New insights into prospectivity of Liberia-Sierra Leone Basin because of improvements in seismic acquisition and processing

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This paper examines how the understanding of the prospectivity of the Liberia-Sierra Leone Basin has developed over the last 40 years largely due to improvements in seismic data over this period. A series of basins developed between major transform fault zones associated with the opening of the South Atlantic Ocean from the early Cretaceous onward. The Liberia-Sierra Leone Basin forms part of the West African Transform Margin that extends from Sierra Leone to Benin. Early hydrocarbon exploration (1972–1985) was targeted at shelfal structural synrift traps of Lower Cretaceous age. None of the wells drilled in this period was regarded as a discovery. In 2001, a new regional 2D seismic survey allowed a new play, deepwater Upper Cretaceous channel fans, to be identified. More recent 3D seismic using the latest data acquisition and processing technologies, including AVO, has enabled drillable prospects to be identified. Wells drilled in 2009–2010 offshore Sierra Leone have established that a working hydrocarbon system exists in this basin.

Introduction

The Liberia-Sierra Leone Basin (LSLB) forms part of the West African Transform Margin that extends from Sierra Leone to Benin. A map showing the location of the basin and the positions of seismic data used in this paper is presented as Figure 1.

Hydrocarbon exploration has been active in this area since the 1970s when offshore seismic was acquired and shelfal wells were drilled. Early exploration was concentrated on the Albian-Aptian structural traps in wells drilled in shallow water above the continental shelf. Seismic data from the 1970s were 2D with short cables (less than 3000 m) and were processed through a relatively unsophisticated sequence that sometimes included poststack time migration. These early data were adequate to define structural traps in shallow water. However, despite oil shows, good quality sandstones and potential source rock, the shelfal wells did not encounter commercial quantities of oil.

There was a hiatus in prospecting activity from 1985 through to 2000 due to various factors including loss of confidence in shelfal plays, lack of technology to image or develop deepwater plays, and political instability. A new regional 2D survey in 2001 allowed identification of channel-fan plays along the continental slope and basin floor in water depths from 1500 m to 3000 m.

After licensing rounds in Liberia and Sierra Leone in 2002–2004, a number of oil companies commissioned 3D seismic surveys over the deepwater plays (1000–3000 m water depth) to better delineate the Upper Cretaceous fan systems and allow prospect generation. More recently, the additional imaging power of prestack depth migration (PSDM) has produced better signal-to-noise ratios (SNR) and coherency within the sand bodies as well as better fault delineation.

The Venus-B1 well (2009) in Block SL-6 and Mercury-1 (2010) in Block SL-7 were hydrocarbon discoveries in basin slope fans with stratigraphic trapping that could not have been mapped in sufficient detail to drill with earlier data vintages.

This paper uses examples data of different vintages from Liberia blocks 13 and 14 to illustrate the improvements in seismic acquisition and processing technology from the 1970s until 2010. These advances have allowed a new play to be identified and proven by drilling in a region previously considered largely nonprospective.

Geological background

A series of basins developed along the West Africa Transform Margin between major transform fault zones associated with the opening of the South Atlantic Ocean from the early Cretaceous onward. The location of the Liberia-Sierra Leone Basin (LSLB) is shown on Figure 1 with the positions of the main transform fault zones (Sierra Leone and St. Paul) that are regarded as forming the boundaries of the basin.

A generalized stratigraphic chart for the sedimentary section (Figure 2) indicates that the synrift/syntransform stage was active from Aptian to Turonian. The Aptian to mid-Albian was the active rifting stage with fluvial/lacustrine conditions generally trending to shallow marine with the final breakup of Gondwanaland. From the mid-Albian unconformity to top Turonian, the seismic data indicate continuing transform movement in deepwater (at times anoxic) conditions. A significant unconformity occurs around the Santonian-Campanian with a passive margin stage from Late Campanian to Recent. Another major unconformity is seen in the Oligocene and has caused up to 1 km of erosion on the slope in places. The Miocene-to-Recent interval tends to be characterized by slumps and canyons created in a deepwater environment.

