A Sediment Thickness Map of South America Using Automated Inversion of Magnetic and Gravity Data for Depth to Basement.

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Abstract

This paper presents the techniques and results of a depth to basement inversion effort over all of South America with a special emphasis on offshore Brazil. The spectral method was applied to magnetic and gravity data. New high resolution data sets for gravity and magnetic data have been merged and now cover all of South America. The data used were derived from a variety of sources, and leveled and merged using techniques specially developed for large data sets.

This paper presents a detailed description of the development of a program to invert gravity and magnetic data using the spectral technique. The results of these developments are applied to determining the depth to basement and sediment thickness over all of South America.

Introduction

We have used the gravity, magnetic, geological, geochemical, seismic and well data to understand basin structure and development. A primary first step is the merging and integration of this wide variety of data into a GIS environment. The next is the development of a description of the basement structure using geophysical techniques, which is consistent with all of the data. The final step is re-integration and interpretation of all data to produce an understanding of basin development and evolution. The results of this approach has been very usefull, for example in a prediction of the deep Santos play off Brazil (Dickson, et. al., 2005, 2008).

As part of the determination of the basement structure over large areas, some new techniques have been developed and applied for automatic depth to basement inversion. These include the use of a Tau-P approach to spectral inversion of gravity and magnetic data. A detailed description of these methods are presented in the following.

Theory and Method

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 displayed in a semi-log plot where 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 an aerially 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.) . This process has also been described for magnetic data by Spector and Grant (1970). These methods can also be applied to gravity data where the surface is composed of randomly distributed density variations.

The spectral method has been extended using a variation of the Tau-P method to make the process automatic. The Tau-P method or Radon transform has been described and used by several authors (c.f. Estill and Odegard, 1979).

The process of mapping the depth to basement first involves calculating the average radial power spectrum over a rectangular window on a magnetic or gravity grid. After the average radial power spectrum is calculated, it is displayed in a semi-log figure of spectral power versus spatial wave number. This is illustrated in Figure 1. A straight line is then fit to the power spectrum, usually in the higher amplitude, lower wave number area. 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. When used in a semi-automatic mode the line fit to the data can be edited by moving the end points.

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 or surface. 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 fact will be used later in the paper to map facies.

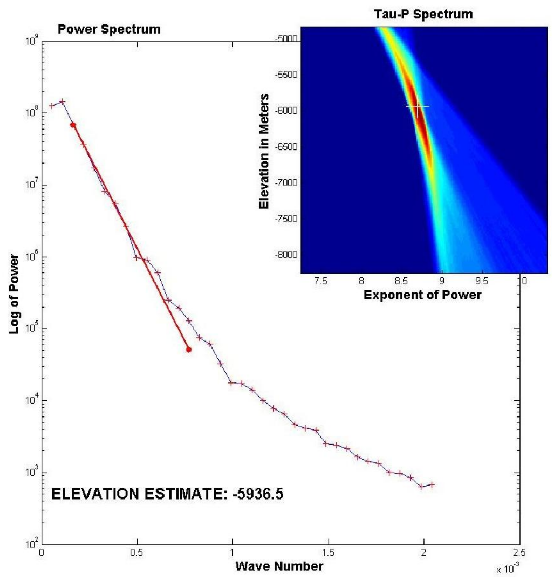

Figure 1: Spectrum and Tau-P spectrum of a 40 by 40 kilometer window of magnetic data over the Santos Basin.

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. The spectral 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.

Data Merging and Leveling

Data for these projects are a combination of data from all available sources. These include data from the US National Geophysical Data Center (NGDC), other government sources, global compilations, and data digitized from published sources. The merged elevation data for South America is shown in Figure 2.

Methods developed to level and merge large data sets (Odegard, 2009) were used to produce the grids of gravity, magnetic and bathymetry data at a resolution of 30 arc-seconds or about 900 meters. Images of the resultant free air gravity and total magnetic intensity grids over the South America are shown in Figures 2, 3 and 4.

The Process

The process of mapping the depth to basement by inverting a grid of data involves calculating the average radial power spectrum over a rectangular window on a magnetic or gravity grid. The windows used are shown over the input data is shown in the lower right in Figure 5, and the output inversion points are shown in the lower left with a color depth scale. Three power spectra are shown at the top in three windows like that in Figure 1 which in this figure are behind the windows. These three windows when poped up are particularly usefull when editing in a semi-automatic mode.

