JME

Journal of Mining & Environment,
Vol.6, No.1, 2015, 31-39.

Subsurface modeling of mud volcanoes, using density model and analysis of seismic velocity

H. R. Baghzendani, H. Aghajani* and M. Solimani

School of Mining, Petroleum & Geophysics Engineering, University of Shahrood, Shahrood, Iran

Received 8 July 2014; received in revised form 4 September 2014; accepted 14 September 2014
**Corresponding author: haghajani@shahroodut.ac.ir (H. Aghajani).*

Abstract

Detection of subsurface structures by means of gravity method can be used to determine mass distribution and density contrast of rock units. This distribution could be detected by different geophysical methods, especially gravity method. However, gravity techniques have some drawbacks and can't be always successful in distinguishing subsurface structures. Performance of the gravity technique could be further improved by simultaneous combination and introducing additional information from other geophysical data. This study used existing relation between seismic and gravity methods to better clarify subsurface structures. This relationship relates mass distribution of the medium to velocity of wave propagation in that media. This method was applied on an area that consists of three mud volcanoes. After completion of the primary model by forward modeling, mass distribution and analysis of seismic velocity were provided on a 2-D profile. Bouguer anomaly map of gravity data of the area was obtained and negative anomalies were identified. These negative anomalies could be related to the existence of mud volcanoes. A 2-D seismic line was also acquired over the greatest mud volcano, as additional information for direct modeling. The Gardner equation was used for further velocity estimation by density values. This velocity model also compared with seismic velocity analysis for evaluation. The final results indicated that density modeling and the use of seismic velocity model increases the resolution of subsurface structures imaging. Separation of subsurface layers was implemented correctly in the velocity model resulting from gravity data and subsurface discontinuities of the area that become more obvious by this technique.

Keywords: *Gardner Equation, Seismic Imaging, Velocity Analysis, Bouguer Anomaly, Mud Volcano.*

1. Introduction

The origin of mud volcano phenomenon has close relations with subduction areas, oil fields in the margins and coasts of seas, oceans, and faults [1]. Most of the mud volcanoes, which are their most active ones, are located on the margins and coastal zones of the Caspian Sea, Black sea, Oman Sea and Indian Ocean and mainly have magma and tectonic origins. Mud volcanoes of South Eastern part of the Caspian Sea in countries of Iran and Turkmenistan, are related to subduction zones and oil and gas field. Focus point of mud volcano is mainly created in depth due to pressure on fine sediments. Some of mud volcanoes such as those in the borders of the Caspian Sea, which are related to the fault activities, have diaperic shape and exert pressure to the walls of gaps while coming up through them. Therefore, the liquid saturated with gas appears in drips on surface of sediments. By decreasing the pressure, the under pressure liquid on the surface of sediment is moved toward the crest of the diaper [2]. Investigations have indicated that there is a close relation between mud volcano phenomenon and the aggregation of oil and gas in subsurface layers. Although this phenomenon can't be definitely as a result of the existence of hydrocarbon materials or considerable resources, it can give much information about subsurface layers [3].

Research history of mud volcano has mostly been accompanied by researches on oil fields, conducted by a number of researchers and included structural stratigraphy and geology of establishment of this phenomenon [4]. Many researches have been conducted to identify the structure of mud volcanoes. Various geophysical methods were applied solely or by simultaneous application of several methods to investigate characteristics and structure of this phenomenon. Combination of gravity and seismic data were applied in determination of Gungula sedimentary field structures in Nigeria and identification of geometry of stratigraphical sequences to explore hydrocarbon resources. Based on these researches, the estimated depth of the bedrock of the area and existing faults of the area were mapped very well. Existence of high values of gravity anomalies in the area is indicative of penetrative masses of ocean bed which it is assumed that it has brought about termination of a portion of hydrocarbon resources [5]. Gauch et al. (2010), in their commentary about complex geology of thrust belt of Manadom area of India, used a combination of gravity, magnetic, seismic, and magneto-telluric data. Through their research, they succeeded to identify a map of rock units in the area, and determined main effective faults and depth of stratums [6]. In a same study, results of geophysical gravimetric and magnetic methods used to design seismic acquisition profiles. Consequently, combining results of 3D seismic and gravity data resulted in accurate structure imaging of sedimentary basins of Santos and Campus of Brazil. The results show that the estimated depth of bed rock of the area is about 10 kilometers, the minimum value of which is about 8 kilometers [7].