Shelfal wells indicated that source rock is present in the Aptian-Albian interval (lacustrine-shallow marine) and the Deep Sea Drilling Project wells (DSDP 367/368) along the West African margin show a high-quality source rock in the anoxic marine shales of Cenomanian-Turonian age.

Exploration history (1970–1985)

Nine wells were drilled between 1970 and 1985 in shelfal locations in the LSLB. These wells were drilled on fault-bounded structural traps that could be identified on seismic data of that vintage. The shelfal wells all contained thin condensed Upper Cretaceous sections and a thick Albian sequence.

An example seismic section, line OA103, is shown in Figure 3. This 2D line was recorded in water depths of 300–

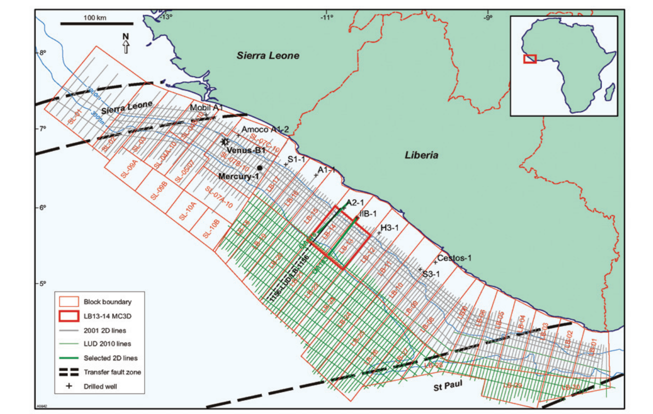

Figure 1. Location map of Liberia-Sierra Leone Basin.

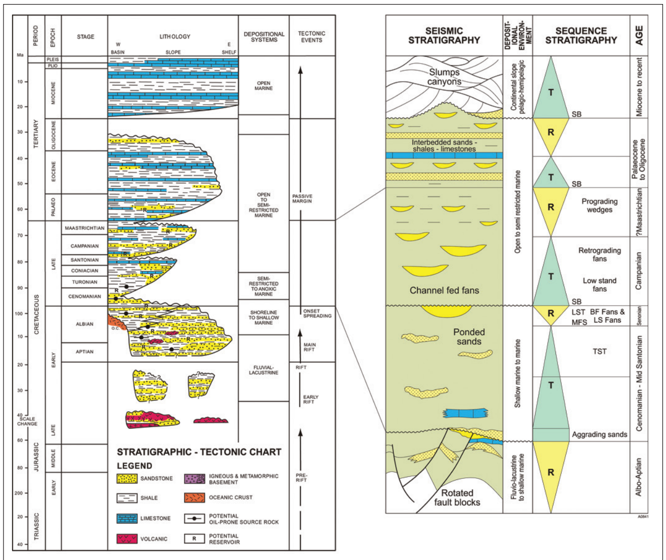

Figure 2. Generalized stratigraphic chart of Liberia-Sierra Leone Basin.

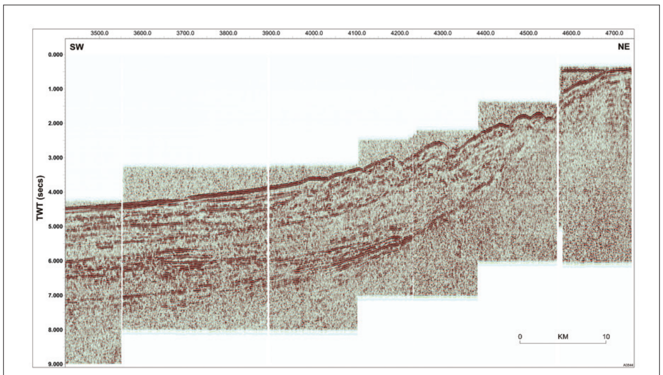

Figure 3. Line OA103, acquired 1976, with poststack time migration.

