Evaluation of the Hydrocarbon Potential of the Inland Basins of Nigeria: An Example of an Integrated Geological, Geophysical, Geochemical and Remote Sensing Study of Frontier Basins*

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Search and Discovery Article #11223 (2019)**
Posted June 17, 2019

*Adapted from extended abstract based on poster presentation given at AAPG 2018 International Conference and Exhibition, Cape Town, South Africa, November 4-7, 2018
 DOI:10.1306/11223Baku2019

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Abstract

The Nigerian national oil company is actively exploring for hydrocarbon in all its Inland Basins that developed along the Western African Rift System. The exploration commenced in 1976 with minimal success of non-commercial discoveries of gas. This paper sets out to identify, rank and explore the most prospective areas of these basins using recent data. The Nigerian Inland Basins have not seen any drilling activities since the mid- 90's due to unsuccessful campaigns. The data collected from the previous exploration effort was analyzed and a new strategy was charged with the re-commencement of activities in 2009. We used a step-by-step approach to effectively advance exploration activities in the Inland Basins of Nigeria. Our re-entry project greatly benefited from several data sets that are not always available for the evaluation of frontier basins including:

- High-Resolution Magnetic (HRAM) that was flown over the entire country and was used to reconstruct the size, shape and depth of all the Inland Basins of Nigeria.
- A comprehensive geochemical survey was collected across the basins and over key prospective structures. These data were used to assess the presence of hydrocarbon systems in each basin and identify the location of major active, surface-hydrocarbon, micro-seepage anomalies.
- High-resolution remote-sensing, radiometric and ground gravity data was used to map exposed buried and obscured structures in different parts of the basins that are not covered by seismic data.

The results of this project are being presented here with selected examples from the sedimentary basins that have been analyzed so far. These basins include: The Chad Basin of Northern Nigeria, the Benue Trough Basins of Central Nigeria, and the Bida and Sokoto Basins of Western Nigeria.

Introduction

The Nigerian national oil company renewed its exploration activities in the Nigerian Inland Basins of the Western African Rift System in 2009. The main goal of this new initiative was to systematically identify, assess, rank, and de-risk exploration targets in different parts of this large rift complex. The effort was done through the integration of existing seismic and well information with several reconnaissance exploration tools which included: high resolution airborne magnetic surveys (HRAM), ground gravity, surface geochemistry, remote-sensing and radiometric data. This effort lead to the recognition of a large inventory of ranked exploration targets and the development of a cost-effective 2D and 3D seismic programs that is designed to prepare these basins for a new and aggressive drilling program.

Presently, the Nigerian oil company is in a process of collecting regional 2D seismic data across several exploration targets in basins that have not been imaged with seismic data before. These basins include: The Middle Benue, Yola, Bida and Sokoto Basins. 3D seismic programs have also been collected over key exploration targets in more mature basins such as: The Upper Benue and Chad basins.

The program has now reached the stage where key exploration wells are ready to be drilled over several targets in Upper Benue and Chad Basin. After 30 years of hiatus, the first exploration target which will be drilled in the Inland Basins has been identified with 3D seismic near the Kolmani-1 gas well that was drill by Shell in the Upper Benue Basin area in early 90’s. It is expected that this well will be completed before the end of 2018.

The main goal of this paper is to illustrate the contribution of non-seismic exploration tools to the development of the exploration programs in these large and relatively untested frontier basins.

Method

The first stage of the re-entry program began with the use of HRAM that was collected and processed over the entire country in 2010. This data was used to assess the size, shape and depth of all the Inland Basins of Nigeria as well as to generate a large inventory of prospective leads. The second phase of the study consisted of the collection of soil samples across each of the Inland Basins and over key prospective leads. Standard geo-chemical analytical techniques such as Acid Extracted Soil Gas (AE), GeoPAC Fluorescence Analysis, and Microbial Analysis were used to define the type of hydrocarbons that were generated in each basin, as well as to identify areas of major concentration of surface and near surface micro-seepages over key prospective leads. The third phase of the study consisted of detailed mapping of prospective structures using a variety of remote-sensing, radiometric, gravity and magnetic (HRAM) data sets. The remote-sensing data included satellite images and the Space Shuttle digital elevation model (DEM) that were downloaded or acquired from different space agencies. Radiometric data was acquired at the same time as the national airborne magnetic survey and ground gravity data was collected in the field during the collection of the soil samples. The final stage of this project aims to integrate the new 2D and 3D seismic data that is presently being collected across the basins and over key prospective structures. This process is likely to continue for several years leading to an aggressive drilling program that will aim to systematically test the hydrocarbon potential of all the Nigerian Inland Basins.

