Depth Estimate and Mapping of source geometries from High Resolution Aeromagnetic (HRAM) data of Benisheikh, Nigeria

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Abstract. Depth to magnetic basement and mapping of source geometries were estimated from High Resolution Aeromagnetic (HRAM) data of Benisheikh using wavelet transformation technique. This technique was chosen because it has been proven to be a powerful and efficient tool in interpreting potential field data. In this work, a non-orthogonal wavelet function with a good symmetry and higher vanishing moment, Morlet was chosen as the analyzing wavelet. Wavelet power spectrums of the aeromagnetic anomalies were obtained using the scaled normalized analyzing wavelet in order to estimate the depth to the magnetic basement. Also, the square of the absolute value of the wavelet coefficient were plotted against the period in order to identify and map variations of pronounced and least energy values which can be regarded as magnetic source geometric features found from the HRAM data profiles. The results obtained from the analysis have shown the ability of wavelet transform as a tool in depth estimation and mapping of geological features of HRAM data of this part of Nigeria.

KEYWORDS: Wavelets transform, High Resolution Aeromagnetic data (HRAM), Morlet Wavelet and geometrics features.

1.0 Introduction

Magnetic technique is one of the geophysical survey techniques that exploit the considerable differences in the characteristics of magnetic minerals on the foundation of anomalies in the Earth’s magnetic field which is as a result of the properties of magnetic rocks beneath earth surface [1]. These anomalies can be analyzed to estimate depth to magnetic basement and mapping of geological features. The importance of basement depth geological features for minerals signatures in basins cannot be overemphasized. This is because of the impact of the basement on the geology of the sedimentary rocks found above it and also the subsequent control on the development of hydrocarbon pools [2]. When the magnetic depth to the basement is contoured, it will provide an illustration of the spatial variation about the sedimentary thickness of the area under consideration. These illustrations correlate meaningfully to the known sedimentary activities in the region of study. The usefulness of these studies is to establish a reconnaissance survey using HRAM data for hydrocarbon or mineral signatures of an area so that Seismic techniques can be applied to these areas for hydrocarbon accumulation [3], [4].
The HRAM method was rediscovered in the 1990s to provide valuable data to solve petroleum exploration problems in the oil and gas industries [4]. This is evident from many reputable publications [2]; [3]; [4]; [5]; [6]; [7]. Some papers on the analysis of HRAM anomaly for hydrocarbon or mineral exploration are those of Western Canada [3]; [4], oil traps in China [5]; [8], over the Chad lineament (North-Central Africa) [9]. etc.

Geologically, Chad basin has been described as a broad sediment-filled depression stranding Northeastern Nigeria and adjoining parts of Chad Republic (Fig.1). The sedimentary rocks have a cumulative thickness of over 3.6 km and consist of thick basal continental sequence and transitional calcareous deposit. The stratigraphic sequence (Fig.2) shows that Chad, Kerri-kerri and Gombe formations have an average thickness of 130 to 400 m. Below these formations are the Fika shale with a dark grey to black in color, with an average thickness of 430 m. Others are Gongila and Bima formations with an average thickness of 320 m and 3.5 km respectively [10].

In this work, we have applied wavelet analysis using Morlet as the analyzing wavelet to the High Resolution Aeromagnetic (HRAM) data of part of Chad basin, Nigeria in order to estimate the depth to the magnetic basement and mapping of source geometries from High Resolution Aeromagnetic (HRAM) data of Benisheikh, Nigeria.

Fig.1: Geological Map of Chad basin Nigeria
2.0. Materials and Methods

2.1 Theory of wavelet transform

The Continuous Wavelet Transform (CWT) of a discrete sequence $X_u$ is defined as the convolution of $X_u$ with a scale $s$ and translated version of the wavelet basis or mother wavelet $\psi_{s,t}(u)$. The CWT is given as [11] and [12]

$$W_u(s,t) = \sum_{k=0}^{N-1} X_u \overline{\psi_{s,t}}(u) \quad s > 0$$

(1)

where

$$\psi_{s,t}(u) = \frac{1}{\sqrt{s}} \psi\left(\frac{u-t}{s}\right)$$

(2)

is the dilated and translated wavelet basis or mother wavelet function, $s > 0$ is the scale factor, $t$ is the translation parameter, and $\overline{\psi_{s,t}}(u)$ is the complex conjugate $\psi_{s,t}(u)$. [11] also interpreted the wavelet transform as a mathematical microscope, where the magnification is given by $\frac{1}{s}$ and the optics are given by the choice of wavelet.