3700 m and has passed through a poststack time migration. The line was recorded in 1976 using a Flexichoc source with a cable length of 2400 m and a maximum record length of 9000 ms. The data were processed to poststack time migration and included prestack deconvolution, NMO correction, and stack. The data quality of this line is relatively poor and the area below the upper slope has little continuity, probably due to nonoptimum migration. There are data gaps along the line, and no coherent reflections can be seen below 7300 ms. However, it should be noted that this line is one of the earliest data vintages to show the thick Upper Cretaceous section in deep water and to give some early indications of the presence of possible sand channel systems.

Line OA318 (Figure 4) was recorded in 1980 in a dip direction in water depths from 150 m to 2950 m. The line was recorded using a Flexichoc source with a maximum receiver offset of 2750 m, 50-m shot and receiver intervals, and a maximum record length of 8700 ms. The final section was a filtered poststack time migration with a simple NMO correction prior to a 24-fold stack. Prestack and poststack predictive deconvolution were used to attenuate multiples.

As can be seen in Figure 4, the data quality is quite good and allows fault blocks to be interpreted under the shelf, but continuous reflections cannot be identified below 7300 ms. The cable is not long enough for AVO studies in the deepwater Upper Cretaceous sands, and the image under the shelf appears to contain some multiple reflections.

None of the shelfal wells were hydrocarbon discoveries although eight of them had hydrocarbon shows and the majority contained significant thicknesses of sandstones in the Albian interval. There are various explanations for this lack of success but failure of seal is considered the most likely.

No further wells were drilled in this basin between 1986 and 2008. The lack of activity over this period was partly due to political instability but the lack of success of the shelfal wells, the perceived difficulties and costs of deep-water drilling, and the lack of seismic data adequate to identify and properly map deepwater stratigraphic plays were also significant factors.

Exploration history (2000–2003)

A regional 2D survey across the complete LSLB was recorded in 2001 (as shown on Figure 1). The data were acquired in water depths from 200 m to 3000 m. Line spacing was 5 km in the dip direction (northeast-southwest) and variable from 6 km to 15 km in the strike direction. In total, 15,000 line-km of seismic data were acquired. The acquisition parameters for this survey were a shooting direction along dip or strike as applicable, with an air-gun cluster source of 3680 in^3, a shot-point interval of 37.5 m, a receiver interval of 25 m, a streamer length of 7200 m, and a record length of 10,000 ms. The data were processed through Kirchhoff prestack time migration (PSTM) with the prestack processing sequence, including Radon demultiple to remove seabed multiples and a 32-ms gap predictive deconvolution.

Long offsets allowed AVO studies to be made on gathers that were flattened with residual NMO and vertical transverse isotropic (VTI) eta corrections prior to the creation of angle stacks. Analysis of gathers has shown that offsets of greater than 5000 m are required to record reflection angles above 45° from basin floor fans in the deep water.

This survey was the first data set that covered the complete LSLB from Sierra Leone in the north to the Harper Basin in the south. The data allowed identification of large-scale Upper Cretaceous sand-prone channel systems in the deep water that could form stratigraphic traps throughout the LSLB. Additionally, the long cable enabled AVO studies of the gathers and angle stacks.

An example PSTM profile, line LB-1156, from the regional survey is shown in Figure 5. This profile was shot in Liberia Block 14, very close to the track of Line OA103 (shown in Figure 3). Coherent reflections down to 8500 ms can be seen on this section, and the deepest reflections are interpreted as true basement. Sand channels can be interpreted in the deepwater Paleocene-to-Upper Cretaceous interval between 5500 ms and 7500 ms, and the high-amplitude reflections between 8000 ms and 9000 ms are interpreted as true basement.

The regional 2D seismic data were available for the Sierra Leone licensing round in 2002 and Liberia's licensing round in 2004. Hydrocarbon exploration in this area was given new impetus in 2006 when the Mahogany-1 well was drilled offshore Ghana into a slope fan of assumed Turonian age with current estimated recoverable reserves of more than 600 million barrels with an upside potential of 1.8 billion barrels.