Results

The results of the first phase of the study are summarized in the tectonic/ play map that is shown in Figure 1. The map shows the size, shape, depth of all the Inland basins of Nigeria as well as key geological structures that were detected through the integrated analysis of the HRAM data. These structures include:

- down to the basin, listric, normal faults that dominate the structural fabric of the Niger delta.
- high-angle normal faults that form the faulted margins of the rift system.
- strike-slip faults and related structures that developed during Late Cretaceous reactivation and inversion of the rift system.
- large intrusive bodies which are also related to the late tectonic events of the rift system.

The rift basins appear to have the potential for the development of four different hydrocarbon systems that can be ranked occurring to their proximity to known and proven hydrocarbon shows in the following order:

- The Amabra and Dahomey basins: These basins received the highest ranking because they are located next to the hydrocarbon kitchen of the Niger delta and are known to contain proven oil and gas discoveries which also include the large tar belt region that is located at the structural divide between the Dahomey and Anambra Basins.
- The Benue Basins complex: This complex includes the Lower, Middle, and Upper Benue basins as well as the Yola Arm. This complex is ranked second because it has a proven hydrocarbon system that is reflected by the presence of several gas wells that where drilled in the Lower Benue Basin as well as the sub-commercial (26 BCF) gas discovery of the Kolmani- 1 well in the Upper Benue Basin. Oil seeps have also been found in the Bima formation that is cropping out at the northern edge of the Upper Benue Basin.
- The Chad Basin: This basin includes the Maiduguri and Chad Lake sub-basins and is ranked third because these basins have been tested by several wells so far and have not produced commercial discoveries to date. Oil seeps have been detected in outcrops of the Bima formation at the western edge of the basin.
- The Bida and Sokoto basins: These basins received the lowest ranking because they have not been imaged with seismic or tested with wells to date. However, oil and gas shows have been reported in these two basins in recent studies.

The excellent capacity of HRAM data to define the size, shape and depth of the Nigerian Inland basins is demonstrated with examples of data from the Bida and Sokoto basins area that is shown in Figure 2. The magnetic image shown in Figure 2A is a derivative product known as the Analytical Signal. This image was used to define the structural fabric of Bida and Sokoto basins. A depth to basement map and related magnetic profiles that are shown in Figure 2B and 2C were generated through the implementation of Extended Euler Deconvolution techniques.

Several key observations can be made here: First, the basins are relatively small and bounded by high angle normal faults that reflect the faulted rim of main rift systems. Second, there is a substantial vertical separation between the exposed rims and the floor of the basins. Third, both basins have reached the depth needed for the generation of hydrocarbon, but the Sokoto Basin complex appears to be more prospective because it contains larger and deeper sub-basins.

The results of the analysis of the geochemical samples that were collected in the Inland Basins are illustrated in Figure 3. A cross plot of all methane/ethane soil samples that were collected so far suggests that most of the hydrocarbon shows that were found in the Inland Basins consists mostly of thermogenic dry gas. The presence of higher concentrations of wet gas also suggests that some condensate and light oil may have also generated in these basins (Figure 3A).

The results of the geochem surveys were also used to evaluate and de-risk individual structures that were mapped in these basins with other exploration tools. For example, a time structure map of a prospective structure that was mapped in the Upper Benue Basin with 2D seismic is shown in Figure 3B. The crest of the structure is well defined and appears to be formed by a major fault that is likely to provide a fault-dependent closure (a in Figure 3B). However, the geochem survey shows the presence of a major micro-seepage anomaly (shown in red dots) at the eastern edge of the structure (b in Figure 3B). These observations suggest that: a) the structure is likely to be charged by hydrocarbons and b) segments of this fault could be leaky and could reduce the size of the prospective structure.

