

Constrained 3D Gravity Inversion for the Mesopotamia Basin - A Case Study

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Abstract: *The present case study is describe a procedures for 3D constrain inversion for the Mesopotamia basin -Iraq. To resolve the non-uniqueness in inversion process, high constrain is used through applying priori available information from different source such as wells. Three depth surface were extracted from wells data and basement depth relief map extracted from magnetic data reduced to pole. The method briefly done by adding these four surfaces with deferent depths and ages as constraint to 3D gravity inversion. Those surfaces are assisted to increase the accuracy and reality of basement image and sedimentary covers that support the understanding the tectonic situation of the Mesopotamia. The procedure of work starting from collecting prior information (wells data, density, geological reports) and prepare the hypothetical surfaces. These constraint surface decrease the misfit in forward modeling, so the inversion step became more accuracy and less ambiguity. The basement depth is estimated using 3D gravity inversion of Mesopotamian basin is ranging from 6.5km to 13km. The result of 3D gravity inversion was three structural relief surfaces (Jurassic, Cretaceous and Tertiary) explain the depression direction where the thickness of layers increased to the eastern side. Two profiles was modeled 2D (Line1 and Line2) and excellent coincidences was shown with 3D inversion and this support the reality of the method. Many faults and closures have been extracted from interpreting the results and apple to follow the fault movement from the basement to the sedimentary cover through different ages.*

Keywords: Mesopotamia basin, constrain 3D inversion, case study, GM-SYS

1. Introduction

The aim of inversion for potential data is to determine model parameters (depth and morphology of the surface) from observations (gravity and magnetic data). Determine solution for the inversion that satisfies the observed data always suffer from non-uniqueness in potential methods and that is related to physical nature of the under-determined problem. To deal with non-uniqueness, a prior information is needed to constrain the solution as possible. Two types of strategy solution are used by many authors concerning potential inversion. The first, using formula presented by [1] and developed by [2], [3] and [4]. The second, using models composed of a large number of contiguous cells that represents prismatic bodies of determined density and depth to top and bottom [5]. Both types of strategy solution start with mean depth for the target surface and the solution will give undulation surface with constant density contrast, so that the final target surface result will be similar in shape to the observed gravity field. the second type has the opportunity to change the density contrast due to using different prismatic bodies in the solution. Nevertheless, the solution is very difficult and need to prior information. The density contrast between the surfaces used in the inversion could be constant or vary linearly or nonlinearly with depth and that depend on the available data to approximate that with depth. In this respect, [6] distinguish two groups: in one, the inverse problem is linear; in the other, it is nonlinear. In the first group, the recovery of the density distribution is linear because this is how it appears in Newton's gravitational law, where density is assumed as an arbitrary function of space [7]-[8]. In the second group, the model consists of one or more bodies of uniform densities and unknown geometry, in which case the combined recovery of densities and shapes leads to a nonlinear problem [5]. Many algorithms is developed for opting the nonlinear solution due to that the

non-uniqueness of the inverse problem is less severe than in the linear option. [9] and [10] reviewed this and other aspects of uniqueness in relation to gravity inversion. [11] present a good review about the history and development of 3D gravity inversion and explain the methods used by authors along time. The reader is referred to these papers for an extensive bibliography on the subject.

Given the great variety of available approaches for inverting potential field data, it would seem that when faced with the problem of interpreting a given set of gravity and magnetic data, all we need to do is simply select the appropriate approach from the existing available data. In most published paper regarding inversion, it is clear that the authors seldom use more than one surface contact with the basement. That is to simplify the solution or no available data at hand. But, as mentioned before, priori information could constrain the inversion and gives convinced solutions for the morphology for the inverted surfaces. It is worth to mentioned here that the solution will became more complex in solution and the data need to be tidied wall so that the program could handle these data with short time of execution. The challenge that we present in this paper is a case study from the Mesopotamia where available data from many wells penetrate the sedimentary cover to Jurassic age beside magnetic covered data that help in determine the depth to basement. GM-SYS program (from GeoSoft Oasis Montaj) will be used for 3D inversion of the gravity data and to make 2D models to support the results. This type of constrains assist to make the images to be more reality for the multiple inverted surfaces in its relief and its matching with tectonic setting of area.

