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Assessment of Vertical Magnetic Gradient Data of Tuzla Fault Using Boundary Analysis and 3-D Inversion Techniques

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Abstract

The magnetic prospection is one of the most useful methods to determine buried geological structures such as shallow fracture zones. The investigation of vertical and horizontal gradient and total magnetic field variations over geological structures, which have been used for many years, may reveal their locations, geometries and physical characteristics. In this study, a proposed iterative 3-D rectangular prismatic model inversion algorithm was modified to interpret vertical magnetic gradient data defining the boundaries and the physical parameters of the anomalous structure. Vertical magnetic gradient measurements were carried out at the Tuzla fault, an active fault system located along NE-SW direction in Izmir (Turkey). Boundary analysis studies were applied to data in order to obtain boundaries of the structures, afterwards the inversion process was carried out considering these geometries. As a result, location, direction and other physical and geometrical features of the fault are achieved.

Keywords

Boundary Analysis, Geothermal, İnversion, Magnetic Gradient, Tuzla Fault

1. Introduction

Gradient or total magnetic field measurements are acquired from the ground, in the air or on the ocean, covering a large range of scales and for a wide variety of purposes. Therefore, the magnetic method has expanded from its initial use solely as a tool for determining iron ore to a common tool used in exploration for minerals [1] [2], hydrocarbons [3], ground water [4], archaeological ruins [5]

[6], environmental contamination issues [7], geothermal resources [8] and complex fault systems ([9] [10] [11] [12] [13]). In study areas where formations carrying a magnetic signature dip at a significant angle, a magnetic survey can be used to map surface geology very precisely [14].

For both regional and detailed explorations, magnetic measurements are important for understanding the tectonic setting. For example, structural terrane boundaries, such as faults, are commonly recognized by the contrast in magnetic fabric across the line of contact [13]. The study of tectonic structures is an important economic application of magnetic surveys, especially in hydrocarbon and geothermal explorations and geotechnical investigations. Besides, for the most part, basin fill typically has a much lower susceptibility than the crystalline basement. Thus, it is commonly possible to estimate the depth to basement and, under favorable circumstances, quantitatively map basement structures, such as faults and horst blocks [12].

The magnetic anomalies are attributed to simple geophysical models such as dykes and faults and the model parameters are usually determined through a properly designed inversion scheme. Rapid interpretation of such simple geometric models is carried out through graphical approaches involving characteristic curves [15]-[20]. Although a rigorous analysis is always through inversion on computers using various optimization techniques [21]-[26].

Both seismological and geodynamic researches emphasize that the Aegean Region is the most seismically active region in Western Eurasia. The convergence of the Eurasian and African lithospheric plates forces a westward motion on the Anatolian plate relative to the Eurasian one. Western Anatolia is a valuable laboratory for Earth Science research because of its complex geological features. Izmir is the third largest city in Turkey with a population of about 4.2 million that is at great risk from big hazardous earthquakes. The Tuzla Fault, which is aligned trending NE-SW between the town of Menderes and Ürkmez Bay, is an important fault in terms of seismic activity and its proximity to the city of Izmir. This study aims to perform a detailed scale investigation focusing on the Tuzla Fault for better understanding of the region's tectonics. Besides, this part of the Aegean region is also known with its geothermal potential and natural hot springs.

The study area is located 65 km southwest of city center of Izmir, within the borders of Payamlı village of Seferihisar district (**Figure 1**). In this study, vertical magnetic gradient data were collected at the Tuzla fault, to determine possible location, direction, geometry and physical properties. A 3-D inversion algorithm proposed by [27] was modified to calculate the gradient response of a prismatic model and used to evaluate vertical magnetic gradient data. Besides, boundary analysis methods such as analytical signal [28] [29] and horizontal gradient [30] were utilized for determining geometrical parameters of the initial model. The possible location and geometry of the fault are achieved after interpreting the data.