The use of different non-seismic data sets to identify prospective structures in the Inland Basins is illustrated in Figure 4. The examples shown here aim to illustrate the size and geometry of the most dominant structures that are found in the Inland Basins of Nigeria. These structures consist of elongated anticlines and synclines that developed either oblique or parallel to regional strike-slip faults. In most case, these structures are exposed at the surface and their crests are breached by differential erosion which produces profound expressions on HRAM, satellite imagery, as well as radiometric data. The examples shown here include:

- A breached anticline that was detected along the faulted edges of the Bida Basin with a digital elevation model (a in Figure 4A).
- A breached fold (most likely syncline) that was detected along the faulted edge of the Middle Benue Basin using a residual map of the HRAM data (b in Figure 4B).
- A large inverted structure that form the Keana anticlinorium in the Middle Benue Basin that was detected with Radiometric data (c in Figure 4C).
- A large double-plunging, reactivated structure that was detected in the central parts of the Yola Basin with Landsat imagery data (d and e in Figure 4D).

The last image shown in Figure 4D also illustrates how the interpretation of these data sets was used to design the collection of 2D seismic in these Basins.

Ground gravity data that was collected in the field during the soil sample survey was merged with existing gravity data to produce new gravity images that were used to constrain the interpretation of deep-seated structures in the study area. The two examples shown here are focused on the two top prospects that were identified in the Maiduguri and Upper Benue Basins. The first example illustrates how the collection of gravity data was used to constrain the size and shape of a prospective structure in the Maiduguri Basin (a in Figure 5A and b in Figure 5B). The second example illustrates the gravity expression of an uplifted, basement involved, horst block that set up the location of the Kolmani-1 gas discovery well (c in Figure 5C and d in Figure 5D). In both cases the gravity data confirmed the size and shape of a three-way closure of the prospective structures. Both prospects have now been mapped with 3D seismic and are ready to be tested by exploratory wells.

Discussion

The success of the re-entry exploration program of the Nigerian Inland Basin was largely dependent on the outstanding quality of the HARM data that was made available for this study. The HRAM images successfully captured the shape, size and depth of the rift basins as well as the magnetic expressions of surface and near surface reactivated and inverted structures. The early detection of these prospective exploration targets with HRAM data provided the basis for the use of other reconnaissance exploration tools to further investigate these exploration targets in a timely and cost-effective fashion.

The result of this project also benefited from the structural setting of the rift system that consists of well-defined rift margins that are bounded by exposed basement rocks. The relatively young reactivation and inversion of key structures clearly contributed to the ability of non-seismic data sets to the detect buried and obscured structures. Recent reactivation and inversion processes also lead to the presence of surface micro-seepages that were successfully detected with geochemical surveys.

Conclusions

The result of this integrated study clearly demonstrates the presence of an active hydrocarbon systems that contains mostly thermogenic dry gas with some condensate and light oil in all the Inland basins of Nigeria. The hydrocarbon that was generated in this basin are likely to be trapped in large anticlinal structures that were formed by a late reactivation and inversion of basement-involved, strike-slip faults. A large inventory of prospective structures has been identified in all the Nigerian Inland Basins and is likely to be tested by drilling soon.