2. Data and Methodology

2.1 The study area (Mesopotamia):

The study area cover most part of Mesopotamia basin (Iraq) and the northeastern part of Salman Zone (Yellow color) with coordinates in UTM (410000E,731000E) and (3394000N, 3629000N) as shown in figure (1).



Figure 1: location map of study area

The Mesopotamian zone is the eastern most part of the unstable shelf. Its bounded in the NE by the folded ranges (Pesh-i-Kuh) in the east and Hemrin-Makhul in the north. The southwest boundary of the Mesopotamia is controlled by faults. The zone was probably uplifted during Hercynian deformation but it subsided from late Permian onwards. The sedimentary column on Mesopotamian zone is thickened toward the east. It comprises up to 1500m of infracambrian, 2500-5000m of Paleozoic, 150-220m of Triassic, nearly 1100m of Jurassic, 500-700m for the lower Cretaceous, 700-1400m for the upper Cretaceous, 200-900m for Paleocene and 150-1500m fill of Neogene and Quaternary section [12]. Tectonically, three chief fault systems controlled the area, these are the N-S Nabitah (Idsas) System, the NW-SE Najd System and the NE-SW or E-W Transversal System. Those fault systems created through Late Precambrian Nabitah Orogeny. It is believed that they were re-activated frequently during the Phanerozoic, Major fault zones correspond to the NW-SE Najd Fault System and the NE-SW Transversal System in (Figure 2).

2.2 Available Data

The gravity Bougure anomaly map for the study area is digitized and gridded with interval of 1000m with dimension of (236 x 322) points of measurement that covered area about 75.992 km from the gravity map of Iraq that has been published by Iraqi petroleum company (I.P.C 1960).

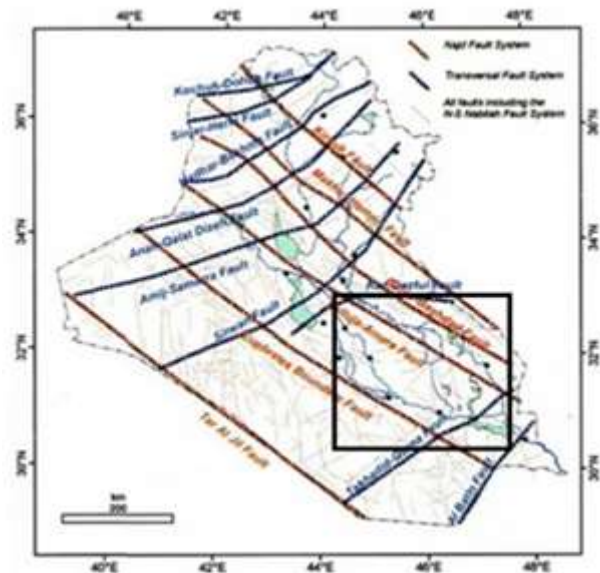


Figure 2: fault system distribution through study area.

The general description of gravity map of area characterized by the gradient of gravity value toward the E and NE with average of decreasing 0.23 mGal per kilometer toward the basin as shown in figure (3). In the west of study area, the magnitude of gravity is higher than E (about -30 mGal) because it lies in the uplifted area (Salman Zone) and the sedimentary cover became more dense and less thickness. The boundary between stable and unstable shelf is located between -35 and -55 mGal and indicated by gradient striking NW-SE. [13]. The magnetic anomaly map for the Mesopotamia was transformed to RTP map using the same digital interval of the gravity data. The magnetic RTP map (figure 4) shows that general gradient of magnetic data is toward the east of the study area but it is different in the south due to the effect of Hormaz Salt (Precambrian age) and lead to less accuracy on depth estimation of sources in magnetic map. Salt movement along N-S strike slip fault in the southern part of the Mesopotamia brings a fragment from basement rocks to the surface and this will distorted the magnetic field and give depth estimation less than the gravity field Compagnie General De Geophysique. [14]

2.3 3D Gravity inversion

The Gravity Structural Inversion function modifies the elevation of the selected layer in order to minimize the gravity misfit. Inversion updates the calculated response and error to reflect the structural changes. GM -SYS contain two types of inversion density inversion and structural inversion which used in present study. In order to run a structural inversion forward calculation must run in order to create the calculated and error grids. These grids are required to optimize the inversion method. After running a forward calculation, structural inversion without constraints run, replace the relief surface with the selected relief layer.