In frequency domain, equation (1) can be equivalently expressed as

$$W_u(s) = \sqrt{s} \sum_{k=0}^{N-1} X_k \psi(sw_k) e^{i\psi_{u,t} \varphi}$$

(3)

From equation (3), the wavelet transform of a discrete profile data $X_k$ can be viewed as the coefficient of the CWT at different scales. Generally, it has been observed that a large-scale wavelet transform can be used to obtain the spectral depth estimation [13]. But the choice of wavelet function depends on the nature of the signal to be considered. It is important to note that the choice of the wavelet function $\psi_{s,t}(u)$ is neither unique nor arbitrary. This function $\psi_{s,t}(u)$ is normalized to have

$$\int_{-\infty}^{\infty} |\psi(u)|^2 du = 1$$

unit energy (i.e., $\gamma$) so that it has a compact support, or sufficiently fast decay, to
obtain localization in space and zero mean (i.e., \(\int \psi(u)du = 0\)). The requirement of zero mean is called the admissibility condition of the wavelet. The normalizing constant \(\frac{1}{\sqrt{s}}\) is chosen so that \(\psi_{s,t}(u)\) has the same energy for all scales \(s\).

In aeromagnetic data analysis, resolution in both time and frequency is necessary. Therefore Morlet wavelet, a non orthogonal transform, whose Fourier transform is a Gaussian function and is fairly ideal band-pass filter, will give a resolution in both time and frequency are adopted in this work.

The Morlet wavelet basis function is given as

\[
\psi(t) = \pi^{-\frac{1}{4}} e^{jw_0 t} e^{-t^2/2} \tag{4}
\]

Where \(w_0\) is a non dimensional frequency and is taken to be 6 in this work in other to satisfy the admissibility condition. This wavelet function of equation (4) is a complex valued (Fig. 3a) which enable one to extract information about the amplitude and phase of the signal being analyzed. Its Fourier transform is also given as

\[
\widetilde{\psi}(k) = e^{-j(k-k_0)^2} \tag{5}
\]

Its spectrum character is shown in Fig.3b. The wavelet function in equation (5) is approximately zero for \(k<0\). This is particularly attractive for certain analyses where one needs to eliminate the interference of negative frequencies for the interpretation of results.

Fig. 3a-b.a) Real and imaginary parts of the Morlet wavelet \((k_0 = 6)\). b) its Fourier spectrum for different scales: \(s = 1\) (solid line), \(s = 2\) (dash line), and \(s = 10\) (dash-dotted lines).
From the definition of the Continuous wavelet transform, the coefficient can be computed by convolution in space domain or in Fourier space using discrete Fourier transform.

We computed the coefficient of the CWT in the frequency domain because it is considerably faster to do calculations in Fourier space and the implementation steps are listed below

1. We computed the Fourier transform $H(k)$ of the original signal $h(x)$.

2. We multiply the Fourier transform $H(k)$ with the Morlet wavelet $\psi(k)$ in the frequency domain and obtain the wavelet transform at scale $s = 1.75$ that is,

$$W(k) = H(k) \times \psi(k)$$

3. We computed the inverse Fourier transform of $W(k)$ and obtain the coefficient of wavelet transform result $W_u(t)$ in space domain.

4. We calculated the wavelet transform at different scales with the dilated wavelet basis and obtain the result of the wavelet transform at different scales following steps 2 and 3.

To obtain the wavelet power spectrum from the implementation steps mention above, the modulus square of the coefficient of the CWT is computed for every profile data that is

$$P(k) = |W_u(t)|^2$$

The maximum decomposition scale relates the dimension of the original data and the scale can take continuous values with a maximum of half of the data dimension [13]; [14]. Here we also adopted [13] scaling relation which is defined as:

$$s_j = s_0 2^{j\hat{\gamma}}, \quad j = 0,1,\ldots,J$$

$$J = \hat{\gamma}^{-1} \log_2 (N\bar{c} / s_0)$$

Where $s_0$ is the smallest resolvable scale and $J$ determines the largest scale. $\hat{\gamma}$ depends on the width in spectral-space of the wavelet function. For Morlet wavelet, a $\hat{\gamma}$ of 0.5 is the largest value.
that still gives adequate sampling in scale. a 0.125 is appropriate because smaller values gives better resolution.