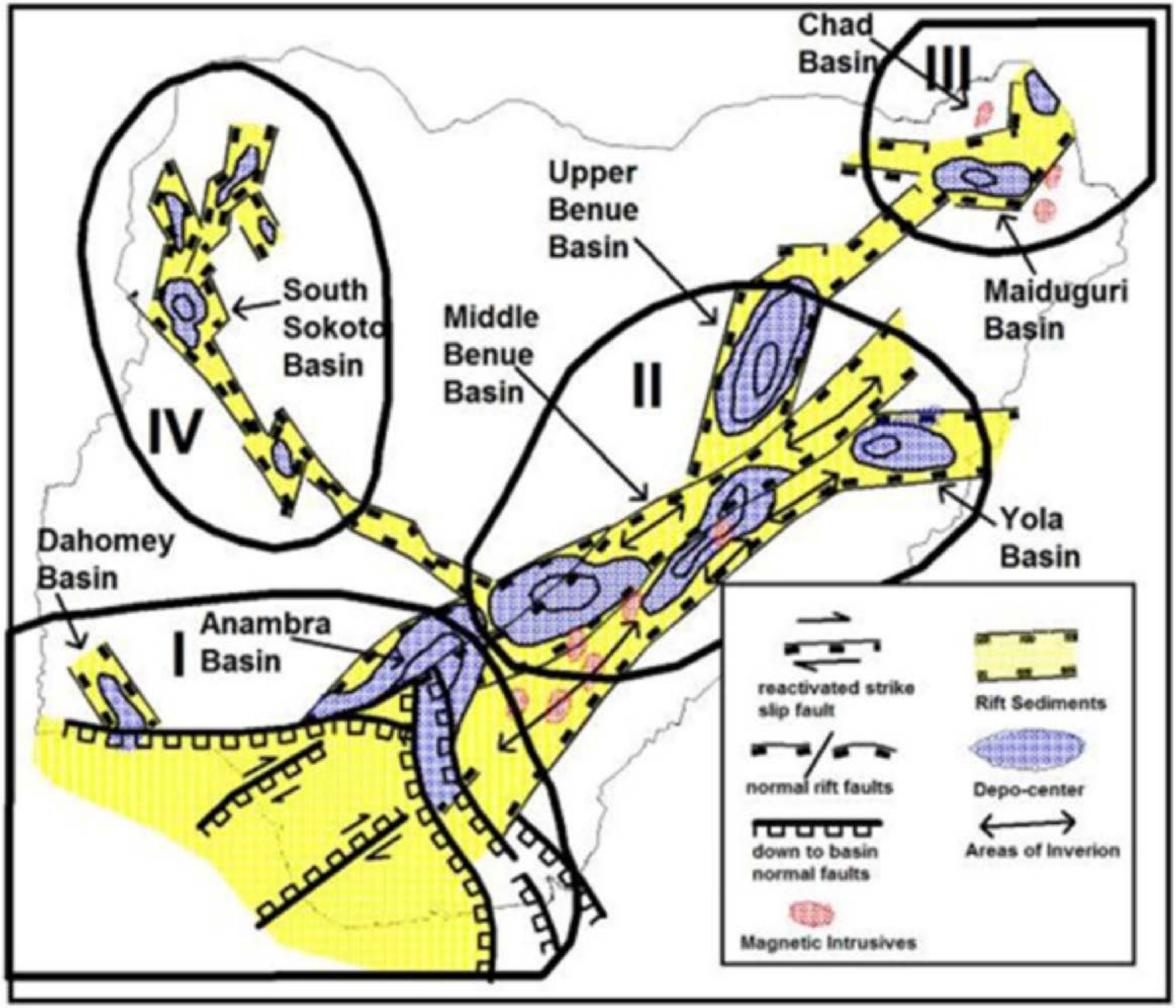

Figure 1. An integrated tectonic map of the Inland Basins of Nigeria showing the location and size of prospective basins. The basins are divided into four separate hydrocarbon systems that are being ranked based mostly on their proximity to proven hydrocarbon shows.

