Improved imaging of complex salt structures in Gabon from integration of seismic and airborne gravity gradiometry

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Summary

The Mutamba Iroru Permit, operated by VAALCO Production (Gabon), Inc., since 2005, is located within the onshore portion of the South Gabon Sub-Basin, which contains some of the largest hydrocarbon accumulations within West Africa. The 30-50m thick Cretaceous Aptian-aged transgressive sandstones of the Gamba Formation form the main producing reservoir in the block. The primary hydrocarbon traps for Gamba sands in the block are four-way structural closures formed over tilted pre-Gamba fault blocks, sealed by the overlying Ezanga salt formation. Seismic imaging is very difficult below the often strongly deformed Ezanga salt formation, and is also problematic when attempting to define the flanks of the salt structures. It was recognized that Airborne Gravity Gradiometry (AGG) could assist the seismic interpretation by providing more accurate mapping of the flanks of the salt structures and help identify other sub-salt structural features. From November 2007 to February 2008 Fugro Airborne Surveys flew a 6,250 line-km FALCON AGG survey over the Mutamba Iroru Permit in a Cessna 208B Grand Caravan over 24 production flights. An integrated interpretation of the FALCON AGG data helped to delineate the outline, geometry and relative thickness of the low density Ezanga salt and near-surface cuvette features, and thus highlighted the sub-areas where seismic imaging is severely challenged. Once these geometries were better delineated, seismic imaging subsequently improved.

Introduction & Regional Geology

The 1,094 km^2 Mutamba Iroru Permit is located within the onshore portion of the South Gabon Sub-Basin (Figure 1), which evolved as a result of Cretaceous rifting and subsequent drifting of the continents of Africa and South America, and which now contains some of the largest hydrocarbon accumulations within West Africa (Teisserenc and Villemin (1989).

The development of the South Gabon Sub-Basin is characterized by several early Cretaceous episodes of continental rifting and infilling of lacustrine basins resulting in thick deposits of mud and organic material. These became the Kissenda and Melania formations, the primary source rocks in the Mutamba Iroru Permit. This was followed by an influx of turbiditic sediments of the Melania and Lucina formations and the fluvial-deltaic sediments of the Crabe and Dentale formations.

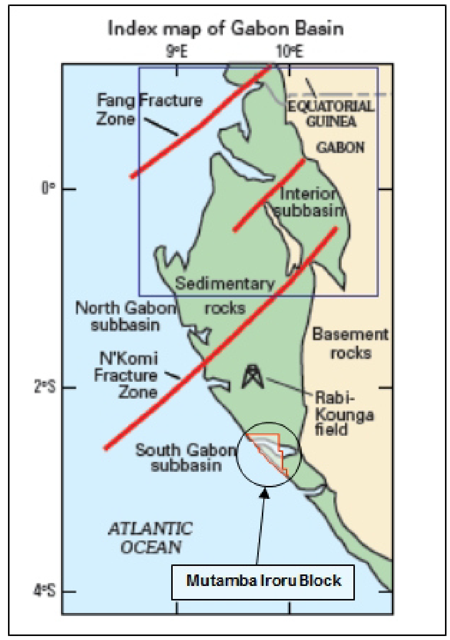

Figure 1: Geology map of the Gabon Basin with the Mutamba Iroru Block (after Brownfield and Charpentier, 2006)

As rift faulting subsided the area underwent peneplanation and was blanketed with the Cretaceous Aptian-aged marine transgressive sandstones of the Gamba Formation, which are now the main producing reservoir in the Mutamba Iroru Permit. The thickness of the Gamba sandstone within Mutamba Iroru is generally 30-50 meters.

Following the deposition of the Gamba sandstones, marine circulation became restricted and several hundred meters of Aptian aged Ezanga salts were deposited over most of the West Africa basins. The Ezanga evaporites form a regional seal separating pre-salt and post-salt hydrocarbon migration routes.

As rifting ceased, the continents split and continued to drift apart. The re-establishment of open marine conditions marked a major change in the basin development. A thick, wide carbonate platform, the Madiela Formation, developed upon near-shore portions of the basin.

Sediments derived from the adjacent continental highlands began to fill the basin from the east. This increasing sediment load initiated the deformation of the underlying salt sequence, triggering the development of gravity-slide "raft" blocks, growth-faults, and salt structures, such as pillows, diapirs, and salt walls. This movement increased as the Atlantic basin deepened and tilted further towards the west.

