



ANALYSIS OF REGIONAL MAGNETIC ANOMALIES IN THE SOUTH CASPIAN BASIN

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Abstract: *The South Caspian Basin stands out as a geodynamically complicated area featuring an unusually massive sedimentary layer. Such a profound sediment thickness creates significant obstacles for conventional seismic methods attempting to map the deep crystalline basement. In order to overcome these structural ambiguities this study employs magnetic field data derived from the Earth Magnetic Anomaly Grid project. These measurements were processed into a 2 km by 2 km grid for comprehensive spatial assessment. Through the implementation of a two dimensional radially averaged power spectrum technique on the mapped anomalies the depths of various magnetic causative bodies were precisely evaluated. Spectral estimations successfully identified deep seated regional magnetic anomalies at an average depth of 16 km. To successfully isolate these deep geological signatures a low pass Butterworth filter was implemented with a specific cutoff wavenumber to extract the regional magnetic field from the total signals. The isolated regional maps effectively emphasize massive structural trends and deep crustal boundaries beneath the thick sedimentary cover. Notably the computed 16 km depth for the regional magnetic source is markedly shallower than the crystalline basement depth exceeding 20 km established by seismic studies. This discrepancy is interpreted to reflect the presence of highly magnetized mafic and volcanic bodies within the deep sedimentary section rather than marking the true sediment crystalline basement transition. Conclusively the integration of accessible satellite magnetic data with advanced spectral analysis serves as a highly efficient non invasive approach for determining the fundamental crustal architecture of exceptionally deep sedimentary basins.*

Keywords: *South Caspian Basin; satellite-derived magnetic data; spectral analysis; low-pass Butterworth filtering; magnetic basement*

1. INTRODUCTION

The Caspian Sea is a unique enclosed inland water body of considerable geological and tectonic significance. It formed where the ancient Tethys and Eastern Paratethys seas existed since the Paleozoic era [1]. In the Caucasus Caspian area earthquakes and ground deformations mostly happen in three main zones namely the Bitlis Zagros Fold and Thrust Belt the Alborz Kopet Dag and the Greater Caucasus with the Central Caspian Seismic Zone [2, 3]. The South Caspian Basin is a very active and complex region located inside the Alpine Himalayan mountain belt [4]. It is famous worldwide because it has one of the thickest sedimentary layers on Earth. The sediment thickness is between 20 km and 32 km covering

a deep crystalline basement that lies 20 km to 30 km below the surface [5]. The basin is very important for the economy because of its huge oil and gas reserves which are created very deep underground sometimes even below 13 km [6]. Because the sediments are so thick normal seismic methods cannot easily see the deep basement making magnetic data extremely necessary for deep exploration [7].

The South Caspian Basin has a complicated magnetic field because the Eurasian and Iranian tectonic plates push against each other. This movement makes the basin rotate clockwise [8]. The magnetic map shows different patterns in the northern and southern parts. This is likely caused by uneven basalt rocks or massive magmatic bodies embedded deeply within the crust [9, 10].

Accurately determining the depths of subsurface magnetic sources remains a significant challenge in geophysical investigations [11]. To solve this problem and map the deep structure of the basin our study uses high quality satellite magnetic data from the Earth Magnetic Anomaly Grid project. We apply a mathematical method called power spectrum analysis to estimate the depths of these massive magnetic bodies [12, 13]. This technique is very important for filtering the data. Specifically we use a low pass Butterworth filter to effectively isolate the deep regional magnetic signals originating from the deep crystalline basement and deep magmatic intrusions. The main goal of this research is to calculate these profound depths using spectral analysis and the low pass filter build a clear geophysical model and compare it with known geological models to better understand the deep crustal structure of the South Caspian Basin.

2. Methodology

2.1. Data and Analysis

The South Caspian Basin is characterized by a very complex geological structure and an extremely thick sedimentary cover. Because this thick sediment makes traditional approaches difficult magnetic data plays a crucial role in studying the deep crystalline basement. For this research the primary dataset is based on the EMAG2 compilation. This dataset is a comprehensive global dataset that combines magnetic measurements collected from satellite airborne and marine surveys. This database offers an improved spatial resolution of two arc minutes and represents the magnetic field at a reference altitude of 4 kilometers above the Earth geoid.

Previous paleomagnetic studies indicate that this region experienced a complicated series of magnetic polarity changes particularly during the Late Cenozoic era [14, 15]. The magnetic susceptibility of the rock formations also shows significant variations. In Eastern Azerbaijan the average values range from 1000 to 2000 and sometimes up to 5000×10^{-6} SI units while in Western Turkmenistan it is around 1000×10^{-6} SI units [16]. Because of this highly complex physical and geological environment interpreting the massive regional magnetic field requires reliable mathematical and spectral methods.