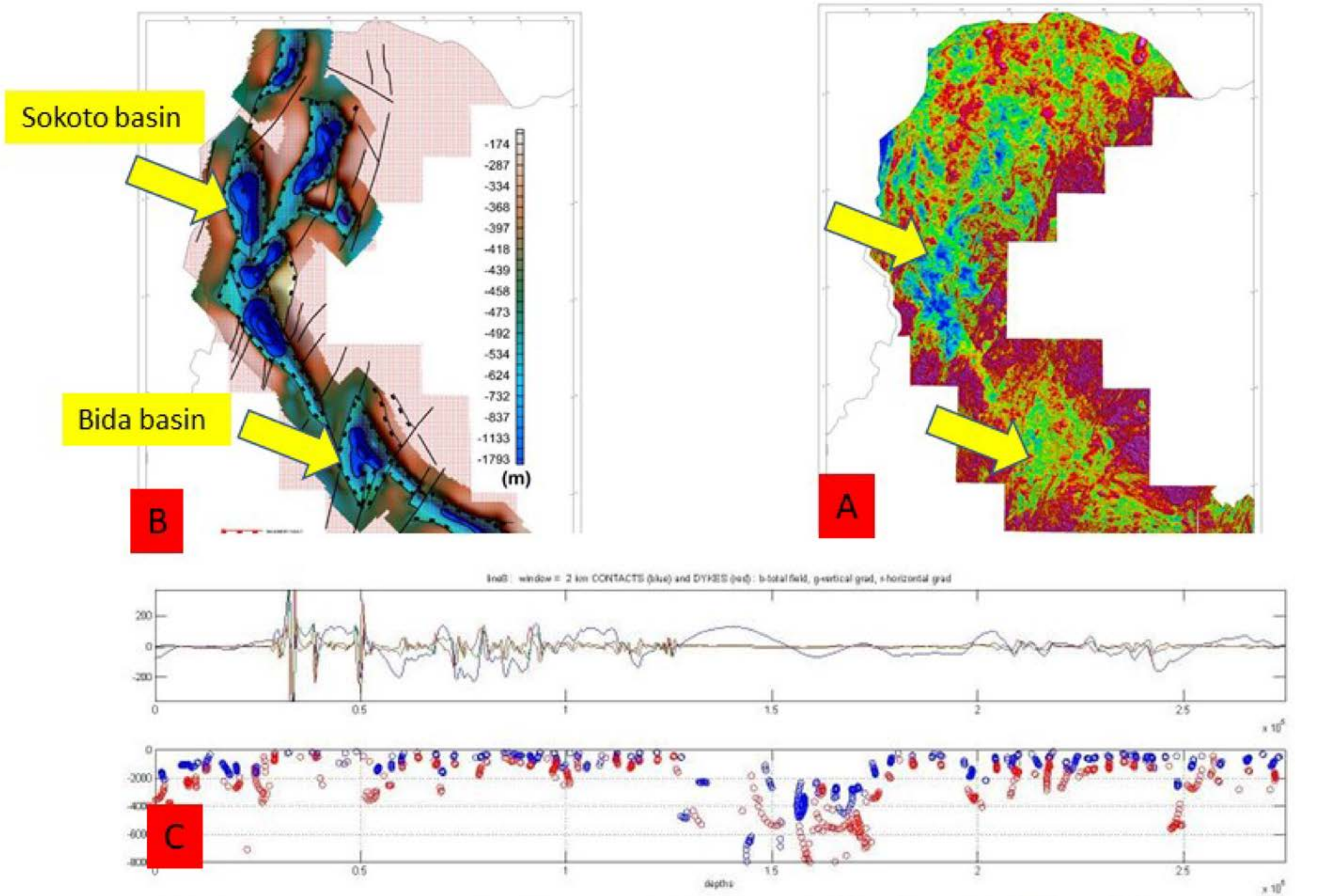

Figure 2. High-Resolution magnetic data of Bida and Sokoto Basins illustrating the process used to determine the size, shape, and depth of all the Inland Basin of Nigeria. The magnetic image in Figure 2A is a derivative product - Analytical Signal - that was used to map basement and sedimentary structures in this study. Figure 2B and C illustrate depth to basement maps and profiles that were generated for this study using extended Euler deconvolution techniques.

