

Improving geologic understanding with gravity and magnetic data: Examples from Gabon, Nigeria and the Gulf of Mexico

John M. Jacques¹, Marianne E. Parsons², Antony D. Price² and David M. Schwartz² draw upon recent work to provide evidence as to why gravity and magnetic survey data can still provide vital geological clues for oil and gas exploration.

Better understanding of geology on regional and prospect levels using potential field data continues to encourage the melding of these fields to produce enhanced interpretations. Three case studies are presented in this article, all with different geologic settings and targets. All of the examples draw on databases from non-exclusive gravity and magnetic surveys.

Two large databases and their interpretation in Gabon and Nigeria were the topics of recent poster papers at the African Symposium, sponsored jointly by the Houston Geophysical Society and the Petroleum Exploration Society of Great Britain (PESGB) in Houston in September, 2003. They are illustrative of the approach that utilizes regional data (in this case satellite-derived gravity) to develop the tectonic framework and more detailed shipborne or airborne gravity and magnetic data to focus on specific targets. The continued high level of activity off West Africa attests to the wide-ranging potential for further development in this region. Many areas, both onshore and offshore, have been extensively explored with 2D and 3D seismic surveys and many wells.

Gravity and magnetic data provide a low cost way to screen large areas as well as construct important alternative models to delineate subsurface structures and reach a better understanding of the geology. The density contrasts presented by the juxtaposition of sediments with shales and salt make detailed gravity modelling in this region a valuable exercise. The magnetic data provide insight into mapping basement surfaces and delineating shallower volcanics and in some cases shale or salt diapirs.

In the Gulf of Mexico, the reconstruction of the paleo-tectonic history is also enhanced by incorporating the potential field data. New work is ongoing which blends the geologic information with the gravity and magnetic data using regional scale modelling techniques. Gravity and magnetic data have been traditionally thought of as regional screening tools capable of providing basin edges or basement mapping. In recent years, the application of these data has been greatly expanded to include modelling of prospect-level targets.

Gabon: geologic alternatives addressed using gravity and magnetics

Gabon is the subject of increasing interest for oil exploration these days. Geologic challenges that are encountered in Gabon are not limited to national boundaries but are found in neighbouring areas, as well as analogous environments around the world. Specific to Gabon, however, is a wealth of multi-client airborne magnetic data (see Figure 1) that has been collected over the years both onshore and offshore. High-resolution marine gravity data have been collected on a number of exclusive seismic surveys, and are not generally available for publishing. A description of the gravity data's utility in this environment will be discussed here.

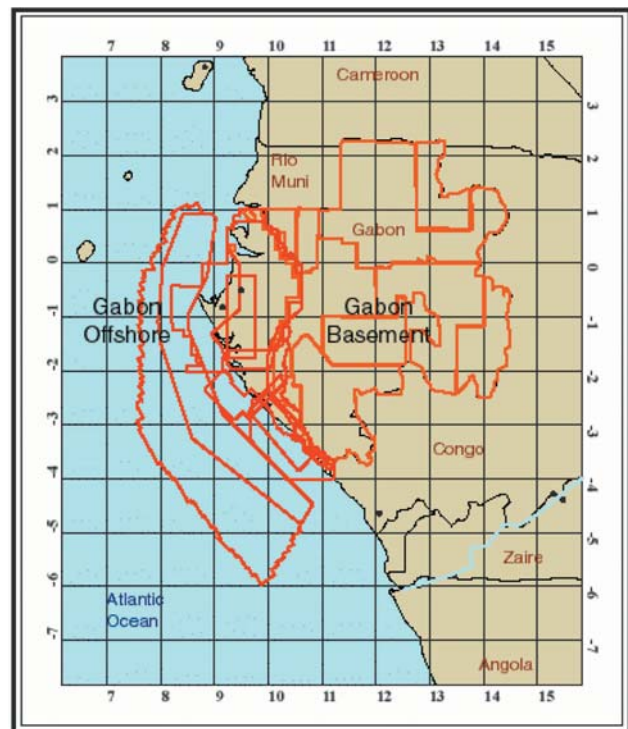


Figure 1 Location of Non-exclusive Magnetic Data.

