Depth to basement using spectral inversion of magnetic and gravity data: Application to Northwest Africa and Brazil

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Summary

Depth to basement is important in our exploration efforts, particularly for the determination of areas where there may be mature hydrocarbons. The use of spectral methods for the inversion of magnetic and gravity data to determine depth to basement has been known for some time. It has seen limited use in practical applications. We have developed a software package that implements this theory. This software application is fast and easy to use, so that large areas can be covered quickly. The method also averages over an area so that, if noise is a factor, the results will give a more accurate result than other methods that are commonly used. The drawback is that the resolution is limited to about one-half the size of the averaging window. Here we describe the method, discuss its application, and apply it to real data in the Brazil and Northwest Africa areas.

Spectral Methods

The spectral method is based on the shape of the power spectrum for buried bodies with a density contrast. Odegard and Berg (1965) showed for simple bodies, and Bhattacharyya and Leu (1975) showed for complex shaped bodies that the depth to the center of mass of the body is easily found from the power spectrum of the gravity field If the spectrum is plotted on semi-log paper, the slope of the spectrum is equal to the depth to the center of mass. Extremely complex shapes and layering can, however, complicate the spectrum. . For magnetic bodies the results are more complex in the sense that, although the same equations apply, in practice, the spectrum gives information primarily about the location of the top and bottom of a magnetic layer (Blakely, 1995, Section 11.4.1 - 2.)

Since the gravity and magnetic fields of the earth are linear systems, this can be applied to inverting for the depth to a surface containing a distribution of complex shapes. The assumption is that the magnetic basement is composed of a randomly distributed number of structures. Then the ensemble average of the spectra is equivalent to that for a single body at the same depth. (c.f., Papoulis, 1965, Chapters 10 and 11.) These methods can also be applied to gravity data where the surface is composed of randomly distributed density variations. This process has been described for magnetic data by Spector and Grant (1970).

Odegard and Berg also showed how anomalies from bodies (and therefore surfaces) at different depths could be separated to determine the depth to each body. This is particularly useful in areas where shallow geological structures mask deeper structures. Examples are shallow salt structures masking deeper structures such as anticlines or reef systems, and shallow volcanic layers masking magnetic basement depth and structure.

This method produces very accurate results when applied to isolated bodies or to surfaces with a broadly consistent spatial distribution. It has problems when the distribution or the type of geological structures varies rapidly in a spatial sense[1]. The method also produces better results over surveys with significant noise than many other methods. This is because the data are spatially averaged over a window of the data.

Implementation in Software

The implementation of spectral inversion is tedious in most available software. To do work in a more efficient manner, a program was written in Matlab™ that implements the spectral method. The display screen from this application is shown in Figure 1, and a single spectrum of the magnetic field over a 40x40 kilometer area over the magnetic data grid shown in the lower right window is shown in Figure 2.

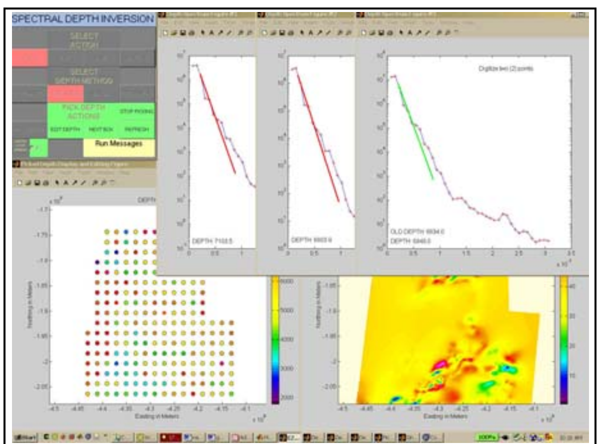

Figure 1: Spectral Depth Estimation Software Application.

[1] This is equivalent to the gravity or magnetic field being spatially non-stationary.

Depth to Basement Analysis for Morocco and Brazil

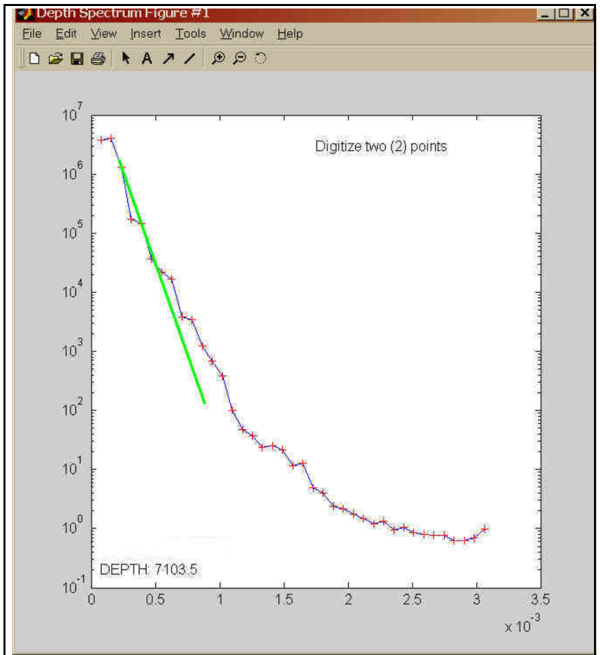

Figure 2: Spectral depth inversion showing a depth Estimate of 7104 meters. The average radial spectrum is from an area of 40x40 kilometers of the magnetic data grid.