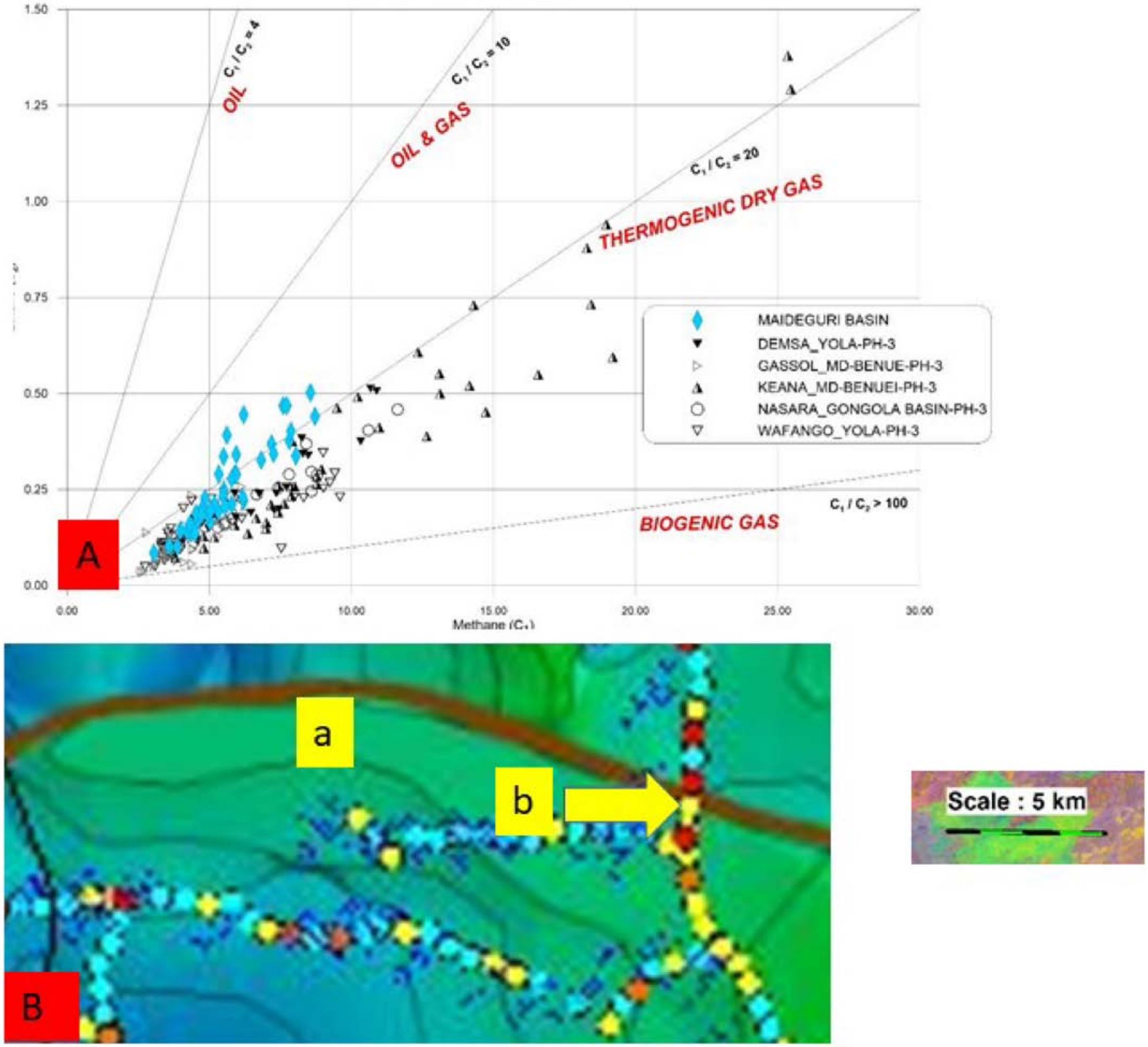

Figure 3. Examples of surface geochem products that were used to evaluate the Inland Basins of Nigeria. The crossplot in Figure 3A shows a methane/ethane gas ratio of all the geochem samples that were collected so far in the Inland Basin. An example of geochem survey results that are plotted on a prospective structure in Upper Benue are shown in Figure 3B.