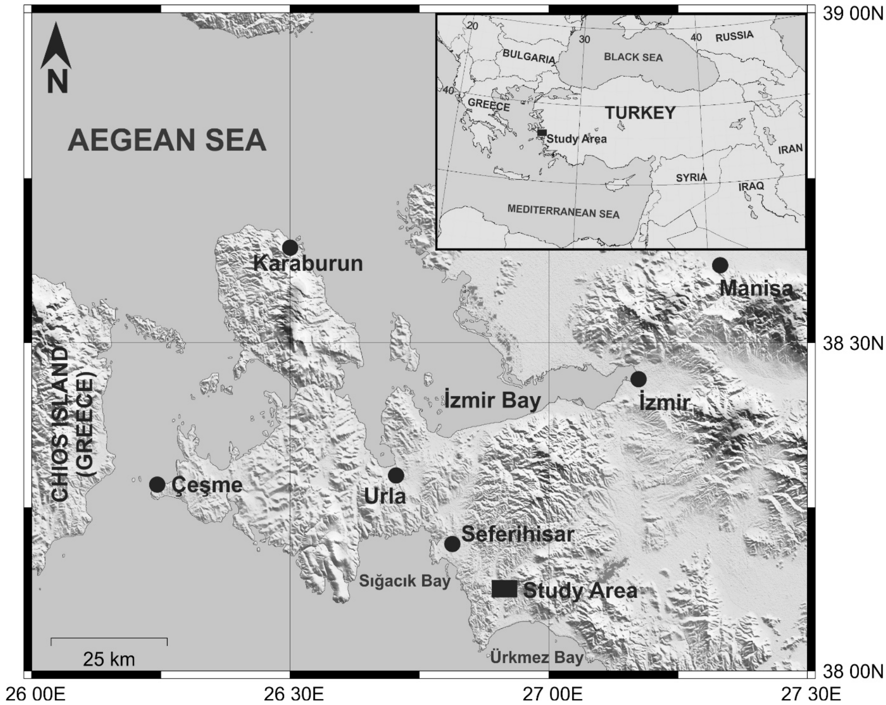

Figure 1. Location of the study area, indicated with black rectangle (not to scale).

2. Measurement Method

Vertical magnetic gradient data acqusition were carrid out by using Scintrex ENVI-MAG equipment at the Tuzla fault. The equipment which is capable of making measurements with a sensitivity of ±0.1 nT has two vertical proton magnetometers.The data were measured along 5 profiles with a profile interval of 10 m and station interval of 1 m. The directions of the profiles were selected to intersect with the fault perpendicularly.

3. Geology of Seferihisar Region

The Seferihisar geothermal area is one of the important geothermal areas in western Anatolia of Turkey, attaining an aquifer temperature of 153˚C. Geothermal activities of the area have been known since ancient times tracing back to the Roman period. People once used the thermal waters in this area for bathing and washing purposes. Thermal waters have formed travertine walls as they flowed along ancient aqueducts. These natural springs are presently used for primitive spa facilities.

The study area is located 65 km southwest of Izmir city center (**Figure 2**). There are many natural thermal spring groups in the area. The thermal springs have total discharge rates of 100 - 150 l/s and their temperatures vary from 30 to 78˚C. Twenty geothermal gradient wells having depths of 56 - 171 m and ten deep geothermal wells having depths of 151 - 2000 m have been drilled by MTA (General Directorate of Mineral Research and Exploration of Turkey) [31]. Unfortunately, this thermal potentials are not presently used except for primitive spa facilities. Additionally, they caused some environmental problems for both