Anderson and Liemen (2002), used gravimetric data as an auxiliary tools to clarify and improve seismic data processing result [8]. In order to achieve more reliable results on subsurface structures, Cai et al. (2009), identified the arrival time of the wave and gravity anomaly value among low-thickness layers existing in rocks by improving inverse modeling of seismic data and Jakobian matrix [9]. Colombo and De Stephano (2007) succeeded to improve velocity model by using gravity data and the relation between density and velocity (Gardner equation), they also determined the real depth of each layer in seismography profile using this model [10]. Montovani and Dagojard (2011) obtained velocity model on a data from an oil field by using density (surface exploration and well measuring) and seismography data and considered migration correction. They also succeeded to correct salt layer boundary in this data which was determined by seismic reflection [11]. Investigation of Colombo and De Stephano (2007) shows another example of this method based on Gardner equation [12]. The purpose of this study is to simultaneously use gravity and seismic data to obtain a high resolution image of the subsurface, enhance the location and define the boundary of mud volcanoes in Gorgan area.

This issue could be a crucial problem in sedimentary some basins with thick sequence of mud. Existence of mud could distort the seismic image and gravity maps in such areas. Therefore, one of the potential methods to suppress this problem is to combine both gravity and seismic information to draw an integrated model. The researchers faced in interpreting seismic data from the Gorgan region to image boundary of mud volcanoes. Based on the seismic data only, it was difficult to create a perfect model of mud volcano. Thus, it was decided to create velocity model by using relationship between porosity and density of the medium. Therefore, after gravity data acquisition, processing of the data and making the Bouguer anomaly, different profile in different azimuth were obtained.

These profiles were obtained from different parts of the medium, where considerable velocity variation observed in the model.

2. Methodology

Obtaining a reliable seismic velocity model, in spite of lateral and vertical velocity variations, is a crucial task. Contamination by noise, will suppress the accuracy and validity of this model. Thus, other geological and geophysical data can improve the accuracy of the velocity model as complementary data. Using these auxiliary data will needs integrating modelling techniques to be applied on the data. Modeling techniques make relations between observation data, define variation of physical characteristics of the media and illuminate discontinuities due to these variations. Consequently, modeling can estimate physical and geometrical characteristic distribution through the medium [13]. Having combined geological data of the study area and the primary estimation of model parameters, a physical model which includes anomaly characteristics is proposed.

The beginning of the model building procedure is the forward modeling. Forward modelling consists of predicting measurement results (data prediction) based on a primary model and its parameters. Forward modeling procedure includes the calculation of an anomaly from an imaginary supposed model based on repeating calculations on the basis of changing model parameters such as density contrast and depth, until appropriate fitting between computational anomaly and observational anomaly (Figure 1).

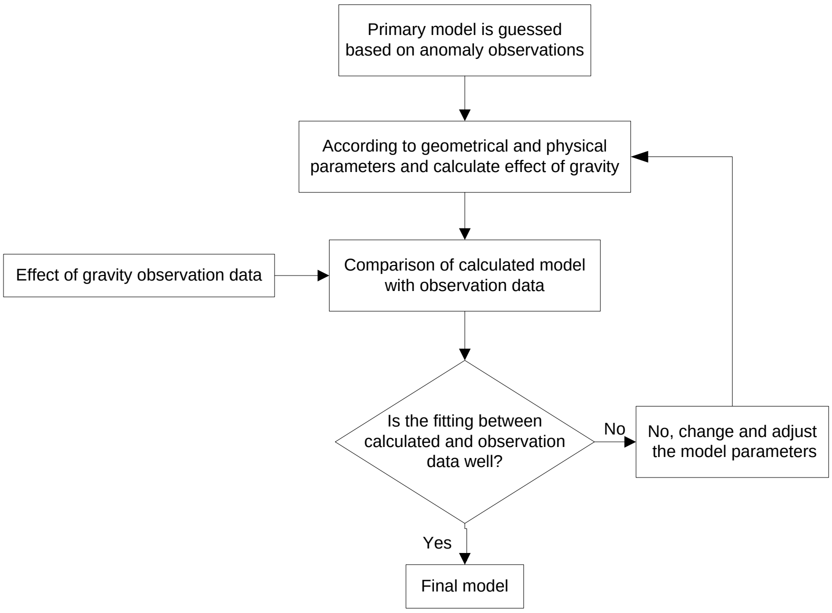


Figure 1. Forward modeling stage [13].

This kind of modeling can be executed manually or by using semi-automatic techniques. Error decreasing is executed by using trial and error method, which is a very timeconsuming procedure, that sometimes never reach an appropriate fitness between observation and computational data by changing model parameters. Undoubtedly, this modeling is also accompanied with deficits that if the interpreter conducts the action intelligently, the model will preserve its geological validity [13].