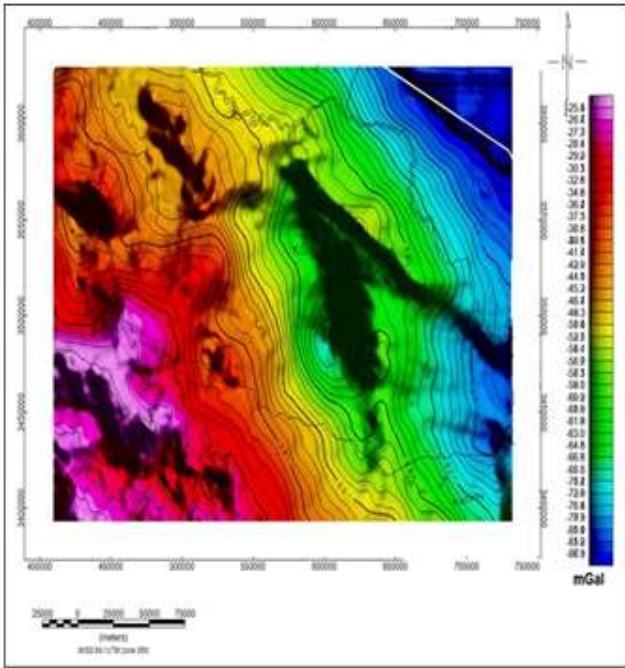


Figure 3: Bouguer anomaly map of study area (I.P.C, 1960)

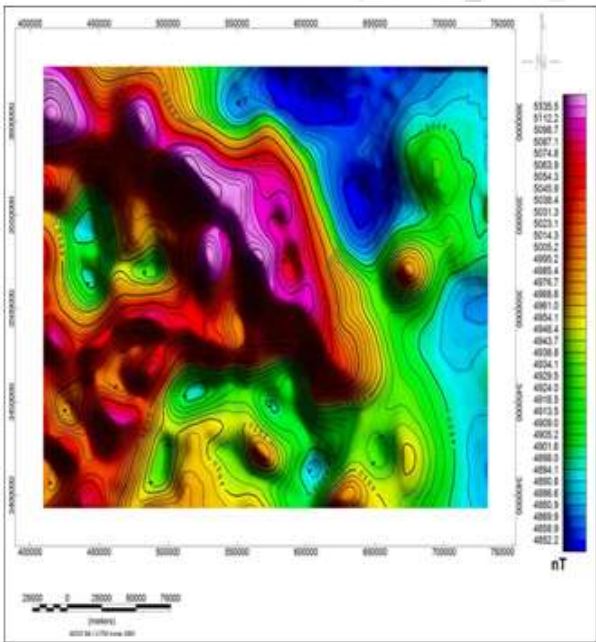


Figure 4: RTP magnetic anomaly map for the study area.

The used program for the 3D inversion is GM-SYS which is a surfaced based frequency domain gravity and magnetic forward and inverse modeling program which run under Oasis Montaj. We mean (by surfaced based) that the model is defined by a number of surfaces, or geologic horizons, which define the model, each surface is defined by grid, each layer is either assigned a constant density, assigned series of sub layers define a density-depth function or assigned by laterally changing in density grid.

In present study 3D gravity inversion is made by GM-SYS which depend on the equation described by [1] to calculate the gravity anomaly caused by an uneven, uniform layer of material by means of a series of Fourier transforms.

This expression, in its one-dimensional form, is defined as:

$$F(\Delta g) = -2\pi G\rho e^{(-k z_0)} \sum_{n=1}^{\infty} \frac{k^{n-1}}{n!} F[h^n(x)] \quad \text{---- (1)}$$

where: $F(\Delta g)$ is the Fourier transform of the gravity anomaly, G is the gravitational constant, ρ is the density contrast across the interface, k is the wave number, $h(x)$ is the depth to the interface (positive downwards) and z_0 is the mean depth of the horizontal interface.

