Airborne Gravity Gradiometer Surveying over the Benin Basin

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Summary

An integrated geological interpretation was performed using a high resolution airborne gravity gradiometer (AGG), magnetic, and radiometric survey that was acquired by CGG for the Government of the Republic of Benin. The purpose of the survey was to define and map the principal geological units in the Benin Basin, located in the southern part of the country.

Based on the gravity and magnetic response, three basement lithological types were identified sub-cropping in the Benin Basin. The sedimentary fill in the Benin Basin contains a sequence of Cretaceous to Miocene clastic sedimentary formations covered by Pleistocene and Recent unconsolidated deposits. These are offset by faults and are deeply incised by erosion. The major faults recognized in the basement are also observed at the surface, where they deform and offset young units. The faults are assumed to be dextral strike-slips and are interpreted to have controlled the formation of local pull-apart depocenters.

Introduction

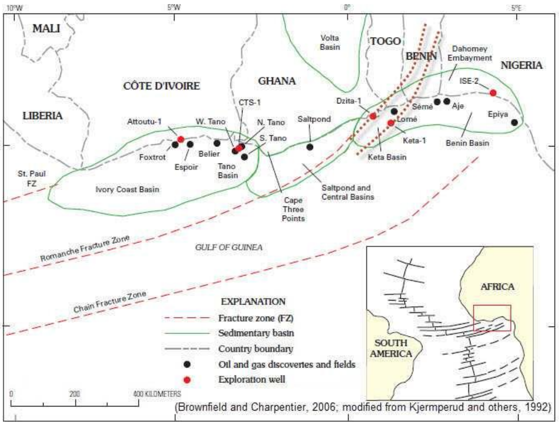
The interpretation has integrated a suite of data sets and images using a rigorous methodology. Airborne magnetic data and airborne radiometric data supplemented the airborne gravity gradiometer (AGG) dataset. Landsat 7 Enhanced Thematic Mapper (ETM+) banded imagery and a digital elevation model (DEM) were also used to provide structural and lithological controls in areas of outcrop. In addition, the interpretation considered both published scientific literature, and proprietary data provided by the Government of Benin. The interpretation was designed to map the lithologies and structure from the AGG and magnetic data, and, where possible, add detail to the surface mapping using the acquired radiometric data.

The interpretation workflow included:

- Advanced image processing of AGG, magnetic and radiometric data incorporated into an ArcGIS geodatabase for interpretation
- Georeferencing of published and proprietary maps to guide structural and lithologic interpretation
- Structural interpretation of the geophysical data sets
- Depth-to-basement modeling to identify basement topography to assist in targeting petroleum systems

Regional Geology

The Benin Basin is one of several basins developed along the south-facing Equatorial margin of West Africa. The basin fill covers a broad arc-shaped region bordering the coast from south-eastern Ghana to western Nigeria (Figure 1). The Benin Basin formed during rifting of South America from western Africa between Late Jurassic and Early Cretaceous time (Omatsola and Adegoke, 1981; Weber and Daukoru, 1975) and is presently a passive margin with a narrow shelf and a steep continental slope. Rifting along the Ivory Coast was controlled by major transform faults that allowed South America to drift westward as the Atlantic opened. Once the spreading ridges had moved west of Africa, the fracture zones were largely inactive. However, the old structures were still zones of weakness that, during later changes of tectonic plate movement, became sites of local deformation. Ancient fracture zones coincide with the boundaries of the Benin Basin. The Romanche Fracture Zone (FZ) defines the boundary between the Ivory Coast Basin and the Dahomey Embayment. The Chain FZ generally defines the boundary between the Dahomey Embayment and the Niger Delta Basin. The fracture zone faults are interpreted by various authors to extend onto land and curve to a more northerly orientation (Affaton et al., 1980; Trompette, 1994). Two major northeast trending shear zones that are mapped in the survey area may be related to splays or strands of the onshore portion of the Romanche FZ (Figure 1).



(Brownfield and Charpentier, 2006; modified from Kjermperud and others, 1992)

Figure 1: Regional trends of major fracture zones in West Africa. Inferred on-land extensions of the fracture zones shown with brown dotted lines (modified from Brownfield and Charpentier, 2006).

The Benin Basin contains a sequence of Cretaceous to Miocene clastic sediments related to the Mesozoic break-up of Gondwana and subsequent marginal marine sedimentation. The strata forming the onshore part of the Benin Basin represent the northern margin of a considerably larger and deeper depositional basin that in parts reflects differential subsidence. The sequence is covered by unconsolidated Pleistocene and Recent deposits. The basin fill overlies basement rocks of the Benin-Nigerian Shield and the Togo unit of the Dahomeyan Orogen.