Exploration history (2004–2010)

A condition of the Sierra Leone and Liberia hydrocarbon exploration license rounds was that oil companies would acquire 3D seismic data across their licensed blocks. From 2004 onward, a series of 3D seismic surveys was recorded in Sierra Leone and Liberia deep water.

These surveys were targeted at the deepwater Upper Cretaceous play in water depths of 1000 m to 3000 m. The first 3D seismic data, acquired in Sierra Leone blocks 6 and 7, identified extensive slope channel and fan systems that were later drilled as Venus-B1 in 2009 and Mercury-1 in 2010. Both wells discovered hydrocarbons in the Upper Cretaceous channel systems.

Offshore Liberia 3D seismic surveys were conducted from 2008 onward. In blocks 13 and 14, a seismic survey was recorded in 2010 with sail lines in the dip direction (northeast-southwest). This survey was recorded with the following parameters: (1) a clustered air-gun array source of 4280 in^3; (2) a shot-point interval of 62.5 m per subsurface line; (3) a streamer length of 7200 m with 6 streamers, with 576 channels per streamer, for 3456 per shot; (4) a receiver interval of 12.5 m; and (5) a record length of 13,000 ms. The source, cable, and record lengths were designed to provide good imaging down to below the basement level and to allow AVO studies to be performed with confidence.

These data were processed through a prestack time migration (PSTM) sequence that included debubble and zero-phase conversion, true-azimuth multiple elimination, high-resolution Radon demultiple, Kirchhoff prestack curved-ray velocity analysis, and time migration. Data were output 12.5 × 25 m at 27 fold.

A 3D inline PSTM profile almost coincident with the LB-1156 2D line is shown in Figure 6. The main features to note on this line are the imaging of the Moho reflection below the basinal part of the survey around 10,000 ms, imaging of the synrift (Aptian-Albian) interval (8000–9000 ms) and clear identification of sand channels in the Upper Cretaceous and Eocene-Paleocene interval (5500–8000 ms).

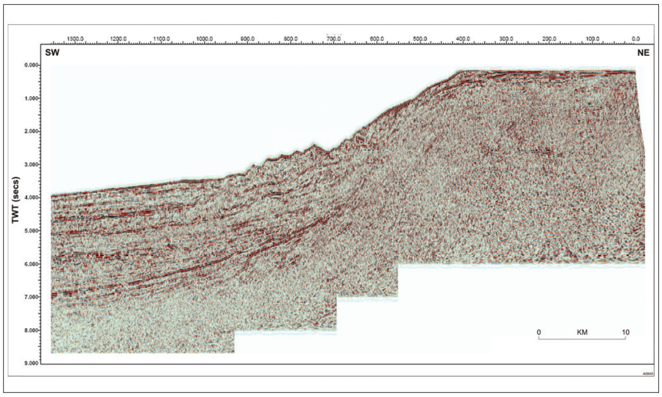

Figure 4. Line OA318, acquired 1980, with poststack time migration.

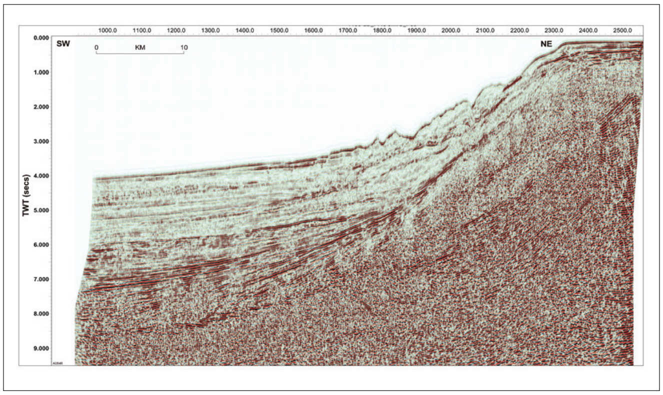

Figure 5. Line 1156, acquired 2001, with prestack time migration.