Oldenburg [2] rearranged this equation to compute the depth to the undulating interface from the gravity anomaly profile by means of an iterative process and is given by:

$$F[h(x)] = -\frac{F[\Delta g(x)]e^{(-k z_0)}}{2\pi G\rho} - \sum_{n=2}^{\infty} \frac{k^{n-1}}{n!} F[h^n(x)] \quad \text{---- (2)}$$

This expression allows us to determine the topography of the interface density by means of an iterative inversion procedure. In this procedure we assume the mean depth of the interface, z_0 , and the density contrast associated with two media, ρ . The gravity anomaly is first demeaned prior to the calculation of the Fourier transform. Then, the first term of equation (2) is computed by assigning $h(x)=0$. The inverse Fourier transform for equation (2) will provide the first approximation of the topography interface, $h(x)$. This value of $h(x)$ is then used in the equation (2) to evaluate a new estimate of $h(x)$. This process is continued until a reasonable solution is achieved.

Following [2], the process is convergent if the depth to the interface is greater than zero and it doesn't intercept the topography. Further, the amplitude of the interface relief should be less than the mean depth of the interface.

$$1/2 \left[1 + \cos \left(\frac{k - 2\pi WH}{2(SH - WH)} \right) \right] \quad \text{---- (3)}$$

As the inversion operation (equation 2) is unstable at high frequencies, a high-cut filter, $HCF(k)$ is included in the inversion procedure to ensure convergence of series. This filter is defined by equation (3) as follow:

$$HCF(k) = -1 \text{ for } WH < k < SH,$$

$$HCF(k) = 0 \text{ for } k > SH,$$

$$\text{and } HCF(k) = 1 \text{ for } k < WH$$

$HCF(k)$ is used to restrict the high frequency contents in the Fourier spectrum of the observed gravity anomaly. The frequency, k can be expressed as $1/\lambda$, being λ the wavelength in kilometres. The iterative process is terminated when a certain number of iterations has been accomplished or when the difference between two successive approximations to the topography is lower than a pre-assigned value as the convergence criteria. Once the topographic relief is computed from the inversion procedure, it is desirable to compute the gravity anomaly produced by this computed topography. In general, this modelled anomaly must be very similar to the one used as input at the first step of the inversion process.

2.3 Applying the constrains method

The method presented in this study is depend on the increasing the constrains to get less ambiguity in the results of gravity inversion. The procedure of work done by the

following steps: 1- Prepare a hypothetical surfaces by collecting data from 22 wells distributed in study area (figure 5) for three age levels that are (Tertiary, Cretaceous and Jurassic). 2- Prepare gridded depths map for each age period (figure 6). 3- Define a mean density for each surface. 4- Prepare basement depth map extracted from magnetic data (RTP) using SPI method [15] as illustrated in figure (7).

will be inverse and after many iteration the result will be appear as structural surface.