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Non-seismic methods

The majority of the oil and gas targets in Gabon are associated with salt structures and basement highs. Unfortunately, the salt makes seismic imaging very difficult and non-seismic methods have been used to aid in the geologic understanding of the area. In the Southern basin of Gabon, the salt (Ezanga formation) was initially deposited above a common reservoir rock (the Gamba sandstone) and as a result of the forces of sediment loading, periodic extension and compression and the reactivation of basement faults has formed pillows, diapirs and salt walls. Similarly, in the Northern and Interior basins of Gabon, the Ezanga salt formation is present and has been deformed to create various complex structures. As would be expected, below the salt layer the seismic imaging is very difficult, and also causes problems when attempting to define the flanks, and even the top of these complex salt structures. There are therefore two seismic imaging problems that can be aided with the inclusion of potential fields: delineation of a basement surface, and better definition of the geometry of complex salt bodies.

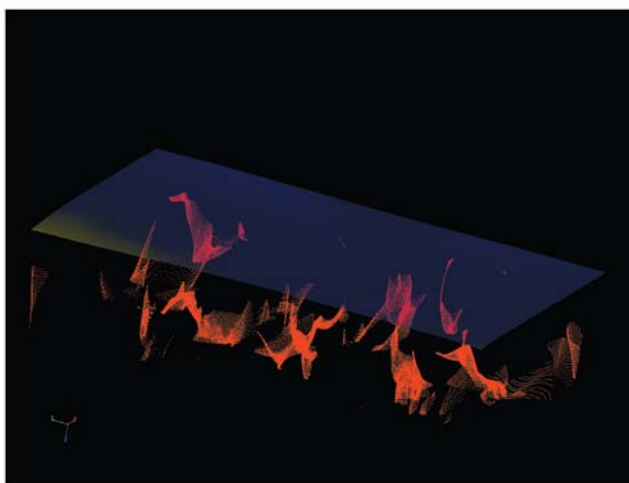


Figure 2 3-D Euler Solutions with Topography Surface

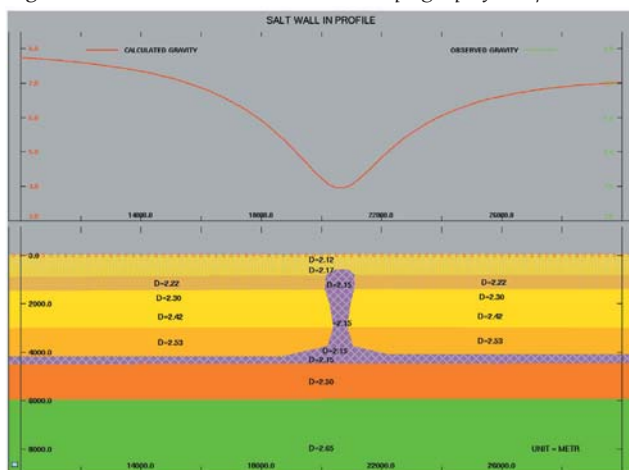


Figure 3 Salt wall as a cross-section.

Magnetic data can be analyzed in a number of ways, with enhanced techniques and imaging making it an increasingly valuable tool. The basic geophysical concept behind this is that different rock types have different magnetic responses. For this reason, there is often a marked difference between the magnetic susceptibility of the basement and that of the overlying sediments. Depth to magnetic basement surfaces are created by carefully analyzing a network of 2D magnetic flight lines with multiple techniques (Naudy, SPI, Extended Euler, Werner, Peter's Half-Slope, Solokov, etc.). A surface is then created by contouring the results of the profile analysis using geologic insight. Fault block highs and grabens become evident and the basement fabric is revealed.

A recently developed 3D magnetic tool is the 3D Extended Euler technique that integrates results from 3D Euler with Werner to achieve a tighter control on the solution surfaces. An example of this is shown in the 3D image (Figure 2). Notice that the solutions form in planes. These are interpreted as fault planes, both in the basement and in the sedimentary column.