As sedimentation loading forced the organic Melania source rocks deeper, hydrocarbons were matured and expelled into the overlying Lucina, Dentale and Gamba sandstones and sealed in places by the overlying strongly deformed evaporites of the Ezanga salt formation.

Exploration History

The area has undergone substantial exploration since the mid-1960's resulting in the discovery of several notable fields in the block. The primary traps for Gamba sands in the Mutamba Iroru Permit are four-way structural closures formed over tilted Dentale fault blocks. A series of commercial hydrocarbon accumulations have been discovered along an up-thrown horst block on the western margin of the Permit. The largest of these is the Gamba-Ivinga Field with combined reserves of 350 MMBO within the Gamba sandstone.

VAALCO Production (Gabon), Inc. has been the operator of the block since 2005. Outside of the Gamba-Ivinga and Bende exploitation areas, there are only 14 exploration wells in the block (including three drilled by VAALCO). Several vintages of 2D seismic cover the block with approximately a 2x2 kilometer grid. However, below the strongly deformed Ezanga salt formation the seismic imaging is very difficult, and also causes problems when attempting to define the flanks of the salt structures (Jacques et al., 2003).

Airborne gravity gradiometry (AGG) model studies showed that the thickness of the Ezanga salt, coupled with the density contrast between the evaporites and the pre- and post-salt sediments, would cause local gravity gradient anomalies of sufficient amplitude to be observed from low-flying aircraft. It was recognized that AGG could assist the seismic interpretation by enabling more accurate mapping of the flanks of the salt structures and possibly provide a better velocity model to the top of the sub-salt formations.

In 2007 airborne gravity (AG) and magnetic data was licensed from Carson Aerogravity to provide a regional tie for any AGG data acquired. Public domain data sets (satellite-derived gravity, shuttle radar topography, and magnetic anomaly data) were also acquired to provide a regional understanding.

Airborne gravity gradiometry survey acquisition, processing, and results

Also in 2007, VAALCO Energy commissioned BHP Billiton to fly a FALCON AGG survey over the Mutamba Iroru Permit in order to map the Ezanga salt structures and the depth to the top of the pre-salt formations.

BHP Minerals (now BHP Billiton) had developed the FALCON AGG system in the 1990's in conjunction with Lockheed Martin (van Leeuwen, 2000). Lee (2001) summarizes the key features of the AGG instrumentation.

FALCON AGG was the first airborne gravity gradiometer system specifically designed with noise and resolution characteristics suited for both hydrocarbon and minerals exploration (Dransfield and Lee, 2004). Five airborne FALCON AGG systems have, since 1999, acquired over two million line-km of data over a range of exploration deposit styles on five continents, including offshore carbonate reefs (Nicholls et al., 2007), transition zone basement faulting (Rose et al., 2006), and onshore basement horsts (Fernandez et al., 2010). The FALCON AGG systems were sold to Fugro Airborne Surveys in 2008, and are now offered to the industry on a commercial basis.

AGG aircraft operator Fugro Airborne Surveys flew the 6,250 line-km survey in a Cessna 208B Grand Caravan over 24 production flights in the period from November 2007 to February 2008. In all, the survey covered 2,256km^2. The survey was flown at a nominal terrain clearance of 80-125 meters (subject to safety considerations) above the terrain, with E-W oriented flight-lines at 400m line spacing and N-S oriented flight lines with 4,000m tie-line spacing. Generally only moderate turbulence was encountered during surveying, resulting in low RMS difference noise levels of 3.3 eotvos in the measured G_{NE} and G_{UV} gravity gradiometer component data (1 eotvos equals $10^{-9}s^{-2}$- making 1 Eo equivalent to 0.1 mGal/km).

The measured G_{NE} and G_{UV} gravity gradient components were converted to vertical gravity, g_D, and vertical gravity gradient, G_{DD}, by standard potential field integration and derivative techniques operating in both the spatial and wave-number domains.

The FALCON AGG system has on-board laser scanner and differential GPS capability to record and construct a Digital Elevation Model (DEM) for terrain correction of the FALCON AGG data. Figure 2 (top) shows the DEM constructed by combining the high resolution FALCON laser-scanner DEM with lower resolution Shuttle Radar Topography Mission (SRTM) data and a third party bathymetry model. The FALCON AGG data have subsequently been fully terrain corrected with a terrain density of 2.2 g/cm^3, and a salt water density of 1.03 g/cm^3.