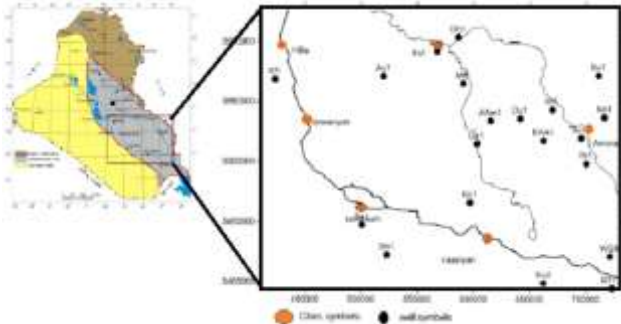


Figure 5: location map of wells distributed in study area

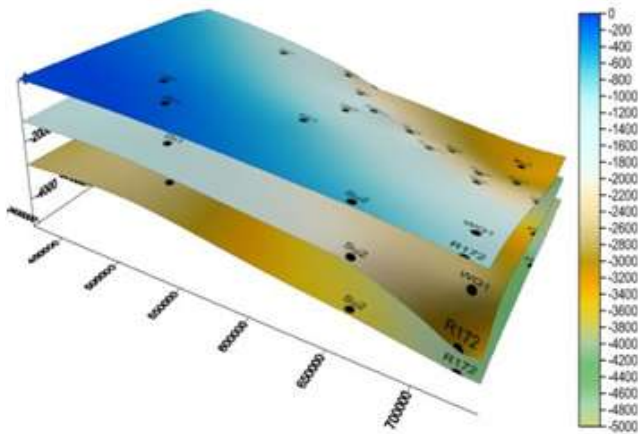


Figure 6: structural surfaces extracted from gridding of well data from below to above (Tertiary, Cretaceous and Jurassic).

These four surfaces are considered as input data (layers) in inversion project and each layer has specific density extracted from well data and core samples. So, now the layers are complete and ready to begin the first step which is the forward gravity.

2.4 Applying the 3D inversion:

The first step is input the four surfaces (that extracted from gridding of well data) as show in figures (6 and 7) to the project and define the density of each layer. Later is adding the gravity data to the project (Isostatic corrected gravity). Before starting of gravity structural inversion, forward calculation must be operated to calculate the forward gravity for each surface to get the misfit between observed and calculated. The next step is adding the gravity survey to these layer (gravity data is Isostatic residual to remove the effect of moho's layer) and starting the forward process to compute gravity effect for each surface and produce the calculated grid and observed grid. After applying the misfit and to reduce the different between two grids, inversion process is apply for each surface to get gravity structural surface which represent the final results. Later is active the surface which

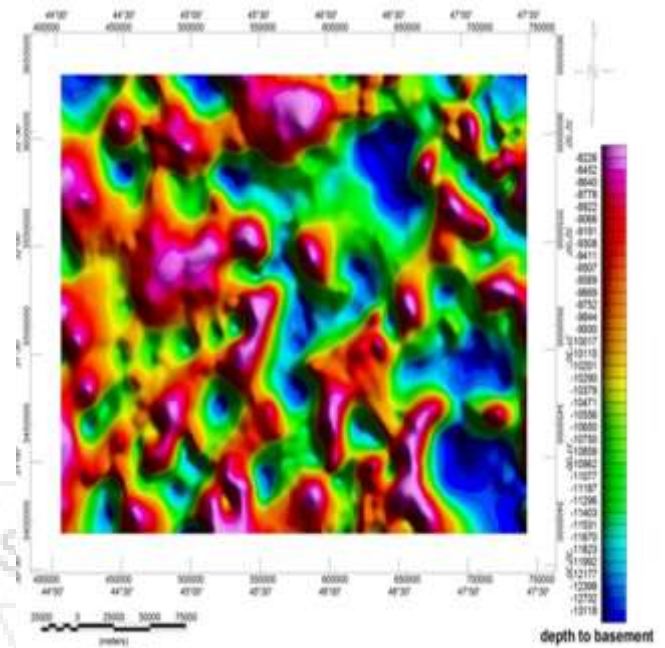


Figure 7: depth to basement estimated from SPI method

Four surfaces are the final result which are basement, Jurassic, Cretaceous and Tertiary as shows in Figure (8) and its combined of gravity and relief surface that will explain the depth of structures (Folds, Faults) and other subsurface features.

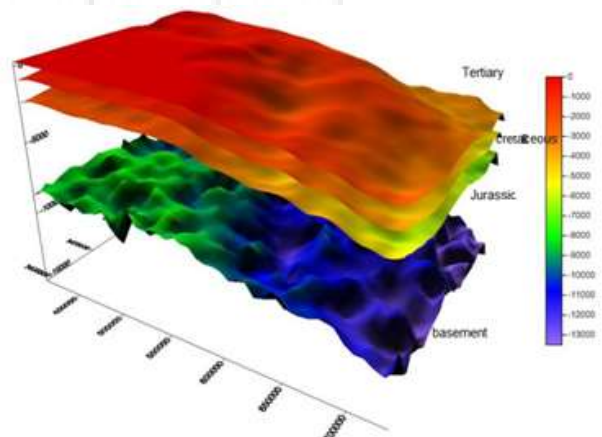


Figure 8: 3D Gravity inversion result as structural surfaces.