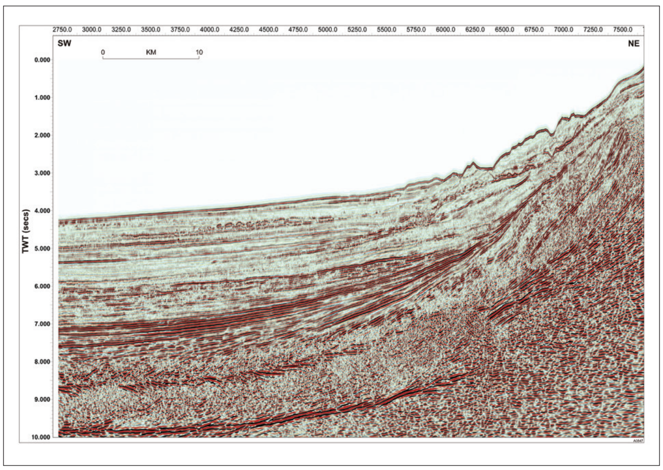

Figure 6. Inline 1498, acquired 2010, with 3D prestack time migration.

The 3D data have allowed identification of individual sand bodies along the slope and basin but there are still some shortcomings in the PSTM data:

1) The images show structure but do not give clear indication of fluid fill.
2) The data are in two-way time and depth-converted afterward.
3) The imaging, although better than earlier vintages, still has some problems particularly in those areas where the slope has suffered deep erosion due to the formation of canyons in the Tertiary.

Hence, the 3D data were also used to measure the AVO responses by analysis of gathers and creation of angle stacks (nears, mids and fars) and a fluid stack formed by a fars-weighted pseudo-gradient volume calculated using this formula: (fars-nears) × fars.

An example of part of a fluid stack compared to a full stack volume is shown in Figure 7. This example comes from an inline profile in Liberia Block 13. On data from a previous processing project, some of the Upper Cretaceous channel systems clearly display a class II or III AVO effect.

The data were also passed through a prestack depth migration (PSDM) to improve the overall quality and get a good depth-domain image of the area to allow a better understanding of the detailed structure within the Upper Cretaceous interval.

The PSDM processing sequence included a three-pass anisotropic tomographic velocity analysis at 100 × 100 × 50 m (x,y, and z, respectively) and Kirchhoff PSDM with a 6000-m aperture and 90° maximum dip. Data were output on a 25 × 25 m grid with 5-m depth samples down to 12,000 m.

The PSDM volume has provided better continuity and imaging below the erosional zones and generally in the deeper synrift interval and basement. This is shown in Figure 8 (along the same profile shown in Figure 6).

The additional imaging power of the PSDM has produced better SNR and coherency within the sand bodies as well as better fault delineation. This is particularly evident in those areas in the mid-upper slope that have been affected by massive erosion in the Oligocene-Miocene and in areas that show dimming, probably associated with fluid conduits.

The combination of good depth imaging and AVO allows better identification and delineation of leads and prospects. It is also important in ranking and risking prospects to provide more confidence in selection of well locations.

A geoseismic section across the Liberia Basin based on the results from the 2010 3D data is shown in Figure 9. A series of prospective sand channel and fan systems have been identified from the Santonian up to the Paleocene in the deepwater part of the basin.

Ultradeep seismic (2010)

In 2010, a regional ultradeep seismic survey was recorded in water depths of 3000–4500 m. This survey reveals possible hydrocarbon potential even further offshore and gives an indication of the distribution of source rock. Additionally, it provides data capable of imaging down to the Moho and

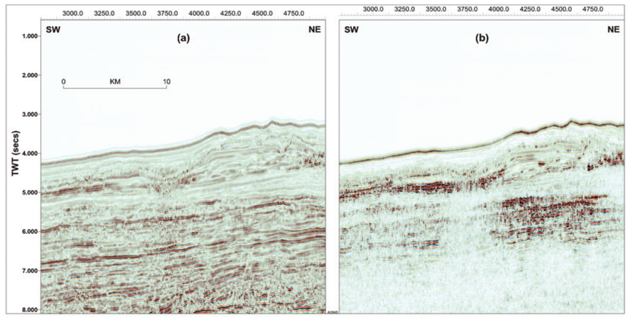

Figure 7. (a) Detail from inline 2930, from 2010 3D prestack time migration volume. (b) Detail from inline 2930, from 2010 3D fluid stack volume.