According to Figure 1, for forward modeling, the value of gravity effect is computed by a primary guess of the model based on gravity data and existing geological information. Then the computed gravity anomaly is compared with observed value. In case of lack of appropriate fitness, unknown characteristics (density, depth and location) of target in the model will be repeatedly changed to reach the best fitness between gravity effect of the model and observed gravity anomaly. In order to better process gravity and seismic data to achieve the best subsurface image, seismic and gravity data were used to perform density and velocity analysis. In this regard, having conducted empirical researches, Gardner et al. (1974), presented an equation for velocity and density relationship [12]:

$$\rho = 0.31\sqrt[4]{V} \tag{1}$$

where V (m/s^2), is the velocity and ρ (gr/cm^3) is density of the environment.

According to Gardner et al. (1974), diagram of density variation corresponding to seismic velocity is a straight line with initiation value of about 1, which consists of the behavior of almost all of the sedimentary rocks. However, Salt, Coal, and Anhydrite do not follow this line, meaning that they are not in accordance with relation of Gardner (Figure 2). In order to improve the relation between seismic velocity and density in carbonated rocks, Rafavich et al (1984), conducted experiments with more details on Gardner model [14]. Dey and Stewart, (1997) indicated that velocity is basically affected by parameters of porosity and density of rocks [15].

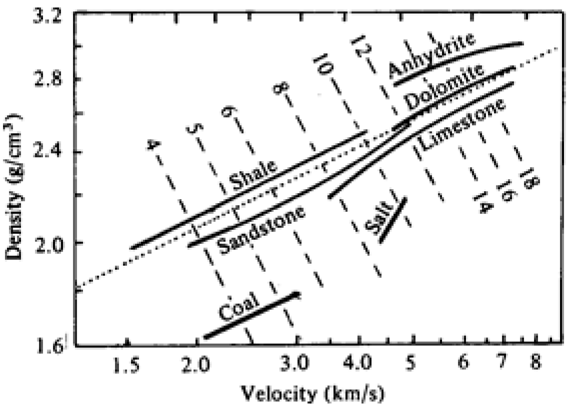


Figure 2. Results of empirical studies on rocks and minerals [12].

3. Real data and geology of the area

To investigate efficiency of the introduced technique above, a real seismic and gravity data from a same region were selected. The study area is located in the north east of Iran, in the eastern bank of the Caspian Sea. This area was selected for this study due to existence of several mud volcanoes. The aim of modeling is therefore, defining exact location and the boundary of these mud volcanoes.

The study area is located between longitudes of 54 and 56 degrees of east, and latitudes of 36.30 and 38.15 of north. According to field observations, there are six mud volcanoes on this area. One of the most important and active of them is named Gomishan which is located around the eastern part of the Port of Turkmen, near Gomishan city, and from many years ago, portions of gas and mud have been emerging from it (Figure 3).

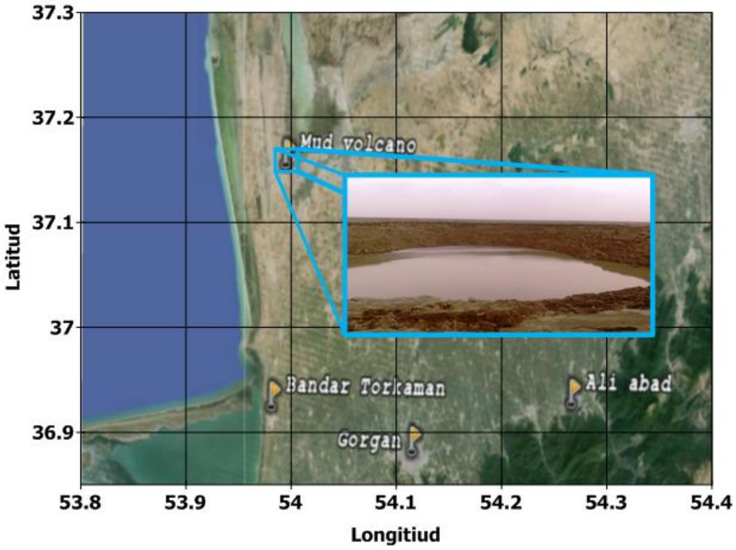


Figure 3. Geographical location of Gomishan mud volcano in Golestan province and a photo of its crater.

Acquisition of gravity data was performed on a regular 500 × 1000 m grid, by East-West oriented profiles.

At the gravity station on the earth’s surface, the observed gravity relates Latitude of point, elevation, mass distribution and topographic around of it, the earth tide, drift of instrument and the contrast of density subsurface structures and anomalies. By eliminating these effects from the observed data, the Bouguer anomaly calculated and the contour map prepared (Figure 4).