Figure 2: Digital elevation model for South America.

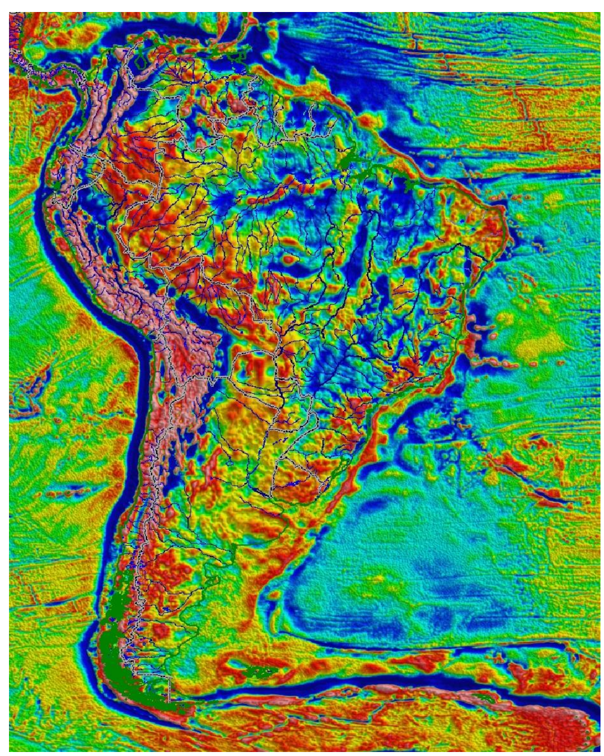

Figure 3: Free air gravity for South America.

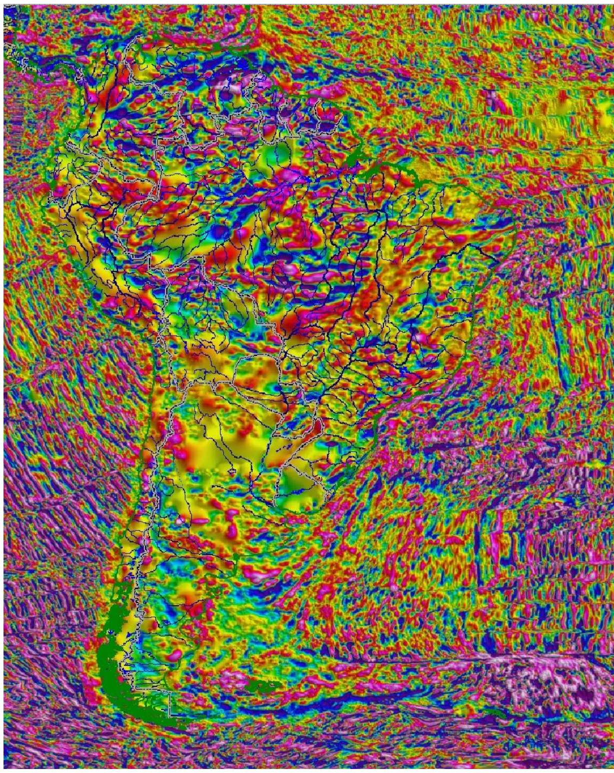

Figure 4: South America total magnetic intensity (TMI).

A 40x40 kilometer window is useful for basement depths encountered in hydrocarbon exploration, however for shallower basement a 20 by 20 kilometer window, and for deeper basement 60 by 60 or 80 by 80 kilometer windows are used.

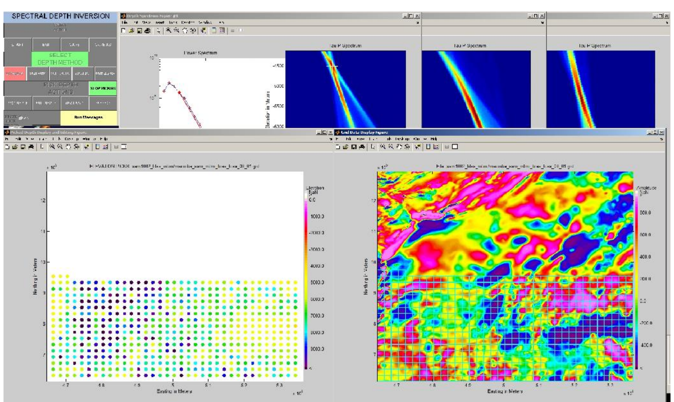

Figure 5: Spectral inversion desktop.