2.5 using 2D gravity and magnetic modeling for correlation with 3d gravity inversion results:

The GM-SYS profile of Oasis Montaj software was used to quantitatively interpret the magnetic and gravity data. The GM-SYS profile is a program for calculating the gravity and magnetic response from a geologic cross-section model.

GM-SYS provides an easy-to-use interface for interactively creating and manipulating models to fit observed gravity and/or magnetic data. Forward modeling involves creating a hypothetical geologic model and calculating the geophysical

response to that earth model while inversion. Two regional lines have been selected to make 2D forward gravity and magnetic modeling with using constrains data (well data, density, 3D gravity inversion and DEM) as explained in Figure (9) to build image from basement to surface and to define the basin direction and geometry of strata and the structural situation of subsurface.

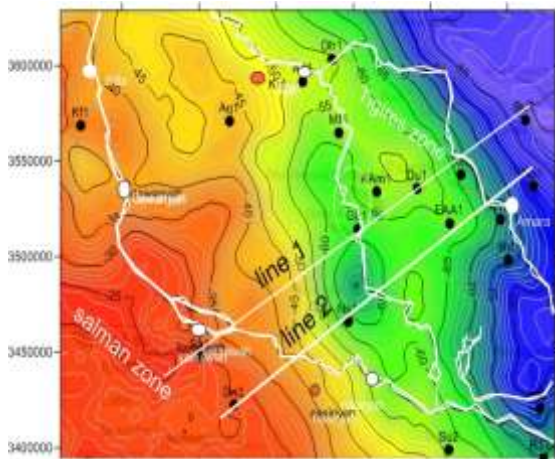


Figure 9: location of 2D profiles modeling and wells.

The result of 2D gravity and Magnetic modeling was 2 lines (figures 10 and 11) with NE-SW trend explain the geological attitude of layers from basement to earth surface. Line 1 has 272km length and pass throw six wells (SA1, GA1, AAM1, DU1, KT1 and BU1). Line2 has 236km length and extend from SW of study area in point x:513108,y:3414369 and end in the NE at point x:711705,y:3543930 and pass through Salman Zone and Mesopotamian zone. Five wells included with profile Line 2 that are (DN1,NS1,EAA1, AM1 and NO1)and extracted the basement depth from 3D gravity inversion .

2D modeling results coincide excellently with 3D gravity inversion results in basement relief, depth and with the trend of sedimentary cover. Because the 2D profiles are regional line, it is difficult to detect the small structures in sedimentary layers and can tracking the general trend and geometry of basin and the sedimentary covers. The result of 2D modeling which represented by the matching between 3D gravity surface (basement) and response of potential data agreed with the prior geological information of area consider as evidence to the success of constraints method.

3. Results and discussion

The results of 3D Gravity inversion was four depth surfaces (basement, Jurassic, Cretaceous, Tertiary) as illustrate in Figure (12). Jurassic depth map show the relief of surface with depth ranging from 2000m to 5000m can easily determine the depth of anomalies and faults and monitor the origin and the end of any structures from basement to surface. In basement map, the general view show decreasing of depth to the east and northeast to reach the deepest point at depth about 13500m as show in figure (13).In the south west of study area the basement is high 8200m located in Salman Zone which characterized by low sedimentary cover and high surface elevation in DEM.

In general the structures have NW-SE trend and the surface smoothly decreasing to the east where the basin direction. In Jurassic layer (figure 12), there are many closures appear with small amplitudes and the contour lines is more sharp and explain more details. In the south west of study area (Salman zone) as show in figure (12), the depth of Jurassic about 2000to 2200m because it represent the uplifted area and gradually the depth is great to basin in the east to reach 3800m in Euphrates zone and about 4100m in Tigers zone and still depression till the Iraq –Iran border to reach 5000m.