The onshore sedimentary sequence has undergone more erosion and is overall thinner and less complete than the offshore part of the basin. It blankets the crystalline basement in a southward-thickening wedge that has a northward erosional limit several km north of the southern survey boundary. The sedimentary sequence is between 2,000- 2,400 m thick at the coast. Clastic sedimentary rocks dominate the stratigraphic column with no known evaporites and only minor carbonates. Episodes of deposition were broken by periods of erosion or non-deposition; these phases are linked to the Late Mesozoic and Cenozoic tectonic events associated with the opening of the Atlantic Ocean and development of a transform margin along the Benin coast.

Petroleum Potential

The Benin Basin has been explored for hydrocarbons since the 1970's. Sémé is the only producing field. The offshore field produced nearly 8000 BOPD from a single well head at its peak in 1984, but was abandoned in 1997. SAPETRO has been re-working the field and is expecting production again soon (Buchanan, 2014). New interest has been sparked in the ultra-deep regions offshore because of recent discoveries in other places along the Ivory Coast. However, no successful wells have been drilled in the on-land portion of the Benin Basin. Based on the possible depositional relationships of the Late Cretaceous units, this study finds that the oil and gas bearing units known in the offshore may continue onshore where they have been uplifted. Some oil may have reached the up-dip parts of the Turonian sandstone before continued uplift and erosion left the key reservoir rock either at the surface or shallowly buried. In-place degraded oil in the form of tar is described from The Ivory Coast and Tano Basins and also from the "eastern tar belt" of the Benin Basin / Dahomey Embayment (MacGregor et al., 2003).

Airborne Gravity Gradiometer Surveying

The FALCON AGG systems have been operational since 1999, and an excess of three million line-kilometers of data have been acquired to date. AGG provides twenty times better spatial resolution [150m versus 3,000m], and five times less noise [0.15 mGal versus 1.0 mGal] than conventional airborne gravity (Dransfield and Christensen, 2013). The AGG system has been designed specifically for use in light aircraft and demonstrates minimum sensitivity to air turbulence. The system can operate in turbulent conditions and routinely acquires in excess of 4,000 line-km per week. This translates into very rapid data acquisition, when contrasted to ground-based gravity acquisition. Fernandez et al. (2010) published an AGG case study from Argentina where a ground gravity survey of similar scale required nearly two years of ground crew field work. In contrast the AGG survey was completed in two months with no safety incidents.

AGG has proven to be an effective method for mapping geological structures across the shallow marine transition zone which extends from the coast line and outwards to water depths in which conventional seismic vessels can operate. Shipborne data acquisition in the transition zone is fraught with difficulties, if possible at all, due to the shallow water depths, wave activity and the proximity of the shore line. Airborne data acquisition is not exposed to such issues and provides a rapid and safe means to map the shallow marine transition zone. An example of transition zone mapping was published by Rose et al. (2006) from the Bass Strait gas-fields in Southeastern Australia. Bain et al. (2013) reported on the successful use of AGG to image the lateral extent of salt diapirs in seismically challenging circumstances in coastal Gabon.

Gravity data reflect lateral variations of density in the subsurface and is especially amenable for basement structural mapping of sedimentary basins. The higher lateral resolution of AGG when compared to conventional airborne gravity results in superior mapping of basement topography in depths less than 6,000m. This information can be used to de-risk further exploration effort by optimizing the layout of any subsequent seismic data acquisition programs. This approach has been used recently by several Australian petroleum explorers. Moore et al. (2012) and Feijth et al. (2015) describe how Buru Energy have used AGG to rapidly and cost-effectively map the basement structures over large areas of the Canning Basin in Western Australia. The basement architecture mapping ability of AGG is not limited to shallow or local basement features: Feijth et al. (2012) have published survey results from a regional large-scale AGG survey over the Morondava basin in Madagascar mapping all sub-basins in the failed Permo-Triassic Karoo rift system. Roberts et al. (2015) have presented AGG survey results from the East African Rift.

The 16,390 line-km AGG survey was flown over the Benin Basin in 2013 with N-S traverse lines at 500 m spacing and E-W tie-lines at 5,000 m spacing. The survey was flown as a draped survey with a nominal terrain clearance of 80 m. A DEM was derived from the on-board high-resolution laser scanner system. Using this, the measured components of the gravity gradiometer were fully terrain-corrected using a terrain density of 2.2 g/cm^3. The terrain-corrected, measured curvature gradients were converted into vertical gravity (g_D) and vertical gravity gradient (G_{DD}) data sets. The survey-wide amplitude range of the G_{DD} data is 46 Eö. The AGG data were low-pass filtered with a cut-off wavelength of 300 m. The average G_{DD} system noise is estimated at 3.0 Eö for the survey. This corresponds to a noise amplitude density of 1.6 Eö√km (Dransfield and Christensen, 2013).