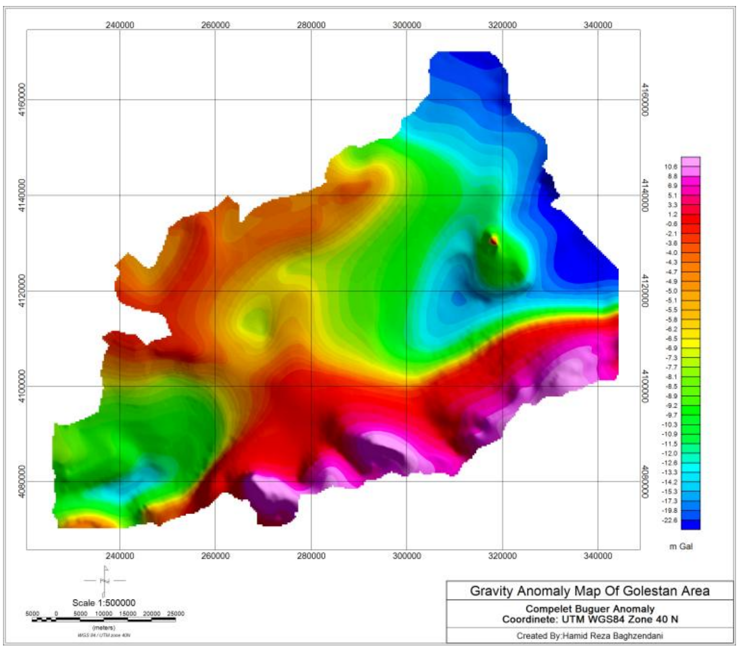


Figure 4. Bouguer gravity anomaly map.

For verification of the velocity analysis based on gravity data, the researchers used a velocity model from a seismic line that passed along the mention mud volcano with small offset. Seismic data used in this research crossed a profile along north east to south west direction, which is around the mentioned mud volcano. Figure 5 shows the seismic section of a profile in the vicinity of mud volcano.

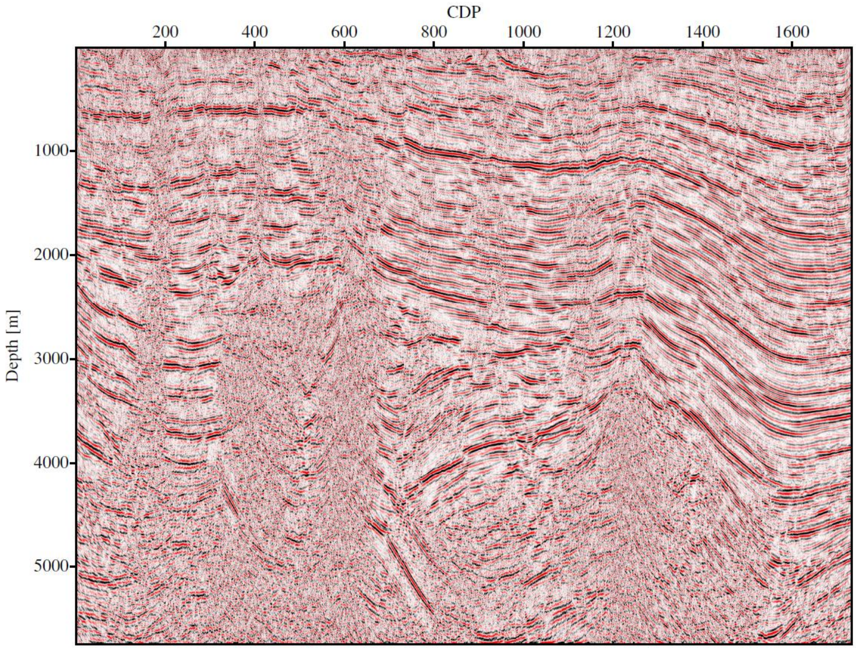


Figure 5. Seismic section of a profile in the vicinity of mud volcano along direction of north east to south west.

4. Processing and interpretation of gravimetric data

The measured gravity field demonstrates a set of effects related to structures with different densities and depths related to studied area or its surroundings structures. In fact, the observed data in the area consists of a spectrum from local to regional anomalies. Defining a gravity anomaly as a local anomaly or regional anomaly is relatively comparative. It means that they are defined according to the vastness of the area and the type of geophysical operation. For instance, it may happen that a local anomaly in oil exploration is considered as regional effect in Chromite exploration. Accordingly, anomalies separations are implemented based on exploration objective.