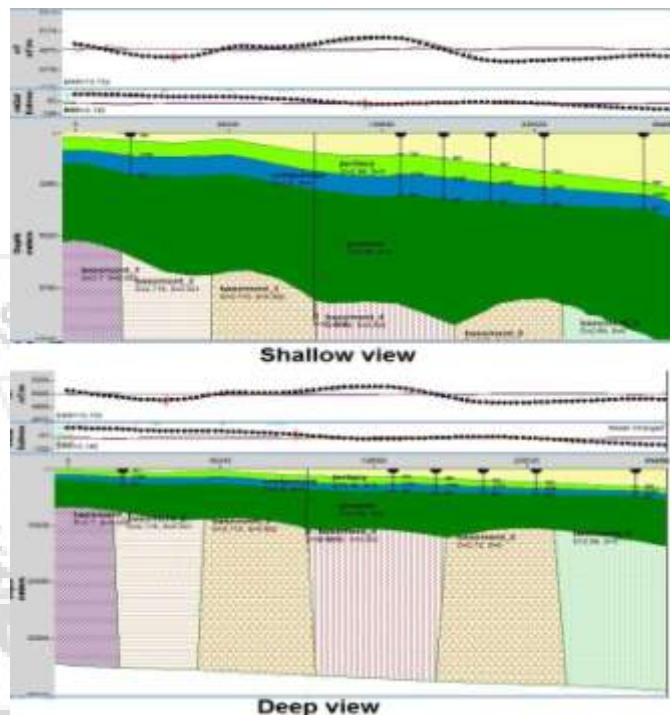


Figure 10: 2D Gravity-Magnetic forward modeling (Line1).

The faults still appear in all surfaces that reflect the impact of basement faults on the sedimentary cover and because of the rare information about Cambrian surface information it's hard to define the structures and faults below Jurassic layer in detailed description.

Cretaceous layer (in figure 12) has depth ranged from 600m to 4500m and has the same pattern of Jurassic layer but with lower amplitude and the anomalies become smoother. The depth in west area is 750m in Salman Zone and gradually decreasing to the eastern side to reach deeper point in basin 4300m.

In Tertiary surface (figure 12), the anomalies are smaller than below surface and low amplitude except some structures still effect and appear in the map and because of the thick soil layer in Mesopotamian plain the effect of structures doesn't reach to the surface and the digital elevation model show flat area except the boundary between Salman Zone and Mesopotamian Zone.

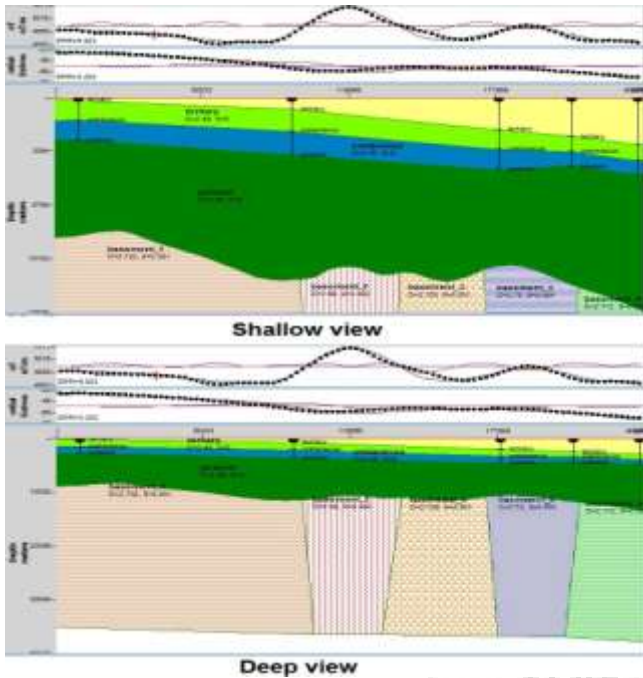


Figure 11: 2D Gravity-Magnetic forward modeling (Line2).