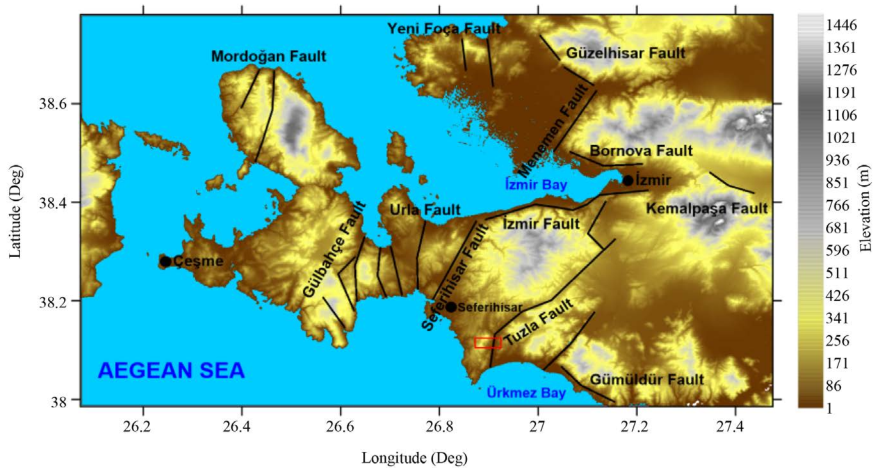

Figure 2. Locations of active faults in Izmir. Study area is indicated with red rectangle (not to scale).

surface waters and groundwaters as they flow uselessly and because their salinities and boron contents are very high and harmful for the agricultural sites in the area. The municipality of İzmir has planned to benefit from this geothermal area for heating purposes. Electricity generation, greenhouse heating, balneological, thermal tourism and heating of swimming pools are the other uses which can be developed for this area.

According to the hydrogeological and lithological properties geological units in the Seferihisar region can be considered in four main groups (**Figure 3**). These units are: 1) Upper Cretaceous-Paleocene Bornova melange [32]; 2) Neogene terrestrial sediments; 3) Neogene rhyolitic volcanics; and 4) Quaternary alluvium. The basement rock of the area is Precambrian to Paleocene Menderes Massif metamorphic rocks, which is consisted of marbles and schists [33], and located about 10 km east of the mapped area in **Figure 3**.

Similar to other geothermal systems in western Anatolia, the circulation of the thermal waters in this geothermal field is directly related to major fault and fracture zones. Major faults, which are called the Doğanbey, Cumalı and Tuzla faults, perform structural control on the geothermal systems of the area. The area between the Cumalı and Tuzla faults suggests graben structures. The thickness of the Neogene sediments reaches to 400 m in this basin. The Cumalı fault was identified as a thrust fault by [34] and [35]. However, recent studies containing new data suggest that these faults are strike-slip faults [36]. The Doğanbey, Cumalı and Tuzla faults show both vertical and lateral displacement. The units potentially behaving as aquifers for both cold and thermal waters.The formations which have high permeability are: limestone and serpentinite bodies of Bornova melange, Neogene volcanics, conglomerates of Neogene terrestrial sediments and Quaternary alluvium [31]. The shallow regional aquifer consists of Holocene alluvial deposits at the seashore in the south of the study area.

First integrated geophysical studies were utilized by MTA (General Directorate of Mineral Research and Exploration of Turkey) using gravity and