After the depth has been calculated over one window a new calculation is made over a next window. In our semi-automated application we usually step the window horizontally or vertically by one half the width of the window, but for higher resolution a 5 or 10 kilometer step can be used. The South America area is partitioned into overlapping tiles. These tiles are in bands of different projections which are best for that latitude. An Albers equal area conic is generally used.

Implementation

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 5.

Because the process of fitting a line to data is similar to the Tau-P method for seismic data a similar process can be used. First, to speed up the process, an estimate is made of the Tau-P spectrum by mapping the gradient (P) and the intercept (Tau) of the tangent to the curve for each point in the power spectrum. This gradient and intercept of the tangent are mapped into the Tau-P domain. The result is shown in Figure 6 for the data in Figure 1.

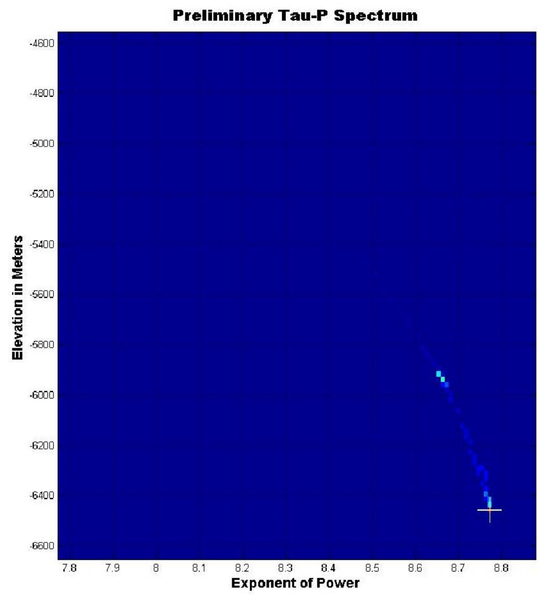

Figure 6: Fast preliminary Tau-P spectrum. Tau is the exponent of power and P is the elevation in meters. The white cross shows the preliminary best solution for depth.

It was found that smooting this grid resulted in a better determination of the maximum of the data. This is shown in Figure 7. The preliminary estimate of the best Tau-P solution is shown by the white cross over the maximum in the lower left corner.

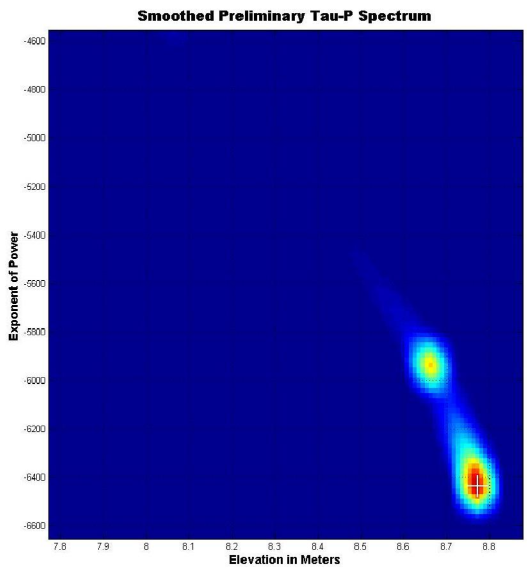

Figure 7. Smoothed fast preliminary Tau-P spectrum.

Finally using the preliminary solution a smaller window is chosen about this solution and the full spectrum is calculated. For each frequency point of the power spectrum a seismic type trace is constructed as a delta function of the exponent of the power. This delta function is then convolved with a cosine wavelet to simulate error in that value of the spectrurn. The set of traces is shown in Figure 8. A Tau-P spectrum, with amplitude that is the semblance of the linear fit, is calculated over the window of Tau's and P's.

Figure 8: Simulated seismic traces for the power spectrum in Figure 1.

The maximum of the semblance is taken as the best fit of a line to the original spectrum. This pick is shown as a white cross in the Tau-P spectrum window in Figure 9. The semblance can be weighted to emphasize shallow or deep solutions. In Figure 9 the Tau is the exponent of the power in the power spectrum and P is the elevation. Note that the best solution from the preliminary spectrum in Figure 7 is not the same as in Figure 9. The secondary peak in Figure 7 is actually nearer the "best" solution.