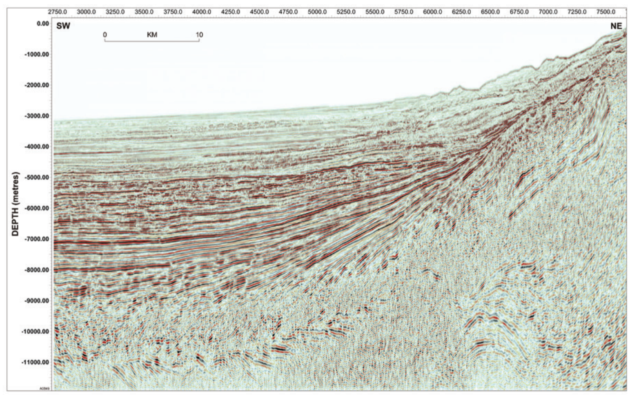

Figure 8. Inline 1498 acquired 2010, with 3D prestack depth migration.

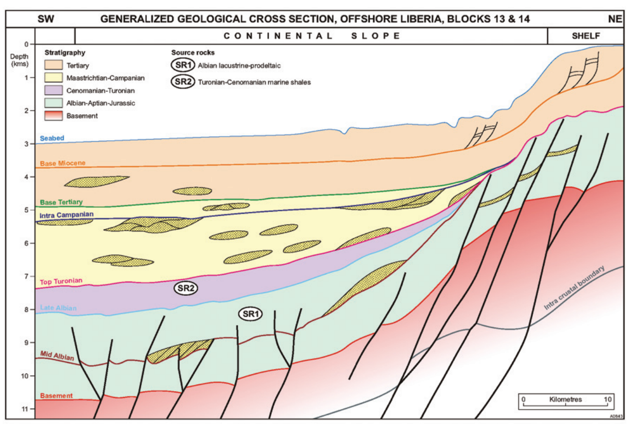

Figure 9. Generalized geoseismic section of Liberia Basin blocks 13 and 14.

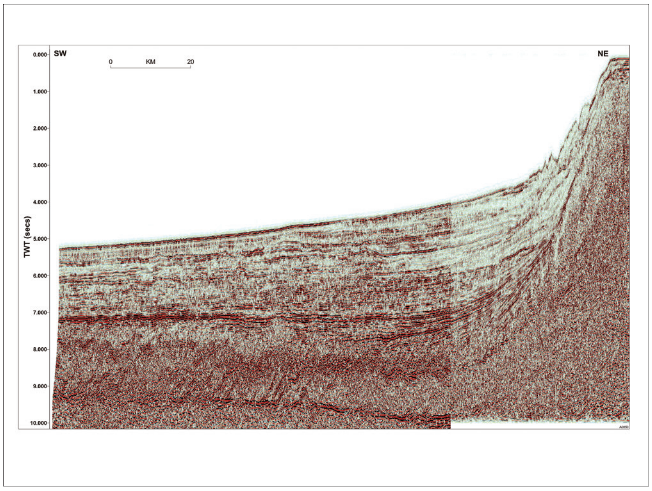

Figure 10. *Merged profile of lines LB-1156 and 1156-LUD with prestack time migration.*

showing the continental-oceanic boundary, as well as giving an insight into the development of the basin system from the early rift stages.

An example line, 1156-LUD, is shown in Figure 10. It has been merged with line LB-1156 from the 2000–2001 regional survey to demonstrate that it is possible to continue seismic interpretation from the shelf to the deep basin over a distance of approximately 200 km.

The ultradeep data show the extension of the channel systems into the ultradeep water and also show the possible boundary between the continental and ocean crusts. In general, the ultradeep data give significant further insight into the structural controls in the LSLB and show the distribution of a thick Turonian source interval extending into the ultradeep water.