The magnetic data were acquired concurrently with the gravity gradient data, then diurnally corrected and leveled using tie line data. The total amplitude range of the magnetic data is 72 nT with an average system noise of 0.2 nT. A suite of various deliverables was subsequently used in the regional interpretation (Figure 2).

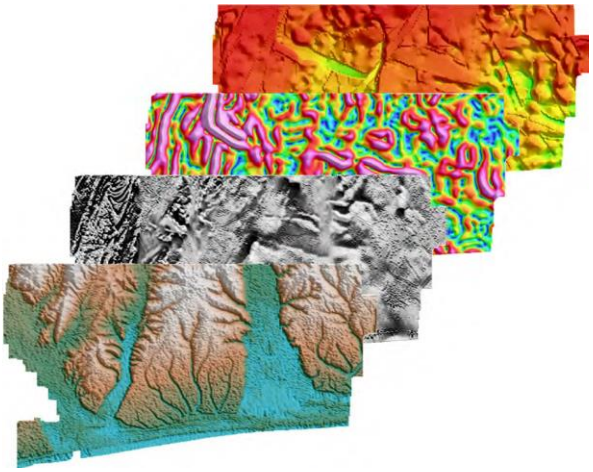


Figure 2: Examples of the survey data sets used in the interpretation: from front to back: DEM, 1VD RTP TMI, AGG Horizontal Gradient of G_{DD}, depth to integrated basement.

Interpretation

The interpretation workflow was applied as follows:

- Data enhancement and image processing of the newly acquired magnetic and AGG data, including generation of various filters and enhancements of the magnetic and AGG data grids
- Data enhancement and image processing of RGB color composites of Landsat 7 ETM+ Bands 3, 2, 1
- Compilation and georeferencing of all available public domain and proprietary data, which was subsequently used in the interpretation
- Interpretation of geological units with magnetic response from various magnetic derivatives
- Interpretation of the surface extent of geological units based on their radiometric response
- Interpretation of faults based on offsets in the magnetic, gravity gradiometer and radiometric data
- Integrated geological interpretation of magnetic, gravity gradiometer and radiometric datasets and digital capture in ArcGIS
- Depth-to-basement modeling to identify basement topography to assist in targeting petroleum systems
- Summary report discussing the interpretation results, including discussion of the petroleum potential of the survey area.

Figure 3 shows an example of a deliverable from the interpretation.

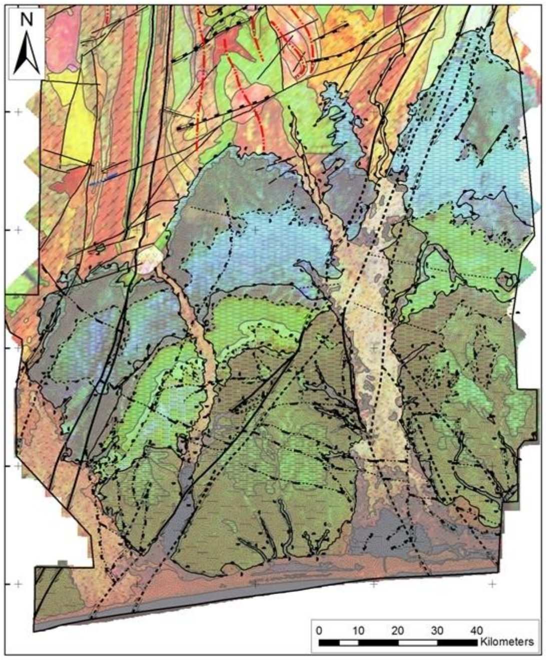


Figure 3: Benin Basin – Radiometric ternary image overlain by interpreted structures and lithology

The interpretation of the basement structure is based on both the magnetic data and AGG data. Major strike-slip faults were interpreted based on the presence of offsets along linear structures. Normal faults were interpreted based on linear or curvilinear changes in magnitude of the g_D and GDD. The main strike-slip faults were assumed to be dextral because of the known tectonic history of the region related to the dextral Romanche Fracture Zone. Several sub-parallel strike-slip faults in the west of the survey area are parallel to the Dahomeyan structure. Other possibly inherited structures, NNW trending faults in the east of the survey area, are interpreted as reactivated pan-African faults. The main strike slip faults are interpreted to have controlled the formation of major pull-apart basins, one to the west of the triangular block defined by the Dahomeyan and Pan-African trends, and another one to the east. The major normal faults are WNW trending.