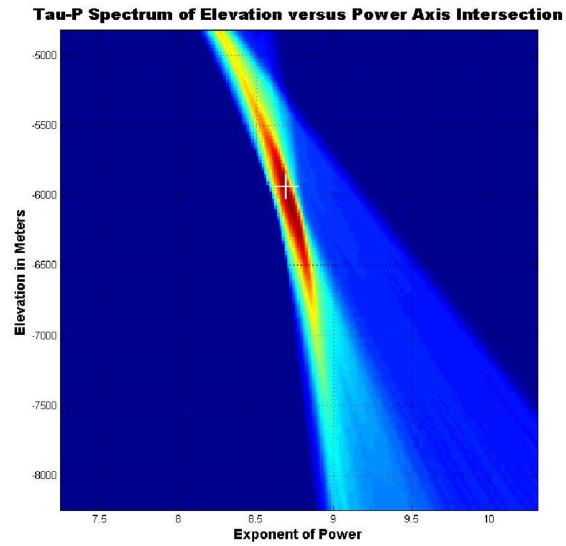

Figure 9. Final Tau-P spectrum of straight line fits to the power spectrum in Figure 1. The white cross shows the maximum semblance in the spectrum.

Quality Control

After the spectral inversion is 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.

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). 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. With the type of data easily available in this area spectral depth estimates are accurate to about 10% to 30%. In areas with good data this accuracy increases to 5% to 10%. It must always be remembered, however, that these estimates are for the average depth over the window in which the averaged radial power spectrum is calculated.

Results

The free air gravity and total magnetic intensity data over South America area were inverted for depth to basement. The resulting inversions were merged, generally selecting the deepest solutions, but using constraining data. The result is shown in Figure 10.

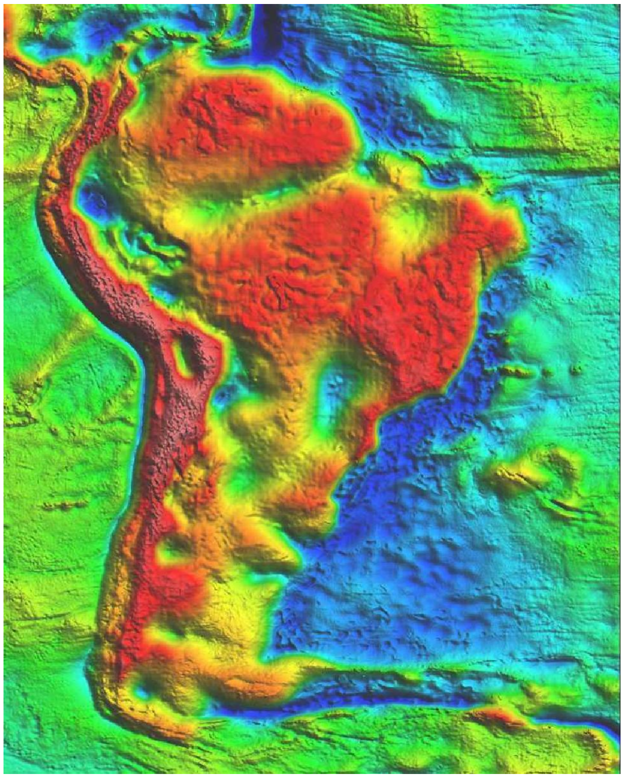

Figure 10: Depth to merged basement over South America. Reds are shallow and blues are deep areas.

Subtracting the depth to basement from the digital elevation model gives the resulting estimated sediment thickness as shown in Figure 11.

The results from inversion of each of gravity and magnetic data show both similarities and differences. Subtracting these two data grids produces the result shown in Figure 11. As noted in the section on quality control above these differences may generally be attributed to shallower volcanism than magnetic basement and are shown in red. Similarly carbonates deposited above or on magnetic basement would give a shallower gravity basement and are shown as blue. In particular note the known shallow volcanics over the Bacia do Paraná. Many areas have similar basement depths which are shown in white and gray. Some areas which show no variation in the difference are generally without magnetic data and so are masked out and shown in gray.