These depth-to-magnetic source solutions can be inserted into and displayed in a seismic volume. Since many of the traps form as a result of the draping of later formations over basement highs, the optimum locations for further geologic exploration are revealed. Understanding the basement, both as a surface and through the fault planes produced in 3D, provides information both on the tectonic history, the present day traps and the potential pathways of the hydrocarbons.

Perhaps one of the greatest benefits of the magnetic data is that prior to committing to an expensive seismic program in a difficult exploration terrain, one can perform detailed magnetic analysis on the readily available magnetic data using the newer techniques and imaging methods to increase geologic understanding of the area. This may affect the acquisition parameters and the orientation of the 3D seismic survey being considered. In addition, the relative cost difference between the magnetic and seismic methods can allow a more detailed laterally extensive analysis of the magnetic data after the initial seismic is shot to extend any trends seen in the seismic.

Another type of potential field data useful in Gabon for better subsurface geology definition is high-resolution gravity data. The gravity method depends on a high-density contrast between the geologic bodies of interest (in this case salt) and that of the surrounding sediment. Gravity modelling has been used for discerning between a number of geologic scenarios possible in this environment, based on both the seismic and the literature.

Among the geologic possibilities (see Figures 3 to 5) are: salt wall with greater width at the top than at the bottom (i.e. a diapiric shape in cross-section), a salt body that has become detached from its root or the autochthonous salt layer, or a

salt wall that has had the upper portion ‘dissolved’ and filled in with unconsolidated sediment (see, for example, Teisserenc and Villemin, 1989). These three scenarios can look very similar in the seismic data, however in a gravity model they have marked and measurable differences in response. Using gravity modelling to improve the geologic model, the pre-stack depth migration (PSDM) process can achieve much better results.

Another gravity method, which we believe has yet to be applied in Gabon, is the direct acquisition of gravity gradient data. This can be acquired using boat or aircraft, and is particularly useful for modelling of small, shallow features. Due to the sensitivity of the gravity gradients to shallow features, it is imperative that the topography or bathymetry is measured careful, such that the effect of the bathymetry/topography can be reduced.

As always, geophysical methods work best when integrated with each other and with the geologic knowledge in the area. The physical attributes measured with the gravity and magnetic methods provide important information that needs to be included to create the most complete geologic solution.

Akata mobile shale: Tectonism in the Offshore Niger Delta

Expanding on the concept that salt can be modelled using a combination of gravity and seismic data, the Akata mobile shale structures in the Niger Delta were examined for possible gravity signatures, with a view to modelling their response. Salt structures produce a relative gravity low due to their inherent low density compared with surrounding sediments. This density is fortunately fairly uniform, making the surrounding sediment the main variable, definable by well logs. The case for shale, however, is somewhat less consistent. Shale densities mentioned in the literature vary, dependent on a number of factors, such as water content, depth of burial and pressure regime, making modelling of shales by gravity rather difficult. The fact that shale behaves somewhat like salt, in that it forms mobile diapirs generally suggests that it has a density less than that of surrounding sediments.

This concept was initially tested using interpreted sections made available by the AAPG in *Course Manual and Atlas of Structural Styles on Reflection Profiles from the Niger Delta* by Ajakaiye, D. E., and Bally A. W., from which 2D gravity and magnetic models were constructed. These fairly simple models appear in Figure 6 and 7, with a fixed density of 2.35 g/cm³ for the Akata mobile shale, and some estimated densities for the overlying sediments. Despite these being highly simplified models, areas that are difficult to image seismically and are known shale structures, are best modeled gravitationally as shale at a lower density than surrounding material. These structures appear in the T_{ZZ}

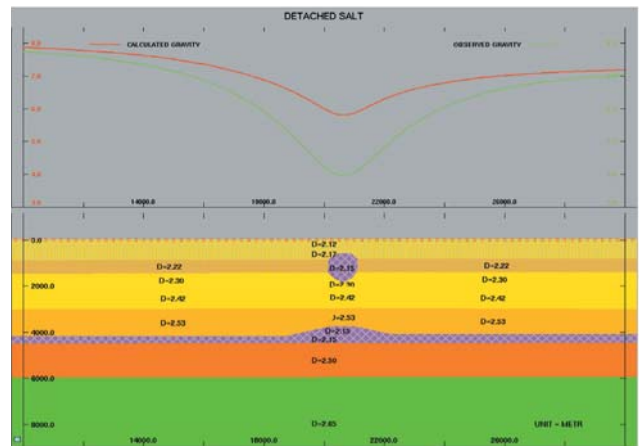


Figure 4 Detached salt body with full-salt wall response in green for comparison.

