and Campanian depositional systems interpreted in SL-4 and SL-5.

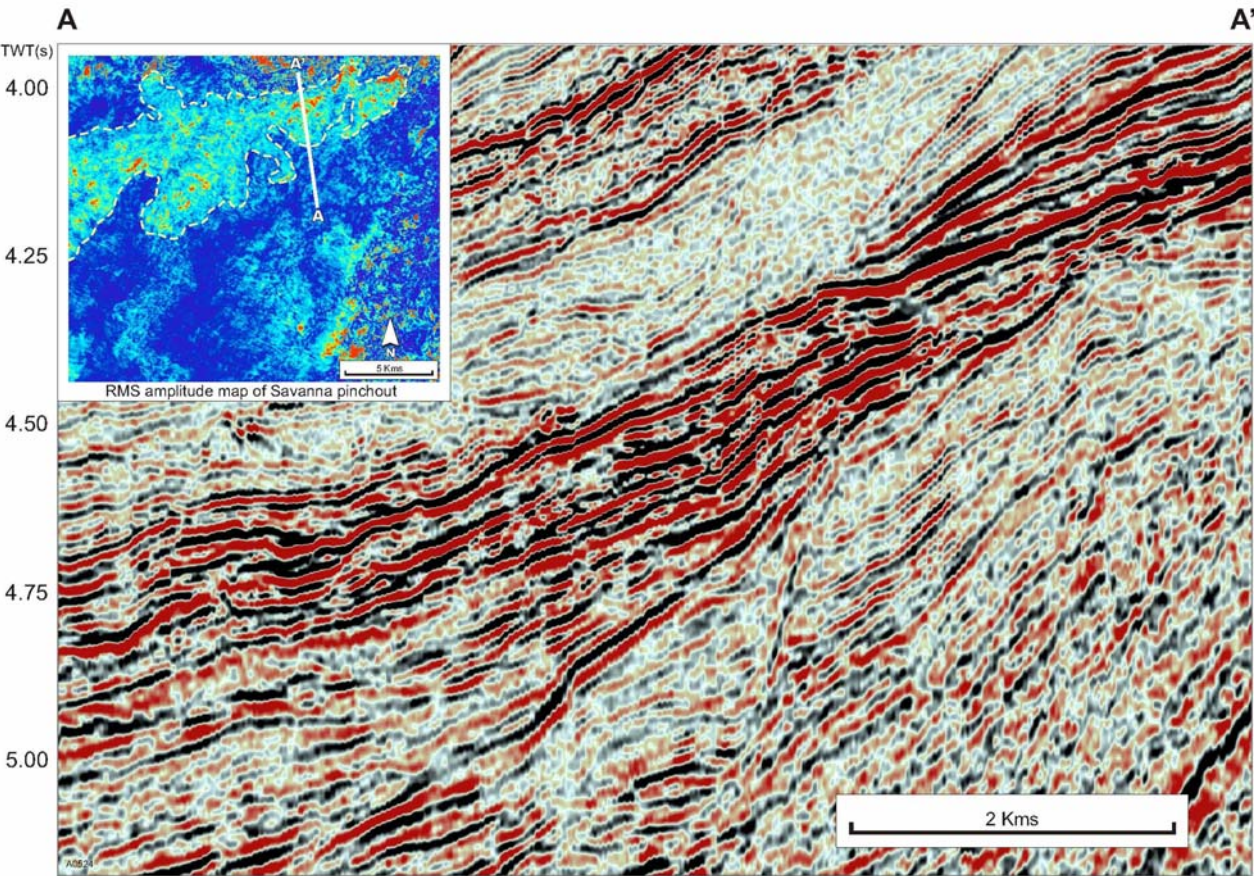


Figure 5: Pinchout trap of Savanna fan.

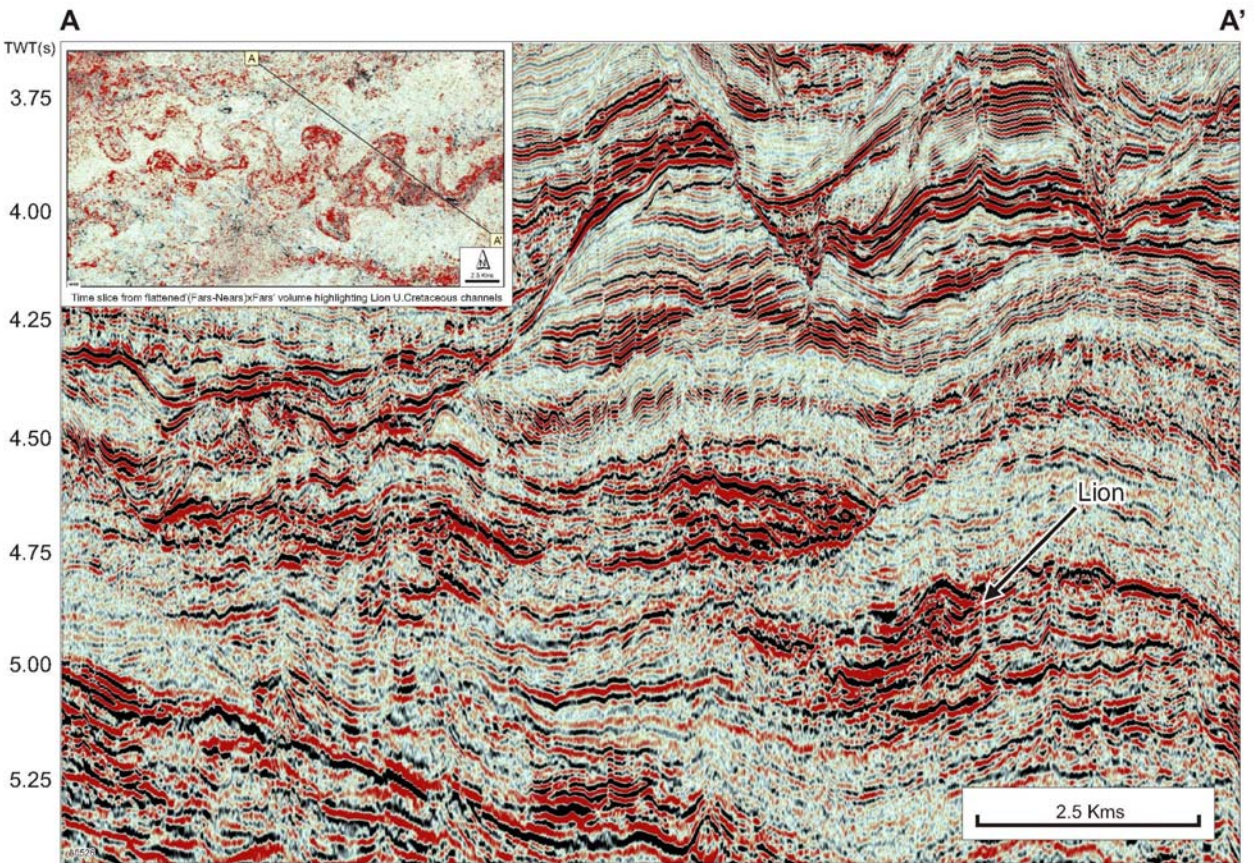


Figure 6: Arbitrary seismic line (full stack) showing sealed Upper Cretaceous channels with updip and post transform traps.