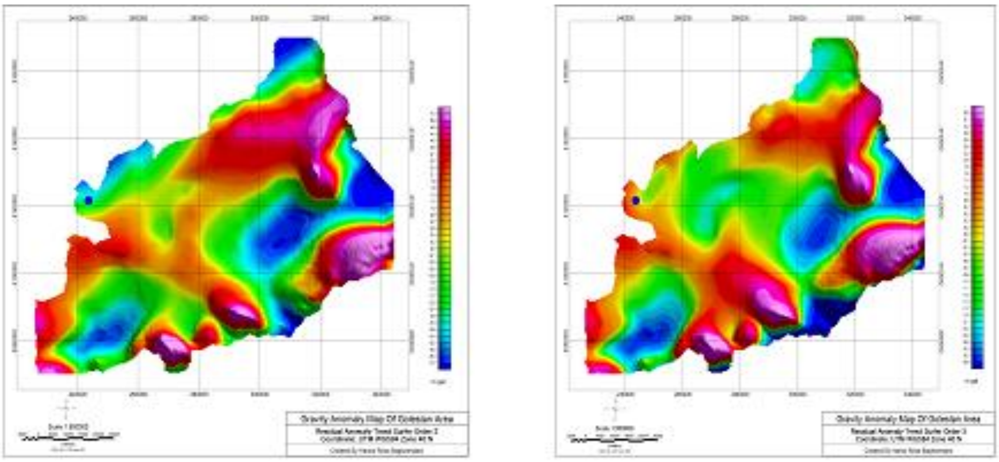
4.1. Trend surface analysis

The purpose of this study is to provide density model and determine velocity model based on density distribution. It was defined that the absolute Bougure anomalies, resulting from the geological bodies in study area, are due to the existence of these bodies from the surface through to the geoid surface. Thus, based on the exploration targets, effect of deep resources (regional anomaly) is separated from the effect of shallow resources (local anomaly) using various methods. To provide a good density model, it is necessary to separate local gravity anomaly from regional ones. One of the methods commonly used is the Trend Surface Analysis with an order of a polynomial function. In trend surface analysis, the order of polynomial function used for separating local and regional anomalies is very important.

Two statistically criteria for defining goodness of fitness (created model to the observed data) are “F” test and residual sum of the squares.

In this study, this fitness was tested in for steps. First of all, order of the fitted surface function to the distributed data should be defined. The results of “F” test pointed out that the surface of order 3, gives the best fitness between data and model, (Figure 6).

Therefore, the third order of trend surface is considered as regional anomaly and then local anomaly related to this procedure is obtained. Figures 6a and 6b show residual gravity anomaly after elimination of trend surface of second and third order respectively.



(a) (b)

Figure 6. Residual gravity anomaly after elimination of (a) second order of trend surface and (b) third order of trend surface.

The residual anomaly map, shows several negative gravity anomalies. These anomalies could be related to the existence of mud volcanoes, (due to the low density of mud) or any other geological downfalls.

In the eastern end anomaly of the area is a semi-closed negative anomaly located on the edge of the map. According to the provided maps and field data, it can be observed that one of the mud volcanoes of the area is the Gomishan mud volcano.

5. Modeling of the data

As it was previously mentioned, different modelling methods are used through interpretation of field potential data. In this study, direct forward modelling was applied on the gravity data to draw a velocity model. The gravity model of the study area was also defined that shows the location of the mud volcanoes. For a better verification of the gravity model, a 2D profiled was drawn exactly from the location of the seismic line. The location of this seismic line is shown in the residual map (Figure 7) and its gravity effect is shown by green line in Figure 8. For direct forward modelling, the Wing-link software was used and different stratigraphical models were created. Based on the geological and seismic information from the region, a four layered model was selected as the final suited model (Figure 8).

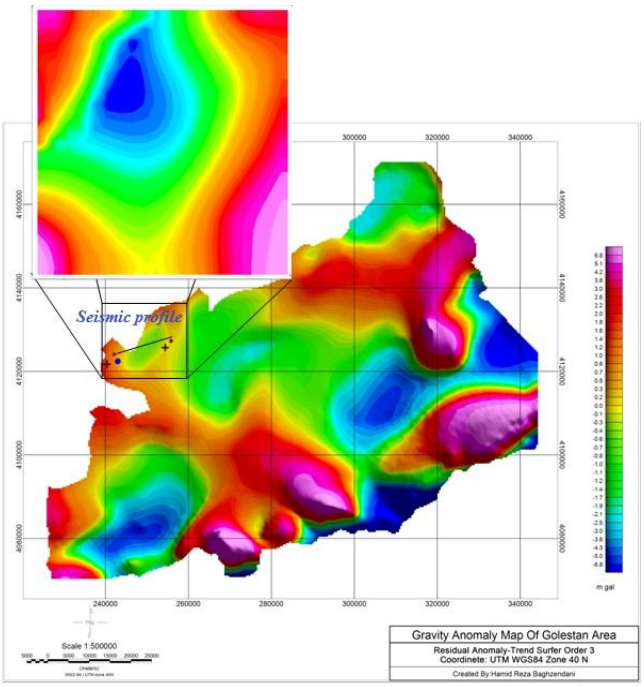


Figure 7. 2D modeling of gravity data on studied area.