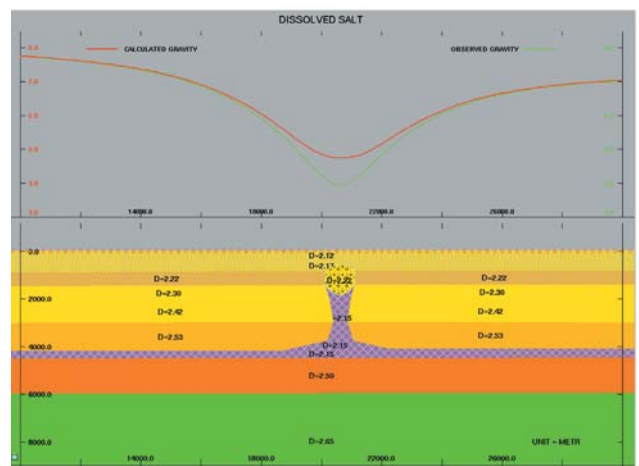


Figure 5 Dissolved top of salt wall, in-filled by unconsolidated sediments with full salt wall response in green for comparison.

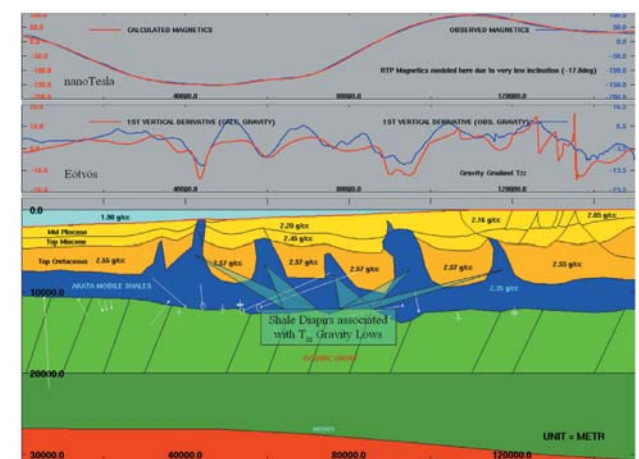


Figure 6 Model D3 based on Figure 1. Ajakaiye, D. E., and Bally A. W., “Course Manual and Atlas of Structural Styles on Reflection Profiles from the Niger Delta”. AAPG © 2002 Reprinted by permission of the AAPG whose permission is required for further use.

Non-seismic methods

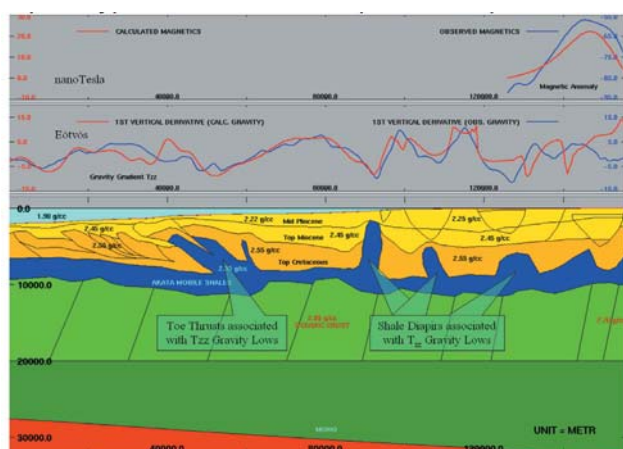


Figure 7 Model D7 based on Figure 24. Ajakaiye, D. E., and Bally A. W., "Course Manual and Atlas of Structural Styles on Reflection Profiles from the Niger Delta". Limited magnetic data were available for this line. AAPG © 2002 Reprinted by permission of the AAPG whose permission is required for further use.