2.2. Power Spectrum Analysis

To estimate the vertical depths of the massive magnetic causative bodies beneath the South Caspian Basin a two dimensional radially averaged power spectrum analysis is implemented on the gridded magnetic data [17]. The core principle of this technique involves transforming the magnetic anomalies from the spatial domain into the frequency domain via the Hartley Transform [18]. Theoretically the natural logarithm of the energy spectrum is plotted as a function of the radial wavenumber [19]. According to standard statistical models the depth of a magnetic source ensemble can

be mathematically derived from the gradient of the linear segments within this energy spectrum [12]. The relationship is defined by the following equation:

$$h = \frac{\ln S(k_1) - \ln S(k_2)}{2(k_2 - k_1)}$$

where k_1 and k_2 denote the corresponding wavenumbers, while $S(k_1)$ and $S(k_2)$ represent the respective power spectrum values at these wavenumbers.

In this theoretical framework lower wavenumbers strictly correspond to the deep seated regional sources which represent the primary focus of our deep crustal investigation. The point of intersection between the main spectral segments mathematically defines the theoretical cutoff wavenumber. This calculated cutoff value is absolutely essential for designing the subsequent low pass filter which is required to successfully isolate the deep regional magnetic field from the shallower localized signals.

2.3. Regional Magnetic Field Separation Using Butterworth Filtering

The total magnetic field recorded over a basin is essentially a combination of signals coming from deep massive geological structures and shallow localized features [9, 20]. To successfully isolate the deep regional signals in the frequency domain a Butterworth filter is applied to the magnetic anomaly data [21, 22].

The standard mathematical expression for a low-pass Butterworth filter, denoted as $H_{lp}(k)$, is defined by the following equation:

$$H_{lp}(k) = \frac{1}{\sqrt{1 + \left(\frac{k}{k_c}\right)^{2n}}}$$

where k denotes the radial wavenumber, k_c represents the selected cutoff wavenumber and n is the filter order, which determines the sharpness of the frequency roll-off. The low pass filter is specifically used to isolate the long wavelength trends associated with deep regional structures and profound crustal boundaries. Theoretically a filter order of one is selected for processing the grid. Using this specific first order parameter ensures a smooth separation of the magnetic components because it preserves the deep structural signals while minimizing unwanted mathematical distortions.

3. Results

3.1. Characteristics of the Total Magnetic Field

The initial phase of this research focused on analyzing the overall magnetic field of the South Caspian Basin. Using calibrated EMAG2 measurements the collected data was interpolated onto a uniform 2 km by 2 km grid to ensure a high fidelity representation of the regional magnetic field architecture. The spatial analysis demonstrates that the total magnetic field is geodynamically highly complex with anomaly amplitudes ranging broadly from approximately -200 nT to +450 nT. The central portion of the basin is mostly characterized by broad long wavelength and relatively smooth anomalies that fall between -200 nT and 0 nT. In contrast the outer margins display very strong magnetic anomalies exceeding +350 nT. These massive large scale zones primarily reflect deep seated regional basement structures and major crustal boundaries underlying the extremely thick sedimentary cover.

3.2. Magnetic Source Depth Estimation

To quantitatively estimate the exact vertical depths of the geological bodies causing these magnetic anomalies a two dimensional radially averaged power spectrum analysis was performed on the gridded data [17, 23]. This advanced mathematical process effectively transforms the spatial magnetic anomaly data into the frequency domain using the Hartley Transform [24, 25]. By calculating and plotting the natural logarithm of the spectral energy as a function of the radial wavenumber distinct straight line segments were identified on the energy spectrum [23]. The resulting power spectrum graph illustrating these linear segments and their intersection is presented in Fig. 1. According to standard statistical depth models the gradient of each line segment is directly proportional to the depth of a specific magnetic source layer.