The Process

The process of mapping the depth to basement using a grid of magnetic data as shown in Figure 3 involves calculating the average radial power spectrum over a rectangular window on a magnetic or gravity grid. We have found that a 40x40 kilometer window is useful for basement depths encountered in hydrocarbon exploration. Smaller windows can be used for surveys with better and higher resolution data. After the average radial power spectrum is calculated, it is displayed in a semi-log figure of amplitude versus spatial wave number. A straight line is then visually fit to the power spectrum, usually in the higher amplitude, lower wave number area of the figure. For gravity and magnetic data the negative of slope of this line is equal to twice the depth to the center of mass of the bodies producing the gravity or magnetic field.

After the depth has been calculated over one window a new calculation is made over a new window. In our semi-automated application we usually step the window horizontally or vertically by one half the width of the window. This continues over the grid until all windows have had their radial spectra calculated and the depths picked. As depths are picked their depth versus color coded locations are plotted as shown in the lower left window in Figure 1. The windows used are also plotted over the magnetic data which is displayed in the lower right window.

After completion of the depth picking for all windows covering the data grid, we edit the individual data points to make the depth estimation over the grid more consistent internally and with external constraints. This consists of clicking on the location of interest, and recalculating the spectrum and re-picking the depth.

After completion of the picking process the depth picks are gridded using an appropriate algorithm. After the gridding the resultant grid usually has noise caused by miss-picked points. These are reduced or eliminated by using a median filter on the grid. The resultant grid is then smoothed using a soft low pass filter.

Quality Control

After the spectral inversion is initially completed the grid depths are compared to constraining data such as well TD's, seismic interpretations, and geological data. The well TD's can be both from basement, which give the actual depth, and other TD's which give a minimum depth.

For seismic data the interpreter should remember that interpreted basement is probably acoustic basement, which may or may not be magnetic basement. In many cases the actual basement horizon may not be visible. One reason is that the sediments just above basement can have approximately the same acoustic impedance. This could be due to weathering of the basement and/or highly consolidated, probably, older sediments. Thus we would expect that magnetic basement is usually deeper than acoustic basement. It may also be deeper than the well TD basement where the basement may have been picked from cuttings, and highly consolidated sediments interpreted as basement type rocks.

If basement is found to be above the well TD or acoustic basement, this could be for several reasons. First, and less probable, is that the basement may not be magnetized either due to weathering or to destruction of the magnetization by high temperatures. Second, there may be intermediate depth sedimentary layers with magnetic material either eroded from material with a high magnetite content or from volcano-clastics. Third, there may be intermediate depth volcanic material either erupted at the surface and buried, or injected as a laccolith. In some cases the magnetic signature from the volcanic material may overwhelm that from the actual basement. But in most cases the signatures from both surfaces should be visible in the displayed spectrum as two distinct linear trends as described by Odegard and Burg (1965)and Spector and Grant (1970). If this is the case then both surfaces can be mapped with important consequences in some exploration plays.

Finally, the accuracy of the method is an important consideration. For noisy data the spectral method may be the only way to determine an estimate of the depth to basement. This is because other direct inversion methods have difficulty in dealing with noise. In these areas spectral depth estimates are accurate to about 10% to 30%. In areas with good data this accuracy increases to 5% to 10%. We must always remember, however, that these estimates are for the average depth over the window in which the averaged radial power spectrum is calculated.

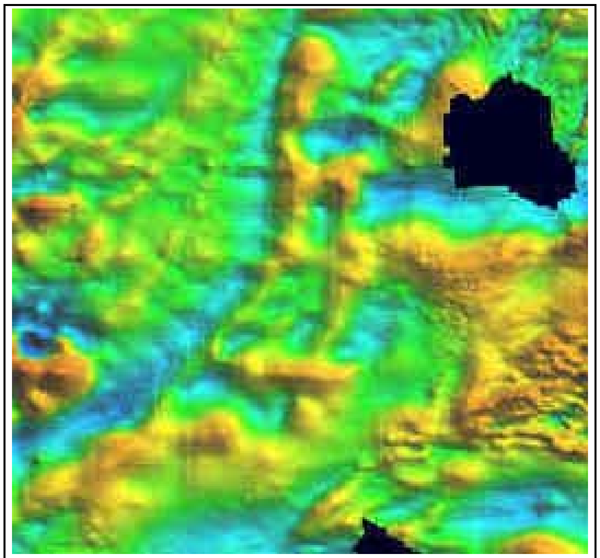

Figure 3: Example of magnetic data used in the Morocco project.