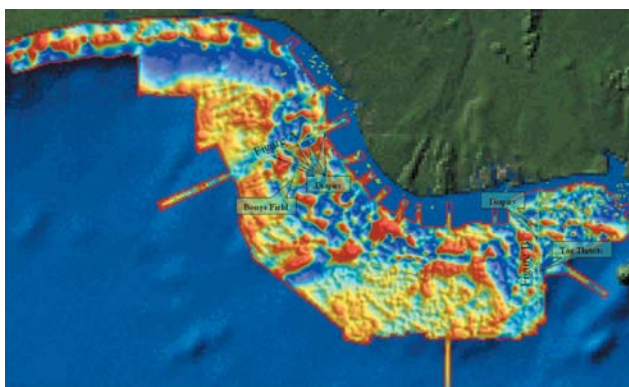


Figure 8 Location of models shown in Figure 7 and 8 over T_{zz} enhancement of Bouguer gravity. Main Akata mobile shale structures and approximate location of Bonga field labeled. Other published locations of oil fields in green.

enhancement of the Bouguer gravity (a vertical derivative of the gravimetry data, scaled to units of Eötvös) as anomaly minima, with the observed data in blue, and the calculated response from the model in red in the middle panel.

The initial models for this investigation are full-earth models, encompassing gravitational elements as deep as the Mantle surface. This is done to account as much as possible for the longer and regional wavelengths, as opposed to using arbitrary filters to isolate the signal of interest. The T_{zz} enhancement is then applied to the observed and calculated gravity profiles, which effectively accentuates the responses from shallower structures.

Exact fit between calculated and observed has not been completely achieved, as these shale structures are three dimensional in nature. The 2D models shown here, with their

assumption of infinite extent in and out of the plane of the model, do not completely characterize the true response seen in observed data. If detailed, perhaps prospect-level quantification of a shale structure were required, a 3D model would be most appropriate.

The calculated and observed magnetic responses appear in the uppermost panel, and the fit is achieved for this parameter by varying susceptibility in the basement compartments, where the majority of the magnetic response is expected to be found. Depth to magnetic source estimations using a number of techniques such as Euler, Werner and Bean Ratio A, were also made using the magnetic profile from Figure 6 (white symbols, different symbol for each technique), profile D3, largely confirming that the basement in this locality has little topographic expression, and is of the approximate depth seen in the model. This basement character is in keeping with the concept that the crust near these profiles is oceanic in nature.

Figure 8 displays the relative line location of Figures 6 and 7, overlain on the T_{zz} enhancement of Bouguer gravity mentioned previously. Major Akata shale structures are indicated as T_{zz} gravity lows, along with the published locations of major oil fields. This figure demonstrates that almost all major shale structures, from diapirs (strong, localized lows) to toe-thrusts (broad shallow lows) are clearly seen in the gravity enhancement. Moreover, trends of shale structure quickly become apparent, such as the linear trend northwest of the Bonga field, allowing rapid qualitative mapping of the Akata shale structures.

The magnetic data can also find utility (as mentioned previously) in estimating depth to magnetic basement, which would put an upper limit on the thickness of source rocks, the base of which may not be well imaged by seismic methods. Major crustal features are also apparent in the magnetic data, such as transform faults, aiding the regional tectonic understanding, and perhaps defining zones of weakness such as shears or faults in basement, that are exploited by the mobile Akata shale in the formation of diapirs and toe-thrusts. There also seems to be some association between the inferred sediment pathways as interpreted from satellite altimeter derived gravity (courtesy of Dick Gibson Consulting), seen in Figure 9, and the 5.7 km match filter (Cowan and Cowan 1993) of the reduced to pole magnetics. This could be due to magnetic material enrichment in the channel systems, or by control of basement topography on the drainage pattern. Either case is worthy of further investigation as channel systems form reservoir sections for the major fields in this area (Tuttle et. al. 1999).