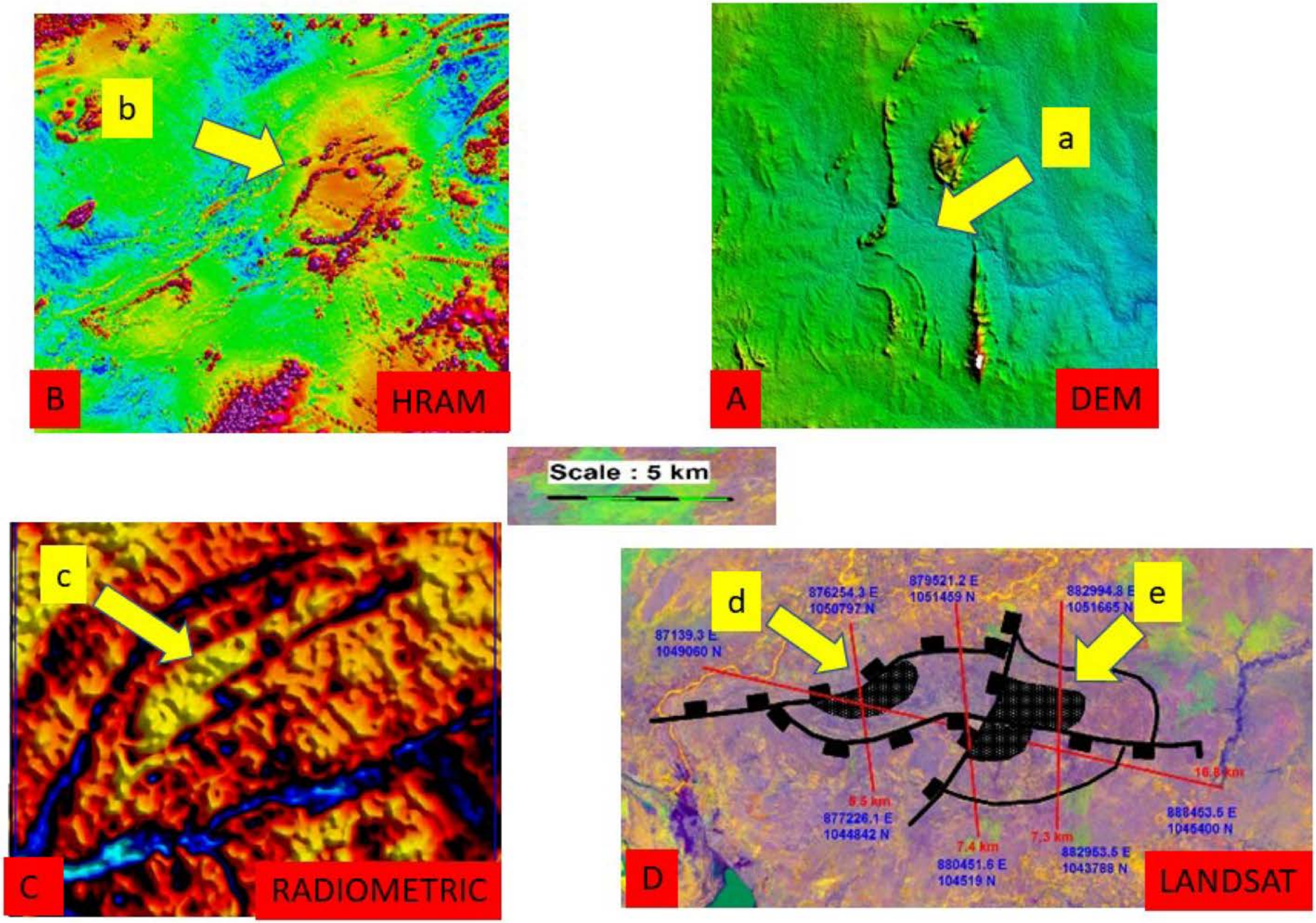

Figure 4. Examples of different remote sensing and non-seismic data sets used to detect buried obscured structures in the Inland Basins of Nigeria.