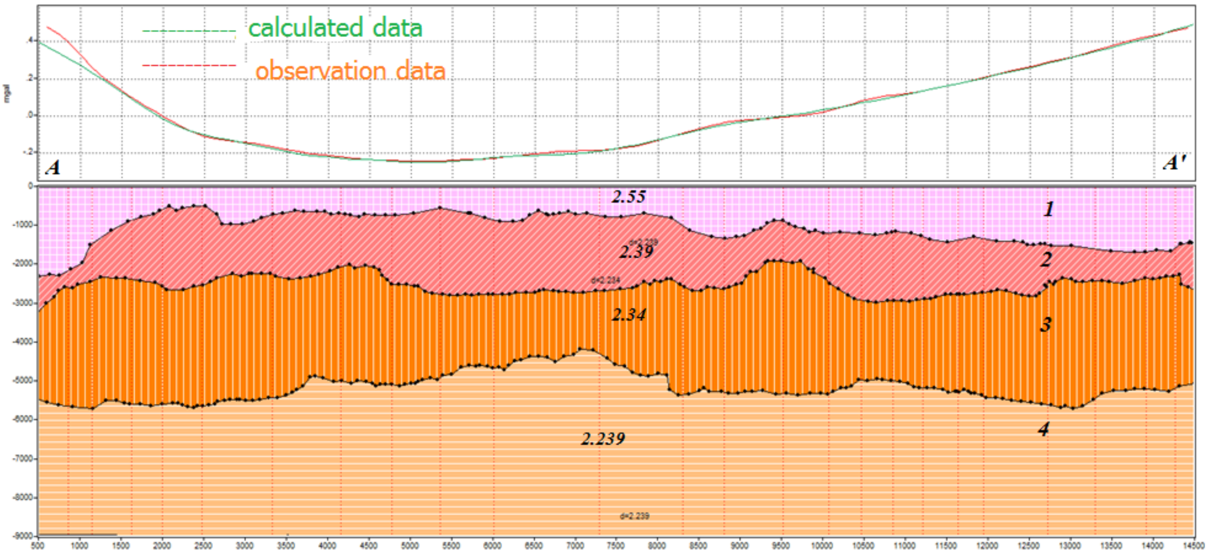


Figure 8. Density distribution was obtained from 2D modeling of gravity data on the studied profile.

In Figure 10, the gravity effect of the direct modeling (calculated data) is defined by red line that shows perfect fitness with observed data. Density variation range in this section is between 2.55 to 2.239 gr/cm^3 that could be the result of the lithological differences from shale to clay and marl. In this section, there is no evidence of mud in the surface and all its effect is limited to the subsurface layers. Afterwards, by fitting the calculated and observed data and by using the program made by MATLAB, the density model was converted to the velocity model, (Figure 9).
For better verification, a velocity model from seismic data was also obtained, (Figure 10). By comparing these two velocity models, it was observed that against the conventional vertical trend of the velocity, the velocity decreased by increasing the depth and after 5000 m in depth, it start to increase again. This phenomenon could be due to the gas leakage in the upper sediments that results in density reduction.
To better compare the velocity model obtained from gravity data and velocity model from seismic data, a 1D velocity function of the these two models were extracted and shown in Figure 11. This figure shows that these two functions do not match perfectly in shallow depths, while the converge more by increasing depth.