Gravity and magnetic data traditionally found use in regional, large-scale tectonic understanding of a basin. These data, in conjunction with public domain satellite altimeter derived gravity, are useful for such purposes, but are also of sufficient resolution and quality for more detailed work. As detailed above, the Akata shale structures of interest can be

successfully interpreted both qualitatively using the gravity enhancements, and also quantitatively using 2D and /or 3D modelling in conjunction with seismic data. Modelling of the gravity response in 3D, in conjunction with interpreted 3D seismic, allows reduction of ambiguities in the seismic interpretation by incorporating independent geophysical methods. This approach should find most use in areas where shale structures seismically obscure targets of interest in a fashion similar to overhanging salt in such areas as the Gulf of Mexico and North Sea.

Source rock distribution and quality in the Gulf of Mexico: Inferences from plate tectonic and gravity and magnetic modelling

Using the Gulf of Mexico as a case example, it has recently been demonstrated (Jacques & Clegg 2002a, b) that an understanding of the plate tectonic history of a region is essential in providing a tool to extend our knowledge of source rock and reservoir distribution into frontier areas. As a means of understanding how tectonics through time have played a key role in determining the present day petroleum systems of a group of genetically-related basins, an advanced exploration programme has to be developed that is designed to focus on the unresolved problems and alternative models for the tectonic evolution of that region, with the first aim of identifying what is known and evaluating what is presumed about its infrastructural framework. To achieve this, it has been shown (Jacques 2002) that we should integrate the diverse range of multiple geological datasets (structural, geophysical, geochemical and sedimentological) available to identify new play fairways and to extend existing play concepts into frontier areas, such as deepwater and sub-salt. Geographic information systems (GIS) provide this technology and the medium by which spatial and temporal relationships can be observed across numerous data layers, and queries can be performed to evaluate data reliability and to perform multi-scenario analyses. This advanced query functionality provides a powerful way of assessing alternative geological models.

Although GIS provides the explorationist with extremely powerful state-of-the-art software for geospatial analyses, the usefulness of performing such analyses is totally dependent on the quality and quantity of the information in the database and on the explorationist's knowledge of the tectonostratigraphic history of the region. It is therefore essential, that the 'basic building blocks' of the region are recognized and, placed in a plate tectonic context, can be confidently used as a predictive, dynamic model. One of the ways to achieve this is to use potential fields data (gravity and magnetics) to produce detailed structural/geological coverage for the entire region. As the first and most important phase of the exploration programme, the integration of potential field data with various geological data sets can be used to define:

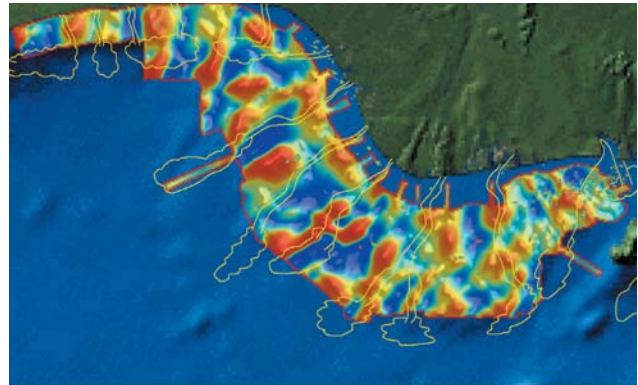


Figure 9 Match filter (5.7 km) of Reduced to Pole Magnetics with interpreted sediment pathways from Satellite Altimeter Derived Gravity (Dick Gibson Consulting).

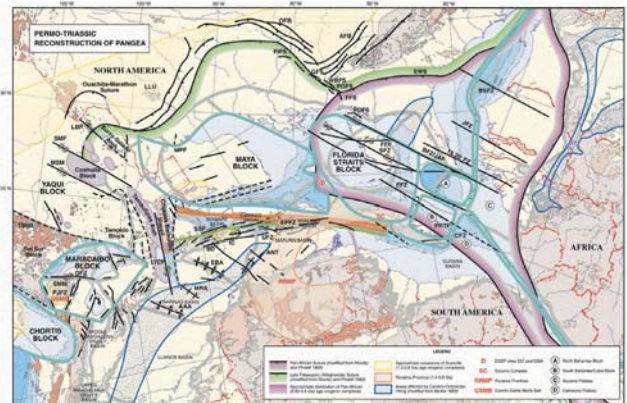


Figure 10 Permo-Triassic reconstruction of Pangea (after Jacques & Clegg 2002a), showing pre-rift continental block outlines, and their configuration and relationships. Present day basement, igneous and volcanics, and selected structural elements rotated for reference.