Discussion

Seismic data acquisition and processing have progressed over the 40 years that hydrocarbon exploration has been active in the LSLB. Imaging of the subsurface geology by seismic data has been improved by a combination of better acquisition and better processing. Both improvements are driven by technological advances which improve efficiency in turn driving down cost.

On the acquisition side, advances in towing and steering streamers have made 3D acquisition possible in a timely and cost-effective manner. The ability to tow several streamers and sources has cut the time to acquire 3D seismic down by an order of magnitude from the early days. The ability to steer this multitude of streamers has also made the acquisition of tighter crossline bins possible.

On the processing side, the exponential increases in computer power have enabled the use of complex imaging algorithms. In a relatively short span of time, computer power has allowed the imaging to go from poststack time migration to prestack time migration, poststack depth migration, and prestack depth migration. The increased computer power has also made possible more complex pre-migration processing. The industry has moved from simple predictive deconvolution for multiple attenuation to Radon, surface-related multiple elimination (SRME) and true-azimuth SRME.

In both the 1976 and 1980 data sets (Figures 4 and 5), relatively short streamers were towed. This does not allow very high fold so that SNR improvements are less than they are with modern, longer cables. Furthermore, these short offsets severely limit the velocity resolution at larger depths. At that time, the only affordable algorithms for demuliple were predictive (or spiking) deconvolution methods. The only option for migration was poststack time migration. This has

Vintage	Source	Streamer Length (m)	Group Interval (m)	Shot Interval (m)	Record Length	Fold	Xline Spacing
1976	Flexichoc	2400	50	50	maximum 9 s/4 ms	24	n/a
1980	Flexichoc	2750	50	50	maximum 8.7 s/4 ms	24	n/a
2001	Air gun, 3680 in^3	7200	25	37.5	10 s/2 ms	96	n/a
2010	Air gun, 4280/4320 in^3	7200/8100	12.5	62.5/per source	13 s/2 ms	57/64	25 m

Table 1. *Comparison of acquisition parameters from different surveys.*

Vintage	Demultiple Processes	Velocity Moveout Correction	Migration Type
1976	Prestack predictive deconvolution	Velocity analyses at 2000-m intervals	Wave equation poststack time migration
1980	Pre- and poststack predictive deconvolution	Velocity analyses at 2000-m intervals	Wave equation poststack time migration
2001	Radon and predictive deconvolution	Velocity analyses at 2000-m intervals plus RMO	Kirchhoff prestack time and depth migration
2010	Debubble, Radon, and true azimuth SRME	Velocity analyses at 500-m intervals plus 100 × 100 × 50 m tomography	Kirchhoff 3D prestack time and depth migration

Table 2. *Comparison of processing techniques for different data vintages.*

produced data that can be interpreted down to just below 7000 ms but do not provide sufficient detail for mapping the true extent of channels in the deep water.

The 2001 2D regional data were shot at an adequate grid to identify and map deepwater channel systems throughout the basin. This allowed successful hydrocarbon licensing rounds to be held and then identification of those areas of the licensed blocks that required 3D seismic data to delineate drillable prospects.

The improvements in seismic acquisition and processing for data acquired in the LSLB are summarized in Tables 1 and 2.

Conclusions

The steady advance of seismic acquisition and processing technology has allowed the definition of a new regional play in the LSLB: the Upper Cretaceous channel and fan systems. The presence of a working hydrocarbon system has since been proven in the Sierra Leone part of the basin by drilling the Venus-B1 and Mercury-1 wells.

The major factors that have led to this improvement in prospect definition are:

- Seismic acquisition advances (larger sources, longer cables, 3D technology)
- Seismic processing advances (AVO, 3D PSTM and PSDM with anisotropic eta corrections, improvements in demultiple techniques such as Radon and true-azimuth SRME)

It is anticipated, that in the future, hydrocarbon exploration in this basin may move to the ultradeep water but the next major step in improvement in the geological interpretation of this area is anticipated as soon as well data from the deepwater area become generally available. We expect to see better understanding of the rock properties, allowing seismic inversion to provide a more confident identification of fluid fill and reservoir quality. TLE

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