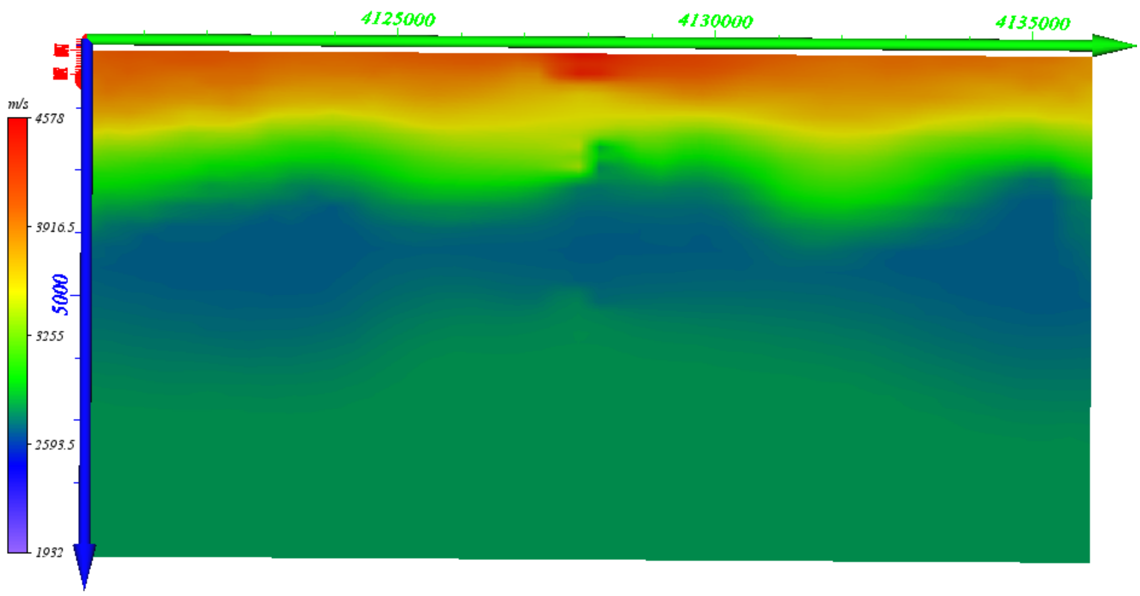


Figure 9. Velocity model resulted from gravity anomaly.

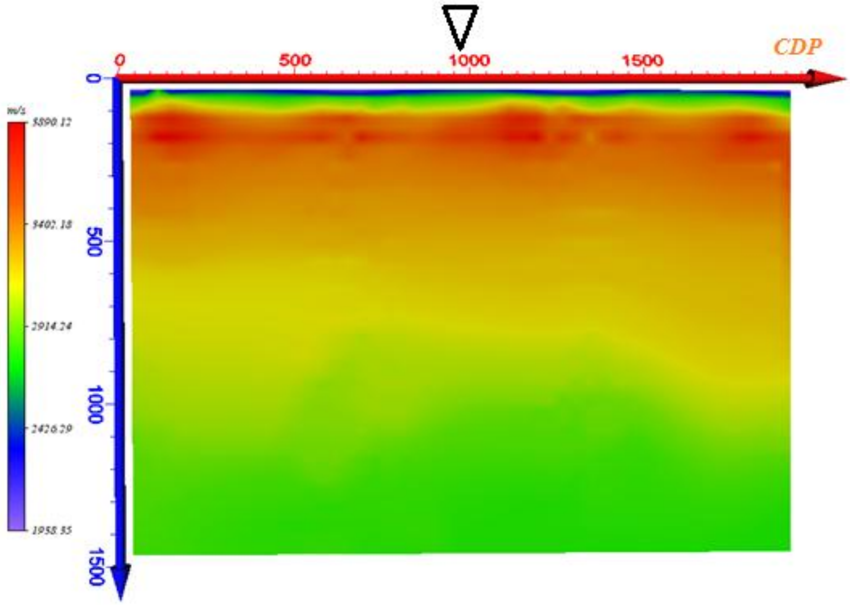


Figure 10. Velocity model resulted from conventional tomography.

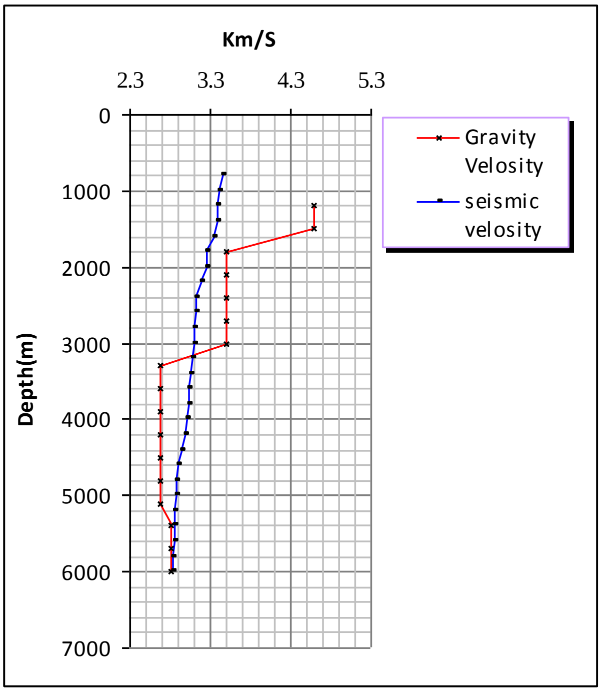


Figure 11. Velocity depth variation obtained from velocity models resulted from gravity and seismic data in center of profile.