Results for Morocco and Brazil

The magnetic data over a portion of on and offshore Morocco is shown in Figure 3. The depth to basement results for this area are shown in Figure 4. And, the resultant sediment thickness is shown in Figure 5. In comparing the sediment thickness to the depth to basement, the topography and bathymetry must be taken into account and are not shown. Based upon our knowledge of the area the results of the depth to basement inversion appear reasonable. Note the correspondence between the high frequency on shore area, the shallow basement, and the thin sediments.

Over onshore Morocco and in shallow water offshore the newly re-leveled magnetic data are of good quality. In these areas the lateral resolution is 20 to 30 kilometers. Offshore Morocco, with good quality data, the depth accuracy is 5% to 15%. Offshore Brazil, with high quality data, the accuracy is 5% to 10% of depth. In the deeper water, offshore of Morocco, data are from public domain NGDC data. In these areas the lateral resolution is 30 to 40 kilometers and the depth accuracy is about 10% to 30%.

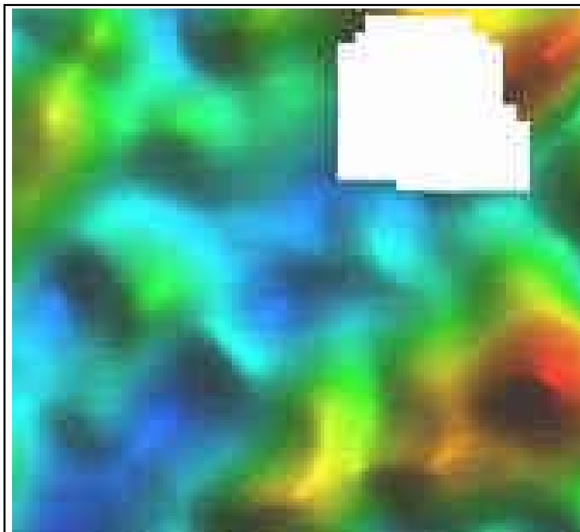

Figure 4: Depth to basement image from Morocco project. Shallow depths are in red.

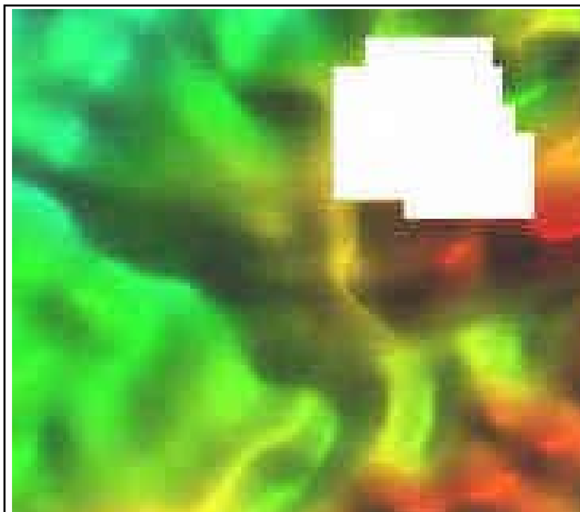

Figure 5: Sediment thickness image from Morocco project. Thick sediments are in red.

Multiple horizons can be picked in many areas. Examples are offshore the Canary Islands in Morocco and the Santos Basin of Brazil. These correspond to the top and intermediate layers of volcanic material. The upper volcanics overwhelm the basement magnetic signature off the Canaries. Thus, there is a thicker sedimentary section offshore in the North and South Canary depositional centers than is derived from our depth to basement data. The ratio of volcanics to deposited sediments probably varies laterally. These volcanics will cause problems for exploration, particularly for reservoir risk.

In all of the offshore areas in both Morocco and Brazil, where there are seamounts or islands, the sediment thickness data will be inaccurate. This is because the averaging windows will generally average over the island/seamount basement and pick the deeper basement in the surrounding basins. As a result, when the bathymetry is subtracted, the predicted sediment thickness will be too thick at the seamounts.

Morocco

Over the Atlas and Rif mountain systems of Morocco there are at least two solutions for basement depth. This is because these are products of thrust tectonics. We have generally tried to pick the deeper solutions, which gives a depth to the deepest thrust.

The more prominent shallow basement areas are the Rharb and Doukkala basins of the Moroccan Meseta. A geo-referenced profile, Figure 3 from Boot, et al. (1998), shows quite close agreement with these shallow and deep basin locations, although our results are somewhat deeper. This shallower depth to basement also extends offshore into the Safi basin. There are also shallow areas related to volcanics in the northeast area of Morocco.

Conclusions

The depth to magnetic basement and sediment thickness data discussed in this report are generally an accurate representation for the Morocco and Brazil area. Where the data is good the results are better. In the deeper offshore where we had to use NGDC data the results are less reliable. The data were carefully analyzed and edited several times to assure accuracy. As noted above the results compare well with published data.

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