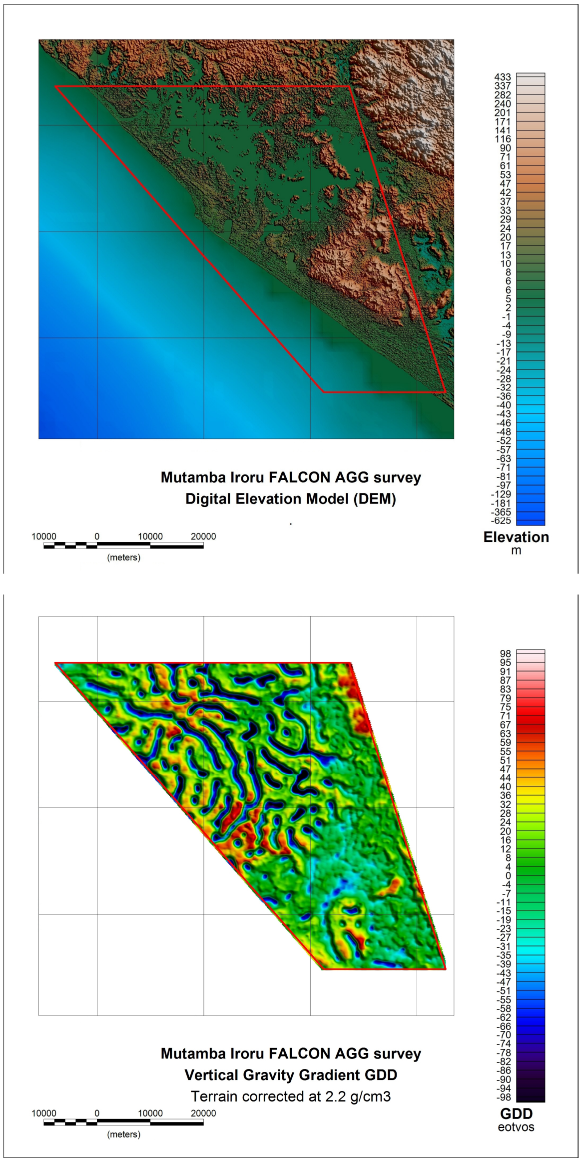

Figure 2: (*Top*) Map of the digital elevation model of the Mutamba Iroru survey area. (*Bottom*) Map of FALCON G_{DD} vertical gravity gradient.

Figure 2 (*Bottom*) shows the resulting fully terrain corrected FALCON vertical gravity gradient data, G_{DD}, over the Mutamba Iroru survey area. The data has been low-pass filtered with a 2nd order Butterworth filter with a cut-off wavelength of 800m (yielding an apparent lateral resolution of 400m); in addition the data has had any first order trend removed. The amplitude range of the data set is quite substantial from -141Eo to +85Eo, indicating significant local density deficiencies along the narrow, elongated, vertical gravity gradient lows in the northern and western parts of the survey area. These shows low-velocity/low-density trends where salt and/or near-surface cuvettes (filled with low velocity deposits) are likely to be found on the block.

Integrated Interpretation

The interpretation encompassed both regional and prospect phases. The regional phase involved: depth to magnetic basement, tectonic interpretation / lineament analysis, and integrated (seismic, gravity, magnetics) 2-D and 3-D modeling and inversion to develop a solid understanding of the basement and tectonic framework.

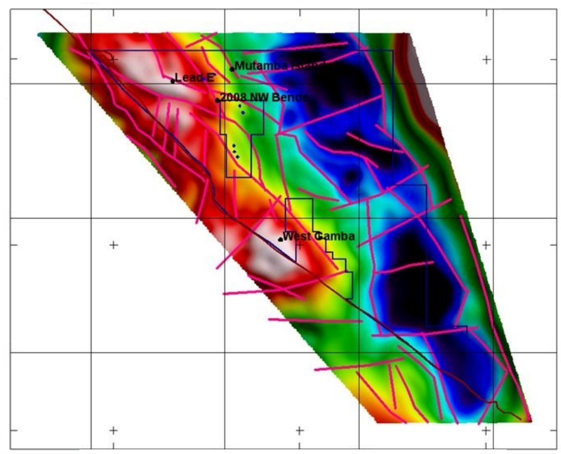

Figure 3: Basement faulting interpreted from gravity, gradients and enhancements. Indicates the Vera Graben is segmented into several sub-basins, multiple 4-way closure structures identified.