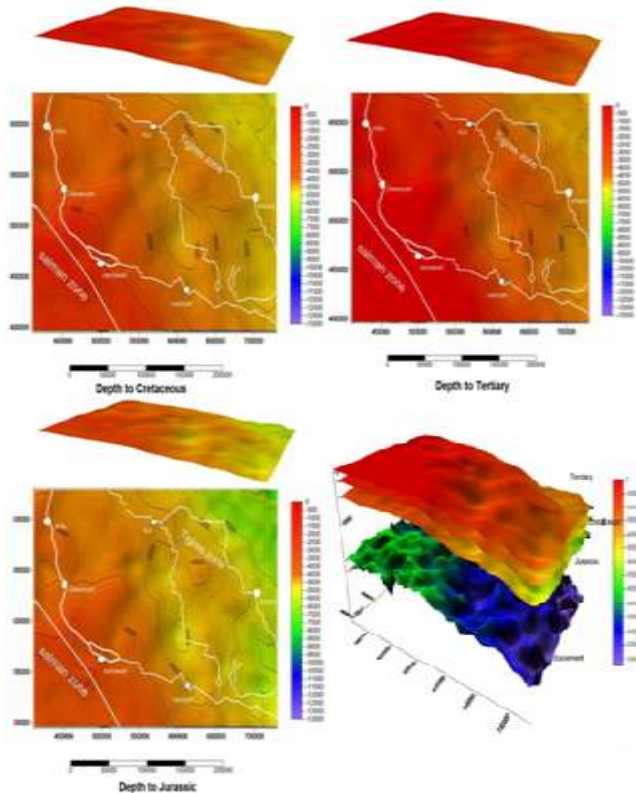


Figure 12: The results of 3D gravity structural inversion (Jurassic, Cretaceous and Tertiary)

Tertiary has the same trend of structures and fault with depth ranged from surface to 3200m as show in figure (12) with same trend of Jurassic and Cretaceous. Some structures are disappeared in Tertiary or become nearly flat that because it reaches near the horizontal weathering layer and the effect of folding force is low.

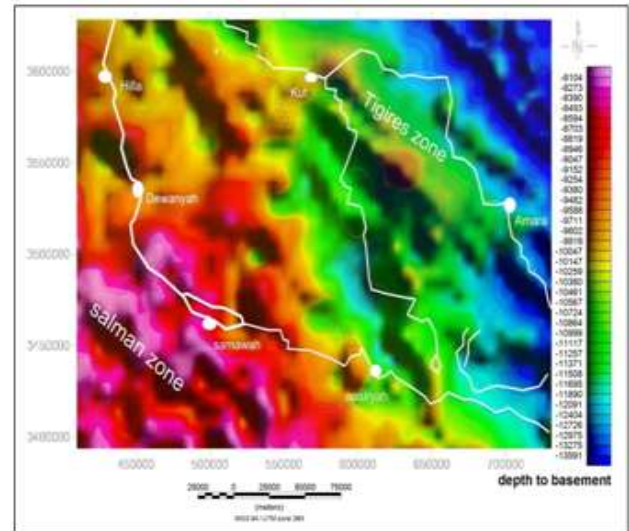


Figure 13: depth to basement extracted from 3D gravity inversion

So, the 3D gravity structural inversion is an active tool to detect the structures and geological features with depth determination and can tracking any feature from its depth to the earth surface from these techniques of gravity and magnetic inversion produce, the results explain Mesopotamian basin geometry which is defined by 2D and 3D gravity and magnetic inversion and it's segmented into blocks (horsts and grabens) by main faults. Also, its gradient in depth is toward the east to reach 13 km near the Iraq-Iranian border with increasing of sediments thickness. Three depth maps extracted from 3D gravity inversion (Jurassic, Cretaceous and Tertiary) which show the depth of anomalies and faults (contacts) with its trend. The results show high degree of similarity between gravity map and depth map, so that the gravity map reflect basin trend and geometry.

4. Conclusions

3D gravity inversion is effective tool used in quantitative interpretation. Its applied in present study and get the information about the geometry and dip direction of layers as well as depth to basement and above layers. The prior information (well data, geological reports, densityetc) play a role in the accuracy of result in both 2D and 3D modeling and can reduce the ambiguity in potential data interpretation. There is high concordance in results between 2D and 3D gravity inversion in present study that confirms the efficiency of each method and produce high quality results when it integrated together. The success in using this method is depend on the availability of prior information wherever it was to increase the result reality and gives more acceptances with geology of area.

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