The basement lithology was interpreted mainly on magnetic character using the analytic signal. The density distribution of basement lithology also seems to be reflected in the g_D and G_{DD}. Three identified basement lithological types sub-cropping in the Benin Basin include: (i) strongly banded units in the northwestern part of the block with high magnetic susceptibilities and possibly higher densities, similar to parts of the Togo structural unit in a northern part of the country; (ii) units with lower magnetic intensities, frequencies and a less linear and flatter magnetic character, typical for migmatite, magmatic gneisses and gneisses of the Migmatite Gneiss Complexes of the Benin-Nigerian Shield; (iii) circular to ellipsoid high intensity low frequency features with high magnetic intensities, typical for mafic intrusions, occurring along major dextral strike-slip zones.

In general, the sedimentary rocks mapped at the surface have no visible magnetic signature. However, the fluvial sediments occupying the broad river valleys have a highly variable magnetic signature with short wavelengths. This may be caused by the presence of volcanic or iron-rich clasts in the river gravels, overprinted by the magnetic signal generated by the relatively shallow crystalline basement within the deeply incised river valleys.

The sedimentary fill of the Benin Basin is offset by major shear faults and is deeply incised by erosion. The major shear faults recognized in the basement are also observed at the surface where they deform and offset young units, indicating relatively recent movement on these structures. Other less significant faults do not offset the entire sedimentary sequence of the basin and therefore could not be identified at the surface.

3D Modeling of Basement

Depth to crystalline basement was estimated using a combination of magnetic depth estimates, fault-based contouring based on geological interpretation, and 3D gravity modeling. The 3D modeling was performed using LCT inversion software. The starting 3D model was assembled using a whole earth approach in that it included Moho (from Crust 2.0), magnetic basement, and topography. Intermediate surfaces were added in the mid-crystalline basement and in the mid-sedimentary section so that increasing density within those layers could also be modeled. Numerous different approaches were attempted including starting with a flat basement, 3D Euler basement, magnetic basement without fault contouring, and various low-pass filters.

The starting model with the best results used the fault-based contoured magnetic basement and a 10 km low-pass filter of the observed AGG gravity data (Figure 4). The structural inversion appears to have been successful in resolving any discrepancies between the interpretation and changes in basement depth.

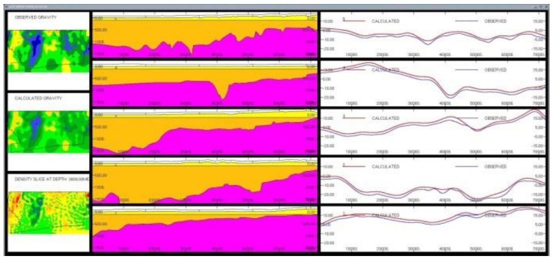


Figure 4: Final 3D model after density inversion of integrated basement.

Basement is at the surface in the northwestern corner of the survey, and is only a few hundred meters deep across the northern boundary of the area. The deepest basement occurs in the southern part of the basin, where the maximum depth is ~2,200 m below sea level.

Conclusions

The geological interpretation was successful in outlining the litho-structural settings in the southern part of the Republic of Benin from newly acquired AGG and magnetic data and to map the surface expression of lithological units based on radiometric data. A depth-to-basement model identified basement highs and lows that can assist in targeting petroleum systems.

The main geological unit in the survey area consists of a reworked Achaean migmatite-gneiss terrane underlying the Mesozoic to Quaternary Benin Basin. Two other basement lithologies were interpreted: high-density, high-susceptibility banded rocks along a major shear zone; and local high-susceptibility units interpreted as basement intrusions. A depositionally and erosionally thinned sequence of Cretaceous to Miocene clastic sediments is covered by Pleistocene and Recent unconsolidated deposits in the on-land portion of the Benin Basin. The interpretation of the surface distribution of sedimentary rocks is based partly on radiometric data. The sediments in general have no significant magnetic signature.

The sedimentary fill of the Benin Basin is offset by major faults and is deeply incised by erosion. The major faults recognized in the basement also have a surface expression. The main faults were assumed to be dextral strike-slips, interpreted to have controlled the formation of local pull-apart basins. One NNE-trending fault is situated to the west of the triangular block defined by the Dahomeyan and Pan-African trends, and another NW-trending fault is located further to the east.

This interpretation should be seen as a starting point for further, more detailed studies involving fieldwork in tandem with detailed remote sensing interpretation.

Acknowledgments

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REFERENCE CHANGE: Reference lists **will not** be included at the end of the expanded abstract, but should be prepared separately and entered during the submission process in the online form.

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