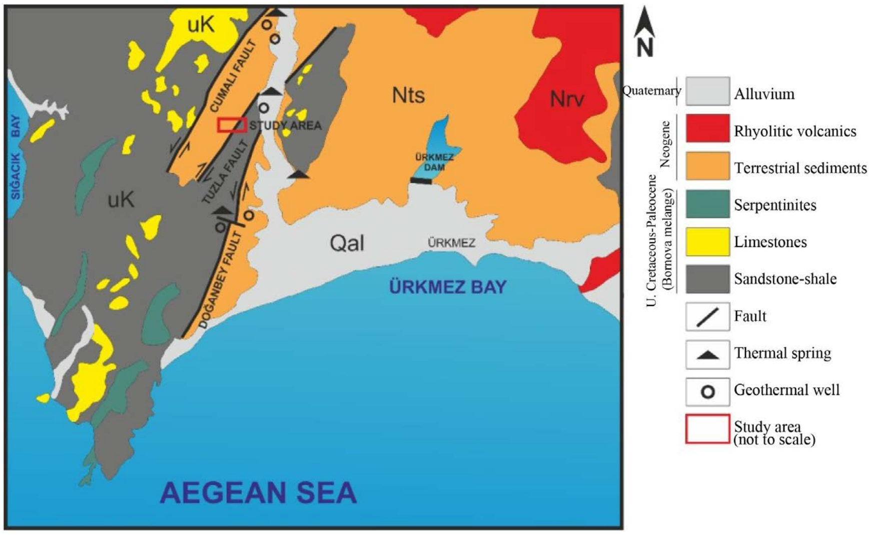

Figure 3. Geologic map of the Seferihisar geothermal region (after [31] and [34]).

electrical resistivity methods within the Western Anatolia Energy Project between 1968 and 1977. Besides, [37] carried out regional gravity investigation, [38] made Self Potential (SP) measurements and heat flow studies and [39] performed magnetic and SP studies at the Cumalı region.

4. Boundary Analysis Methods

An important purpose of the interpretation of magnetic data is to determine the location and the type of the magnetic source. Recently, this aim has become particularly important as a result of the expanding volumes of magnetic data that are being collected for environmental, archaeological and geological applications. For this aim, a variety of mathematical methods, based on the use of derivatives of the magnetic field and image processing techniques, have been developed to determine magnetic source parameters such as locations of boundaries and depths. These methods have been investigated in detail by [14] and [30]. In this study, analytic signal and horizontal gradient methods were utilized and the results were compared.

4.1. Analytic Signal

Nabighian [28] introduced the concept of the analytic signal for magnetic interpretation and showed that its amplitude yields a bell-shaped function over each corner of a 2D body with polygonal cross section. For an isolated corner, the maximum of the bell-shaped curve is located exactly over the corner, and the width of the curve at half its maximum amplitude equals twice the depth to the corner. The determination of these parameters is not affected by the presence of remanent magnetization. Horizontal locations are usually well determined by this method, but depth determinations are only reliable for polyhedral bodies. 3D analytic signal amplitude of a total magnetic intensity (TMI) map, introduced by [29], is widely used in magnetic interpretation as a means of positioning anomalies directly over their sources.The analytic signal of a magnetic field intensity anomaly is defined in 3-D as

$$A = \frac{\partial M}{\partial x}\hat{x} + \frac{\partial M}{\partial y}\hat{y} + i\frac{\partial M}{\partial z}\hat{z} \tag{1}$$

where M is the magnetic intensity, $i = \sqrt{-1}$ and $\hat{x}$, $\hat{y}$ and $\hat{z}$ are unit vectors in a Cartesian coordinate system [29]. The results, however, are strongly dependent on the direction of magnetization, in sharp contrast with the 2D case [14].

4.2. Horizontal Gradient

The steepest horizontal gradient of a potential field anomaly tends to overlie the edges of the body. Indeed, the steepest gradient will be located directly over the edge of the body if the edge is vertical and far removed from all other edges or sources [40]. The horizontal gradient tends to have maxima located over edges of magnetic or gravity sources. When applied to two dimensional surveys, the horizontal gradient tends to place narrow ridges over abrupt changes in magnetization or density. Locating maxima in the horizontal gradient can be done by simple inspection, but [41] automated the procedure with an algorithm that scans the rows and columns of gridded data and records the locations of maxima in a file for later analysis and plotting (**Figure 4**).

Interpreting the horizontal gradient in terms of density or magnetization contrasts, and ultimately in terms of geology, requires several underlying assumptions. In particular, it is assumed that contrasts in physical properties occur across vertical and abrupt boundaries isolated from other sources [30].