2.2 Depth estimation

Generally a mathematical basis for the application of power spectrum analysis to aeromagnetic map interpretation has been developed by [15]. They studied the relationship between the power spectrum of aeromagnetic anomalies and the average depth of source bodies using some statistic assumption. This provides a foundation for anomaly source parameter estimation of depth to magnetic sources. The power spectrum of aeromagnetic anomalies can be written as:

\[ \langle P(k) \rangle = 4\pi^2 M^2 \left( e^{-2hk} \right) \left( 1 - e^{-tk} \right) \langle S^2(k) \rangle \]  \hspace{1cm} (9)

Where \( \langle \rangle \) stands for ensemble average, M is the magnetic moment/unit volume, h is the depth of the top of the source body, t is the thickness of the source body, k is the radial wave number and \( \langle S^2(k) \rangle \) which is defined in equation (9) represent the horizontal size of the source body.

\[ \langle S^2(k) \rangle = \frac{1}{\pi} \int_0^\pi \left( S^2(k, \theta) \right) d\theta \]  \hspace{1cm} (10)

[15] found that the \( e^{-2hk} \) term which is the depth factor is invariably the dominating factor in the power spectrum and that the effect of the extension factor \( 1 - e^{-tk} \) and the horizontal factor \( \langle S^2(k) \rangle \) is comparatively small, especially in low-frequency bands. From equation (8), the third and the last are relatively small, therefore it becomes

\[ P(r) \approx Ce^{-2hk} \]  \hspace{1cm} (11)

Taking the log of equation (11), we have

\[ \ln(P(r)) \approx -2hk + C \]  \hspace{1cm} (12)

\[ h = -\frac{s}{2\pi}, \]  \hspace{1cm} (13)

Where C and \( C \) are constant coefficients and h is the average depth of the source body. From equation (12), the plot of log power spectrum against the radial wave number gives results of different spectrum segments. The slopes obtained from the above plot indicate the average depth to the source bodes.

2.3 Mapping of source geometries from HRAM data of the study Area

High Resolution Aeromagnetic map with sheet number 88 was procured from the Nigeria Geological Survey Agency (NGSA). The study area is bounded by the UTM coordinate Northings, 1270000 mN and 1330000 mN and Easting, 830000 mE and 880000 mE. The map was windowed from the National sheet index data base delivered in Oasis Montaj format. The contour interval is variable at 5, 10, 25, 50 and 100nT. The average magnetic inclination across the survey area was from 9° in the north to 0°in the south. The map was carefully gridded and digitized using Oasis Montaj at an equal spacing of 0.875km yielding an approximate eleven (11) profiles which cut across the entire study area.
3.0 Results and Discussion

For the purpose of estimating depth to the magnetic sources which is a quantitative interpretation technique, profile lines labelled (1-11) were drawn on the aeromagnetic map shown in the Fig. 5 and it would be observed that these profile lines cut across various anomaly of interest. Therefore, the implementation steps of CWT in the frequency domain described above was applied to each of the profiles and the wavelet spectral analysis was computed using equation (12). From the wavelet spectral analysis, logarithms of the spectral energies against the frequencies for four out of eleven profiles on a map are shown in Fig. 6. Two linear segments could be drawn from each graph, the gradients of each linear segment were evaluated and equation (13) was used to estimate the depth to the shallow and deeper basements. The wavelet power spectral of the anomaly is mainly concentrated in the low frequency (0.0-0.3 km$^{-1}$) region and linear segment from this region represent contributions from the deep-seated causative bodies obtained from the profile graph and the high frequency region (0.35-0.5 km$^{-1}$) represents contributions from the shallow bodies. The gradient of the linear segment was evaluated and depth to magnetic sources was determined from each of the profile plots. The result obtained from the deeper sources varies from a thickness of 0.41 to 6.10 km while the shallow source depth ranges from 0.10 to 1.51 km respectively.

In other to map the geometric source, the results of the implementation steps described above as applied to some of the profiles and scalogram plots are shown in (Fig.7). The results shows two types source geometries, namely spheres and horizontal dykes. Profile 5 has a dyke like source geometry while other profiles are predominantly spheres. It can also be observed that majority of these sources are found at the low frequency portion of the scalogram plots and are located a varying distances in the profiles. This is an evidence to show that magnetic sources identified from this study are deep-seated structures and they can be regarded as sources responsible for hydrocarbon prospects.
Fig. 6: Depth estimate from the wavelet spectral analysis of some selected profiles
Fig. 7: Some Selected Profiles (P₁, P₃, P₅, and P₁₀) and their Scalogram plots.

4.0 Conclusions

Wavelet transform has been applied to the HRAM data of Benisheikh, Nigeria. It has efficiently analyzed and interprets both geometries and locations of the magnetic sources. It can therefore be suggested that these sources are responsible for hydrocarbon prospect. The technique can equally be applied to other part of the study area in other map the distribution of magnetic sources and this will serve as a guide before other methods such as Seismic can be applied for hydrocarbon exploration.

5.0 References

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