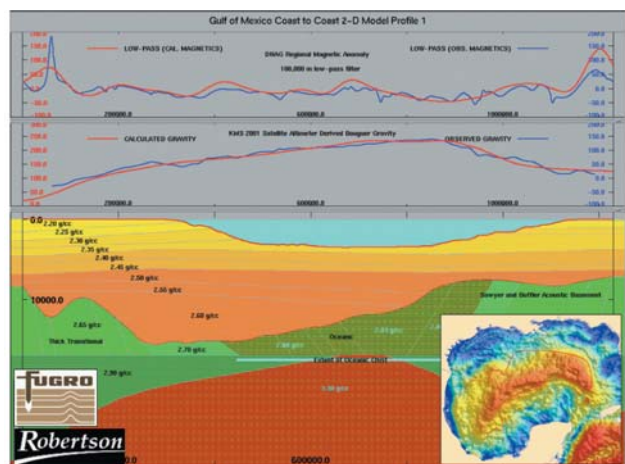


Figure 11 Example mega-regional gravity and magnetic 2-D profile across the western Gulf of Mexico. Public domain data displayed here.

Non-seismic methods

- Predominant structural basement fabrics that characterize the region
- Distribution of different crustal types (continental, oceanic and heterogeneous) and their boundaries
- Salt distribution and geometry
- Extent of igneous intrusives and volcanics

Once the present day structural/geological framework of the region has been established, it is then necessary to define individual tectonic units ('building blocks') that will form the basic components for developing a composite plate tectonic model. For this to happen, the 'original' continental block outlines (pre-tectonic block shapes and their positions), the distribution of principal crustal types, and the position of first order tectonic elements have to be identified and rigorously assessed, again using potential fields data. Shaded relief images from map enhancements of potential fields data are used to define salt geometry and distribution, and distinguish between deep basement faults, crustal domain boundaries and sedimentary growth fault systems. This should ultimately result in the development of a paleotectonic-template that can be used to create the composite plate tectonic model.

Placed in a time-referenced framework, the movements of the possible first order structures identified from the potential fields data are evaluated on the basis of several basic constraints: (1) if their kinematics are justifiable at local through to regional scale, from both field-scale observations and plate tectonic modelling; (2) if the timing of these movements are realistically feasible and can be used to explain continental block overlap and underlap issues at different stages of the region's evolution; and (3) they provide a means of explaining present-day structural and/or geological characteristics and relationships of the region. Only when compliance with these constraints is achieved for individual structures (e.g., continental transfer and oceanic transform faults) are they considered to represent an integral part of the region's tectonic development. The resultant 'paleo-template' (an example appears in Figure 10 for reference) can be further evaluated and modified using potential fields data, in particular, by creating a suite of 2D mega-regional gravity/magnetic profiles that traverse the region (example in Figure 11).

With a framework in place, different crustal types can be defined with greater confidence, the kinematic history of major continental blocks can be determined and the distribution and timing of deformational activity can be explained across the region. The end result is a thoroughly assessed set of palaeotectonic basemaps. These can be used to create a series of palaeotectonic reconstructions onto which depositional environments can be compiled for key source rock and reservoir horizons (Figure 10). Enhanced with datasets of source rock and reservoir characteristics, combined with a variety of other techniques, such as basin dynamic modelling, drainage net analyses and burial history modelling, this advanced exploration

programme can be successfully used to identify new and extend existing play fairways into frontier areas. Again, the potential fields data is an invaluable set of data, which can be used in the subsequent stages of the exploration programme, particularly during the basin dynamic and burial history modelling stages, to predict paleo-heat flow gradients for determining basin subsidence and source rock maturation histories.

Conclusions

Geologists and geophysicists have many tools at their disposal to aid in developing a complete understanding of their areas of interest. Incorporating all data available goes a long way towards enhancing that understanding, especially when high quality data are readily available from literature or data libraries.

Acknowledgements

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