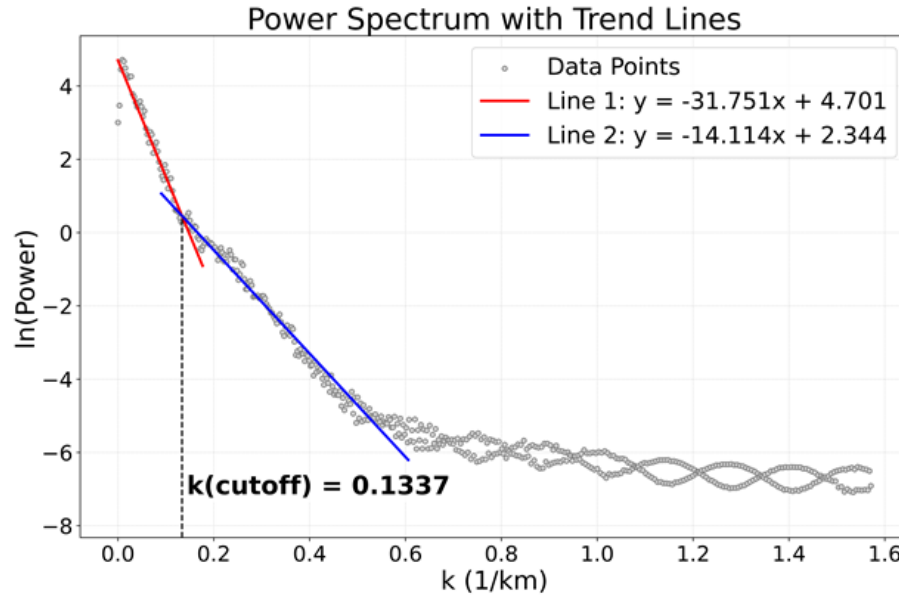


Fig. 1. Radially averaged power spectrum of the magnetic field data in the study area.

The spectral evaluation successfully revealed a clear depth model for the massive magnetic sources of the basin. The steepest line segment (red line) which occurs at low wavenumbers corresponds to deep and massive regional geological sources. The mathematical calculation from this slope gave an approximate estimated depth of 16 km for the profound regional magnetic basement. The intersection point of the distinct spectral lines provided a theoretical cutoff wavenumber of approximately 0.1337 km^{-1} . This threshold value is critically essential for the subsequent filtering process aimed at extracting the deep regional magnetic field.

3.3. Extraction of the Regional Magnetic Field

The observed total magnetic field over the South Caspian Basin represents a complex superposition of deep regional geological structures and shallow local features [9]. To clearly isolate these deep components and make the profound internal structures visible a Butterworth filter was applied to the magnetic anomaly grid in the frequency domain [21]. This filtering technique utilized the theoretically derived cutoff wavenumber of 0.1337 km^{-1} to ensure accurate separation.

A low pass Butterworth filter was specifically used to extract the long wavelength regional magnetic field which is presented in Fig. 2. The resulting regional anomaly map successfully highlights the broad structural trends of the basin associated with deeper crustal architectures. Specifically it reveals

a massive positive anomaly stretching from the northwest towards the east which strongly indicates the deep presence of the Turkmenbashi-Makhachkala fault system. Additionally another significant positive anomaly was found in the southwestern area which is highly consistent with the deep location of the Sefidrud uplift.