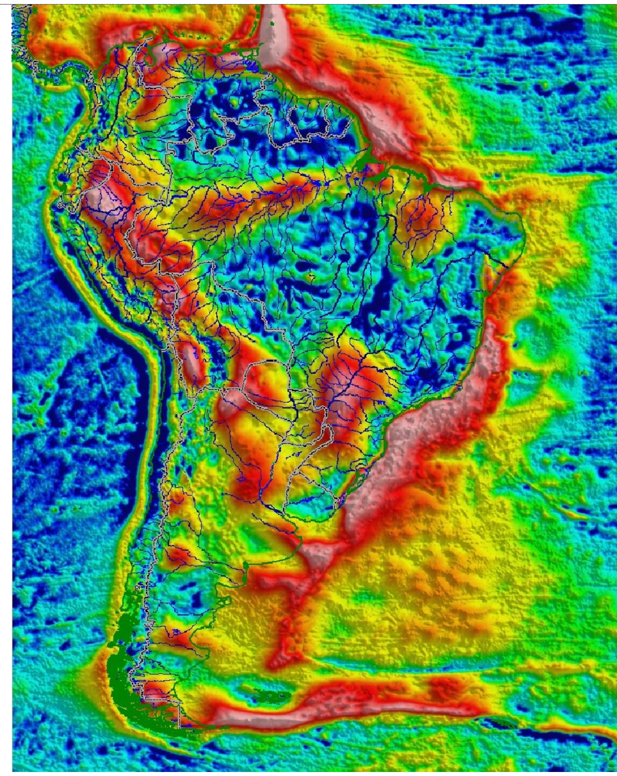

Figure 11: Estimated sediment thickness over South America.

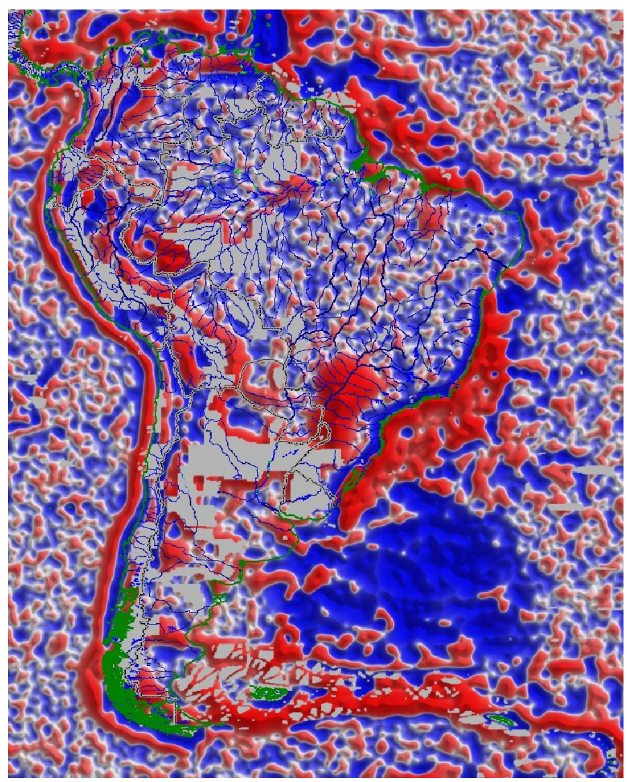

Figure 12: Results of subtracting the gravity from the magnetic depth to basement estimates. Red is for shallower magnetic and blue is for shallower gravity

estimated depths. Areas with similar depths are shown in white and gray.

Correlations between the basement structures have been made with known geology. In most areas the correlation is very good. In other areas where there is no geological or seismic control, structural and tectonic trends can be interpreted and extended into these areas. In some areas the correlation is contrary to published results and we evaluate all the available data to develop the best interpretation. In some of these areas the resolution of the depth to basement results, about 20 kilometers half wave-length, is insufficient to discriminate among various interpretations. In other areas we conclude that the initial interpretations are incorrect, generally due to the early lack of sufficient data. The results of the interpretation have been documented in several papers as documented on my web site: grizgeo.com.

Other Areas

Depths to basement and sediment thickness projects have been completed over Southeast Asia (Odegard, et al., 2007), the east coast of the United States (Odegard, et al., 2008), the Bay of Bengal, and Africa (Odegard, 2011).

More detailed projects have been done over Morocco (Odegard, et al., 2004) and Suriname (Odegard, et al., 2005).

Conclusions

We have used gravity, magnetic, seismic and well data to determine a depth to basement structure over South America. This structure has allowed us to constrain the early tectonic and basin development of the area. Additionally we have been able to predict the location of shallow volcanic facies, and the location carbonate facies probably residing on basement. Results have validated the use of the automatic and semi-automatic spectral inversion method over large areas.

Acknowledgments

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