5. 3-D Inversion of Magnetic Data

The vertical prismatic models are widely used geometrical models for 3-D

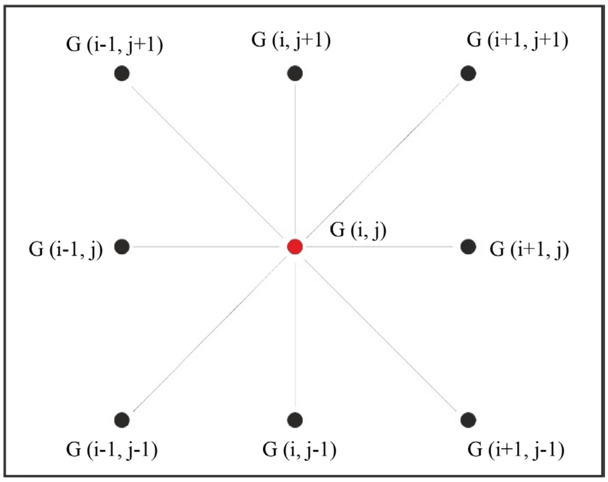

Figure 4. Location of grid intersections used to test for a maximum near $G(i,j)$ and 8 neighbour points (modified from [41]).

interpretation of magnetic anomalies. [42] presented an equation for the total field magnetic anomalies of prismatic models. Generally, the magnetized bodies are close to each other and separation of the anomalies resulting from individual prisms is difficult. Nonlinear optimization techniques such as the [43] algorithm may be used for inversion of the magnetic anomalies.Besides, [44] developed a new procedure of Cholesky decomposition for solution of the normal equations. In addition, [45] simplified the logarithmic and trigonometric terms in the anomaly equation using complex notation. Finally [27] presented an efficient method for 3-D modeling of magnetic anomalies and approximate equations for rapid calculation of anomalies and derivatives are derived. Approximate anomaly equation has been developed which treat the prism as a line mass [27].

$$\Delta T(x,y,0) = A\left[(G_1\beta + G_2\alpha)\left(\frac{1}{R_1^3} - \frac{1}{R_2^3}\right) + \frac{G_3C_1\alpha\beta}{(\alpha^2+\beta^2)} - \frac{G_4(C_1\beta^2 + C_2)}{(\alpha^2+\beta^2)} - \frac{G_5(C_1\alpha^2 + C_2)}{(\alpha^2+\beta^2)}\right] \quad (2)$$

where $G_{1,2,3,4,5}$ are physical, A, α, β, R_1, R_2, C_1 and C_2 are geometrical parameters.Program M3DPRISM is modified for the R_1 and R_2 parameters for the inversion procedure of magnetic gradient data. The 3-D prismatic model for vertical magnetic gradient anomaly is presented on **Figure 5**. Besides, different receiver orientations and receiver separation have been investigated by [46] for the magnetic gradiometer survey used for the exploration of shallow underground structures.

6. Field Studies

Tuzla fault was investigated by in large scale using VLF-EM [5] and SP [47]

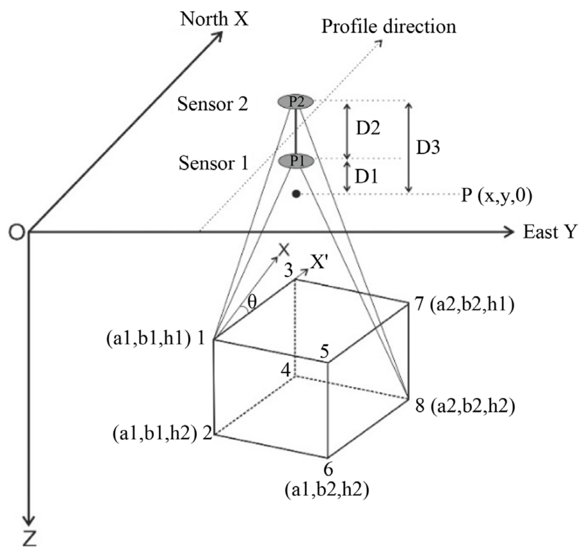

Figure 5. Modified model of 3-D rectangular prism (modified from [27]).