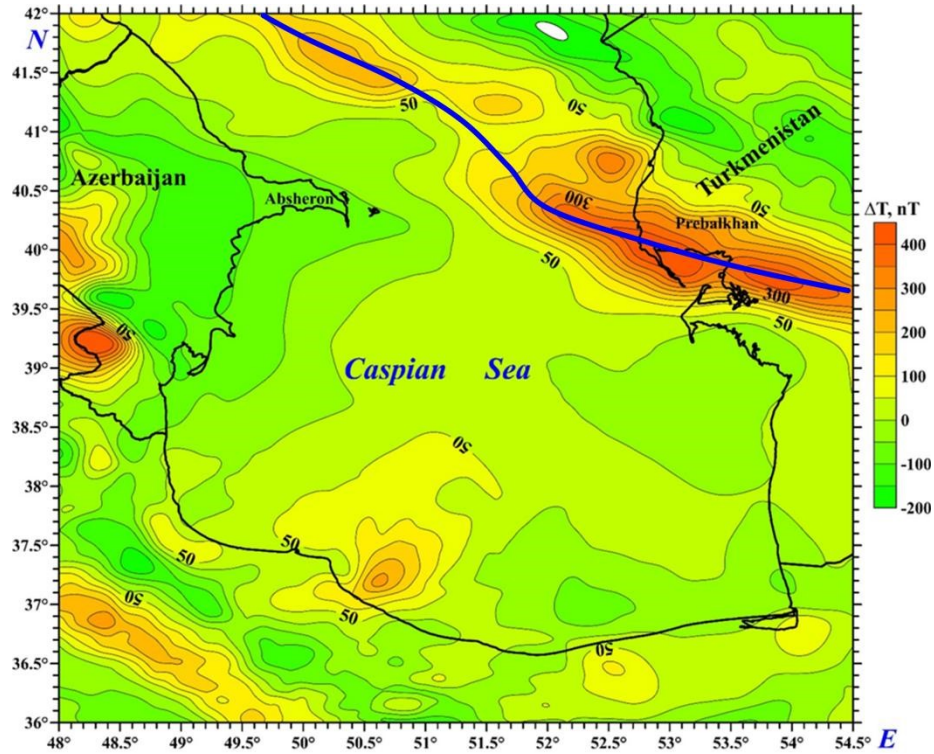


Fig. 2. Regional magnetic field of the study area separated by low-pass Butterworth filtering. The blue line represents the approximate trace of the Turkmenbashi-Makhachkala Fault.

4. Discussion and recommendations

The geodynamic evolution of the South Caspian Basin and its surrounding sedimentary depressions is directly linked to the most complex tectonic processes of the Alpine Himalayan orogenic belt [26]. According to regional geophysical studies the basement of the basin primarily consists of an oceanic type or severely thinned continental crust [27]. Overlying this basement is a massive sedimentary cover that accumulated rapidly reaching thicknesses of 20 to 30 km in some areas [28]. Since such anomalous sedimentary thickness makes mapping the deep crystalline basement with conventional methods challenging the spectral analysis of satellite magnetic data offers an essential alternative geophysical approach to reconstructing the regional crustal architecture.

The 16 km regional magnetic boundary determined through the spectral analysis holds significant physical importance for interpreting the deep crustal model. Typically in deep sedimentary basins the depth to the magnetic basement serves as an indicator of sedimentary thickness [29]. However the identified 16 km depth is significantly shallower than the overall basement depth determined by seismic methods which exceeds 20 km [7]. This specific depth discrepancy suggests the presence of highly magnetized mafic volcanic rocks basalts or ophiolite complexes deeply embedded within the sedimentary section or directly beneath it rather than marking the actual crystalline basement [30]. In regional tectonic models such a magnetic environment is strongly explained by Mesozoic andesite basalt magmatism and

deep rifting processes [31, 32]. The discovery of volcanogenic rocks at great depths in the Saatly superdeep well also directly confirms the existence of such strong geomagnetic sources deeply buried in the section [33].

From an exploration perspective major deep water hydrocarbon fields are situated primarily within the broadly negative to near zero regional magnetic field domain rather than directly over the high amplitude regional anomalies associated with major fault systems. Studying these massive deep seated structures is indispensable for evaluating the hydrocarbon systems and fluid geodynamics of the basin. The formation and preservation of reservoirs at great depths are regulated by deep formation pressures and regional faults while active extensional and compressional tectonics within the deep crust play a key role in fluid migration [34].

For future exploration strategies it is highly recommended to integrate these satellite derived regional magnetic models with high resolution three dimensional seismic data. Such a comprehensive approach will enable much more precise mapping of deep crustal boundaries hydrocarbon migration pathways and significantly reduce geohazard risks during deep water drilling operations.

CONCLUSION

This study applied two dimensional radially averaged power spectrum analysis and Butterworth filtering to EMAG2 satellite magnetic data to constrain the deep crustal architecture of the South Caspian Basin. The spectral analysis successfully resolved massive regional magnetic sources centered at an average depth of 16 km using a cutoff wavenumber of 0.1337 km^{-1} . Because the 16 km regional depth is markedly shallower than the seismically defined crystalline basement exceeding 20 km it more plausibly reflects highly magnetized mafic and volcanic bodies embedded within the deep sedimentary section rather than the true sediment basement transition. This interpretation is highly consistent with volcanogenic rocks recovered in the Saatly superdeep well and with regional models of Mesozoic andesite basalt magmatism.

Major deep water hydrocarbon fields are shown to occupy the low amplitude regional field domain rather than the high amplitude Turkmenbashi-Makhachkala anomaly indicating that hydrocarbon accumulation in these deep areas is not directly controlled by the strongest regional magnetic sources.

More broadly these results demonstrate that satellite derived magnetic data combined with spectral depth estimation offers an efficient noninvasive means of constraining deep basement architecture in basins where extreme sediment thickness limits conventional seismic imaging. Given the approximately two arc minute resolution and 4 km reference altitude of the satellite dataset the correlations presented here should be treated as broad regional trends rather than precise feature by feature matches. Integrating these deep magnetic models with high resolution three dimensional seismic and gravity data represents the logical next step for refining massive basement geometry and deep fluid dynamics in the South Caspian Basin.

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