The regional interpretation allowed the team to focus in on the prospect scale issues, primarily, how to use the gravity gradiometry to improve the seismic imaging around and beneath the shallow salt structures. Multiple seismic processing methods, over a number of years, were tested for improved imaging. Some of the methods showed promise, but only after incorporation of the salt geometries interpreted directly from the airborne gravity data. Similar improvements have been noted by Mantovani and Dugoujard (2010).

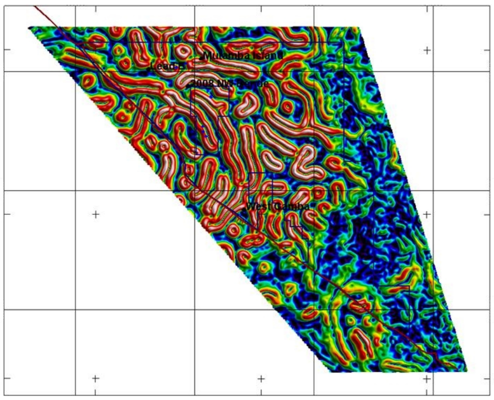

Figure 4: Horizontal gradient of the vertical gravity gradient field

The gravity maps in Figure 2 and Figure 4 allowed the interpreter to segregate the salt-prone areas, as well as to identify the geometry and relative thickness of the salt walls and the near-surface cuvettes filled with low velocity/low density deposits. In addition the FALCON AGG data allowed for a reasonable prediction of the thickness of the salt in two subsequently drilled wells.

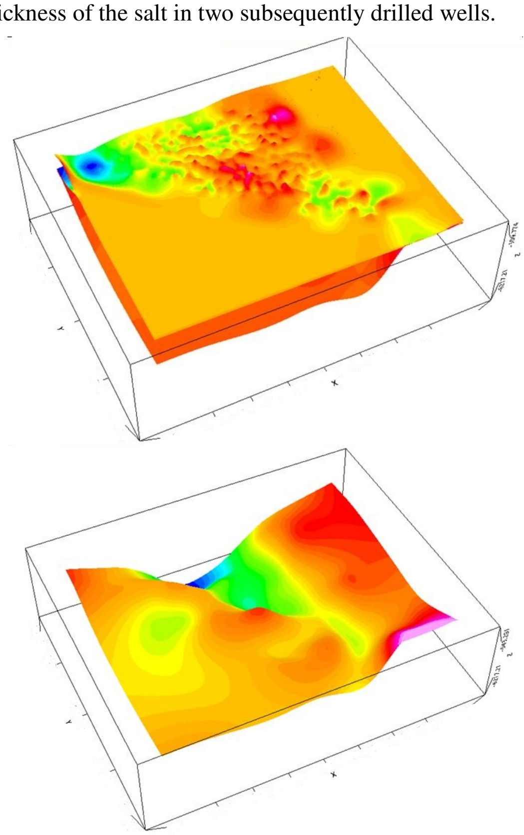

Figure 5: Interpreted depth to basement used as input to model (*Bottom*) followed by inversion for top Ezanga salt (*Top*).

2-D modeling was initially performed to test concepts and to help improve ongoing seismic imaging. 3-D modeling and inversion was then carried out to integrate both the regional and prospect-level work in to a single, integrated geological model. Gravity inversions were subsequently performed to achieve an integrated (seismic, gravity and well control) top Ezanga salt map (Figure 5), which was then used to help control the geometries of salt for seismic imaging.

Conclusions

The integrated interpretation of the FALCON AGG data in conjunction with existing seismic data clearly delineated the outline, geometry and relative thickness of the low density Ezanga salt and near-surface cuvette features, and thus highlighted the sub-areas where seismic time/depth conversion is particularly unreliable, and where seismic imaging is severely challenged.

Interpreted basement depth was achieved using depth to magnetic source techniques, augmented with gravity and magnetic inversion methods. This provided the explorationists with information for basin modeling and allowed a better understanding of the petroleum system.

Ongoing work involves "stripping" away the now-better-imaged salt features from the observed gravity field, to assist in the interpretation of prospects beneath the Ezanga salt features. Accordingly, the AGG gravity data and magnetics continue to provide benefits during the entire exploration process.

Acknowledgements

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