methods and the magnetic investigations were performed at a limited area for a more detailed study. The vertical magnetic gradient data were collected along 5 profiles at 1300 stations in W-E direction and each profile has a length of 260 m (**Figure 6**). The data were mapped and presented in **Figure 7(a)**. According to the geological features and structural characteristics of the area, the low magnitude blue color anomaly is considered as the effect of the fault. The location and direction of the anomaly observed between 150 - 200 m of each profile is concordant with the possible location of the Tuzla fault, representing a structure which has a width of approximately 20 m in N-S direction.

After collecting and mapping the data, Analytic signal and horizontal gradient boundary analysis methods were utilized to data respectively, in order to obtain precise geometry of the buried geological structure. Results of Analytic signal method presented the boundaries of the fault with high amplitude red color anomalies (**Figure 7(b)**) and possible boundaries of the structures were demonstrated with black dash lines. The results of horizontal gradient studies were mapped and presented on **Figure 7(c)**. According to continuity and persistance of the red color anomalous boundaries,the edges of the structure are identified clearly. Again, the boundaries were indicated with black dash lines for determining the initial prismatic model geometry, used in 3-D inversion.

Geometrical initial parameters of two prismatic model were determined, considering the outcomes of the boundary analysis studies. Initial geometrical and physical parameters used in the inversion process are indicated in **Table 1**. Relatively small difference between the initial and interpreted geometrical values support that the initial model represents the actual structure successfully. In addition, calculated top and bottom depths of the prisms are in accordance with the depths calculated by [5] using the 2-D fault model inversion scheme of

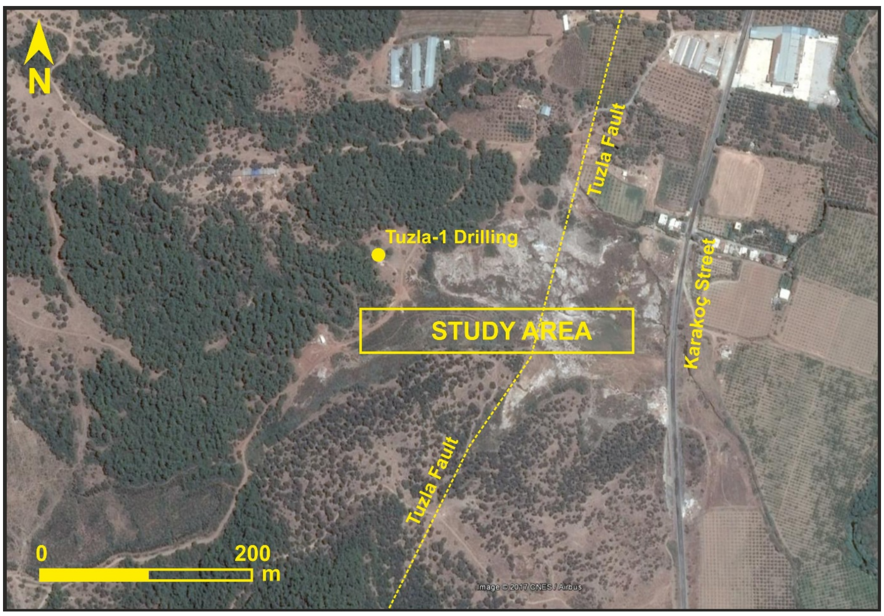

Figure 6. Location of the study field (modified from Google Earth).