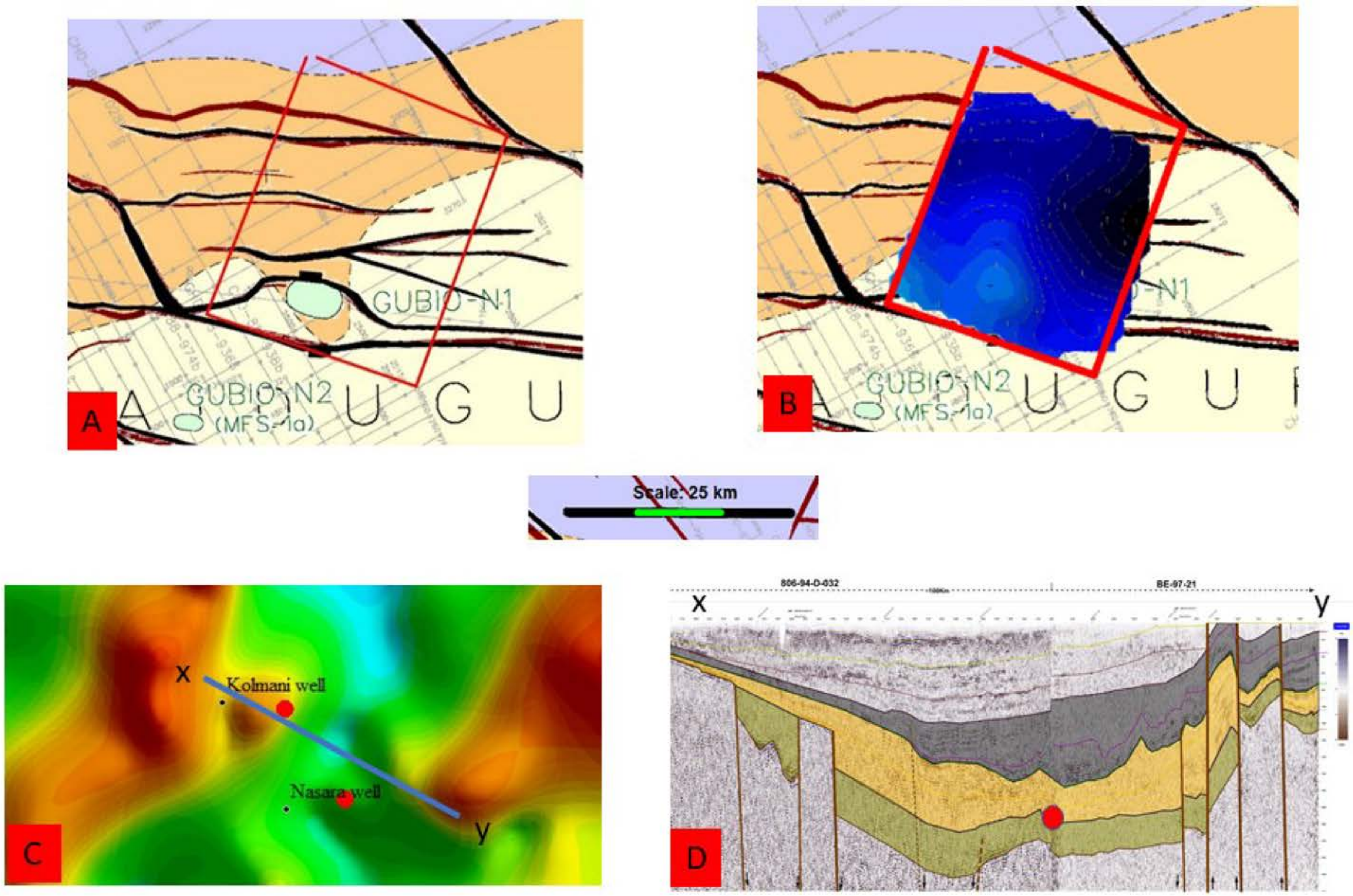

Figure 5. Bouguer gravity maps and seismic data of the two top prospects in the Inland Basin of Nigeria. The Gubio structures in the Maiduguri Basin (top and the Kolmani prospect (bottom).