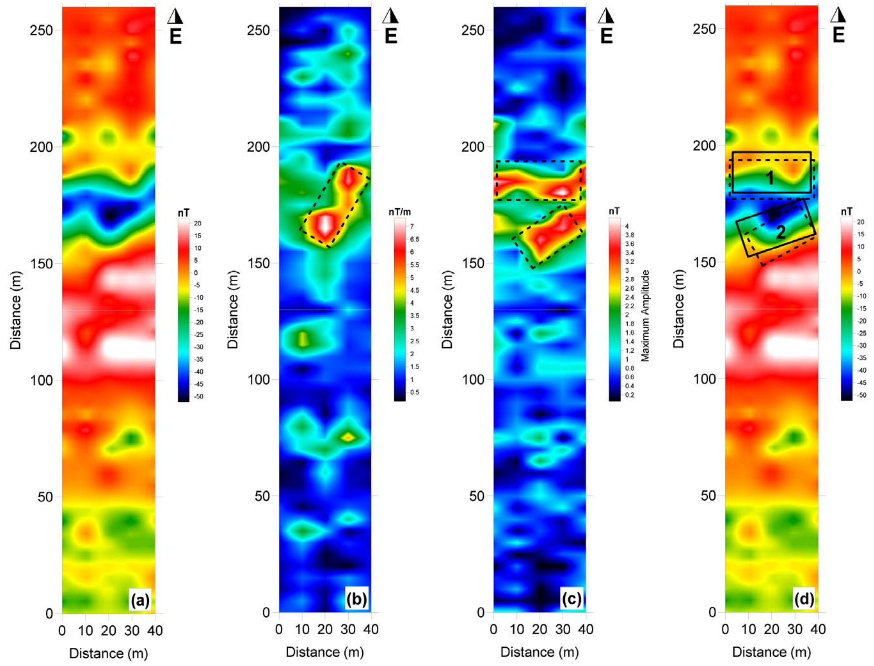

Figure 7. (a) Vertical magnetic gradient anomaly map of study area; (b) Analytic signal map of the magnetic data; (c) Horizontal gradient map of the magnetic data; (d) Initial (black dash line) and interpreted (black line) models overlayed on magnetic map.

Table 1. Initial and interpreted model parameters for two prismatic body.

Prism No	Model	a_1 (m)	a_2 (m)	b_1 (m)	b_2 (m)	h_1 (m)	h_2 (m)	I_O (Deg)	D_O (Deg)	Θ (Deg)	EI (CGS)
1	Initial Model	2	39	178	194	25	50	57	3	90	0.005
	Interpreted Model	3.2	38.6	181.4	198.2	28.3	38	47.6	4.1	90	0.0064
2	Initial Model	17	32	150	175	5	25	57	3	32	0.005
	Interpreted Model	10.3	34.8	153.1	176.9	7.3	32.6	45.1	3.9	28	0.0072

[48]. Both initial and interpreted models are presented on **Figure 7(d)**. The calculation of the interpreted model parameters took 11 iterations for Model-1 and 13 iterations for Model-2. The errors for these calculations were less than 0.01.

The location and direction of the interpreted models are similar to the initial model geometry outcome of horizontal gradient method. The interpreted Model-1 represents the footwall and Model-2 represents the hanging wall of the Tuzla fault. Initial depth parameters (h1 and h2) were selected from the previous 2-D inversion results [5]. It is clearly identified that the fault lies at a very shallow depth in the study area. The location of unproductive Tuzla-1 drilling, digged in 1980s, is in 50 m north of the study area. It is determined that the drilling should have been opened between the 170 - 180 m of the investigation site.

7. Conclusion

It was aimed to determine the location and geometry of the Tuzla fault in Seferihisar geothermal area. For this purpose, vertical magnetic gradient data measured at 1300 stations, perpendicular to the fault structure. The data were mapped and interpreted using boundary analysis methods and 3-D inversion. Both of two edge detection methods supported very valuable information for constructing initial model for inversion. Analytic signal and horizontal gradient studies gave similar results but maximum horizontal gradient map was more similar to the interpreted model geometry. Modified 3-D inversion algorithm gave eligible results for the location, direction and depth of the fault. It was determined that 3-D inversion using prismatic models can be used successfully for interpreting vertical magnetic gradient data. Also it is recommended that a new drilling should be opened between the locations of two interpreted models.

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