6. Conclusions

The results of comparing the velocity modelling from gravity data and velocity analysis from seismic data show that integrated modeling could be suitable tool for interpretation and structural analysis of the subsurface layers. Therefore, according to the acquisition and type of gravity data (less cost, less time, more coverage), the velocity model obtained from this data could play an important role in structural interpretation. However, it goes without saying that the more dense acquisition grid, the more accurate final velocity model. The result of the density modelling in the study area shows that the variation of the range of density variation from the surface to depth is 0.32 gr/cm^3 that show a smooth change in lithology. This could also be an evidence of a quite sedimentary basin. The other results obtained from the survey studied in this paper indicated that supplying density model using gravity data and velocity model from seismic data is the key step in the ability of gravity data to separate sub-surface layers with respect to the precision of the measurements. By applying Gardner's equation, we can determine the velocity model, which exhibits a huge proportion of sub-surface structures. In this study, we applied this method on seismic data and gravity data of the same field to enhance the location of mud volcanoes. The seismic section has higher resolution in separating layers and better estimation in velocity of the media. This information was then used in gravity modelling finally by combination of seismic and gravity information, the boundary of mud volcano was detected well.

References

[1]. Deville, E., Battani, A., Griboulard, R., Guerlais, S., Herbin, J. P., Houzay, J. P., Muller, C. and Prinzhofer, A. (2003). Mud volcanism origin and processes: New insights from Trinidad. Special publication 216 of the Geological Society (London) on Subsurface Sediment mobilisation. 475- 490

[2]. Huseynov, D. (2004). Mud volcanic natural phenomena in the south Caspian Basin: geology, fluid

dynamics and environmental impact, Environmental geology. 46: 1012- 1023.

[3]. Michaiel, C. and Daneile, D. (2007). Geophysical modeling via simultaneous joint inversion of seismic-gravity and electromagnetic data, Society of Exploration Geophysicists. 26: 326- 331.

[4]. Reynolds, J. M. (1997). An introduction to applied and environmental geophysics, John Wiley &Sons, 796 p.

[5]. Epuh, E. and Olorode, D. (2012). Analysis of Gongola Basin Depositional Sequence Using Seismic Stratigraphy, European Journal of Scientific. 3: 42- 58.

[6]. Gosh, G. K., Basha, S. K., Salim, M. and Kulshreshth, V. K. (2010). Integrated interpretation of seismic, gravity, magnetic and magneto-telluric data in geologically complex thrust belt areas of Manabum, Arunachal Pradesh, Journal of Indian Geophysical Union. 14 (1): 1- 14.

[7]. Yalamanchili, S. V. and Nieuwenhuise, B. V. (2002). Arial Gravity and Magnetic Data Usage for Seismic Survey Planning and the Integration of 3-D Gravity and Seismic Data in the Santos a Campos Basins, Brazil, Society of Exploration Geophysicists. 1: 775- 778**.**

[8]. Anderson, B. and Lyman, G. (2002). Using Gravity and Magnetics to Enhance Seismic Velocity Models - Case Study form Offshore Brazil, 64th EAGE Conference & Exhibition. 1- 10.

[9]. Cai, W. Z., You, L. T. and Yao, G. J. (2009). 3D Joint Inversion of Gravity and Seismic Data for Multilayer Medium" Chinese Journal Geophysics. 24: 1216- 1224.

[10]. Telford, W. M. Geldart, L. P. and Sheriff, R. C. (1991). Applied geophysics, 2nd edition, Combridge University press, 770 p.

[11]. Mantovani, M. and Dugoujard, T. (2011). Salt detection and interactive interpretation by seismic-gravity simultaneous joint inversion, First Break. 29: 59- 64.

[12]. Gardner, G. H. F., Gardner, L. W. and Gregory, A. R. (1974). Formation Velocity and Density the Diagnostic Basics for Stratigraphic Traps, Geophysics. 39: 770- 780.

[13]. Blakely, R. J. (1996). Potential Theory in Gravity and Magnetic Applications, English, 440 p.

[14]. Rafavich, F., Kendall, C. H. S. T .C. and Todd, T. P. (1984). The relationship between acoustic properties and the petrographic character of carbonate rocks, Geophysics. 49: 1622- 1636.

[15]. Dey, A. K. and Stewart, R. R. (1997). Predicting density using Vs and Gardner's relationship, CREWES Research Report. 9: 1- 9.

مدل‌سازی زیرسطحی گل‌فشان‌ها به کمک مدل چگالی و آنالیز سرعت لرزه‌ای

حمیدرضا باغزندانی، حمید آقاجانی* و مهرداد سلیمانی

دانشکده مهندسی معدن، نفت و ژئوفیزیک، دانشگاه شاهرود، ایران

ارسال ۲۰۱۴/۷/۸، پذیرش ۲۰۱۴/۹/۱۴

* نویسنده مسئول مکاتبات: haghajani@shahroodut.ac.ir

چکیده:

در این مقاله، نقشه توزیع جرمی و اختلاف چگالی واحدهای سنگی در یک منطقه را می‌توان با آشکارسازی ساختارهای زیرسطحی به روش گرانی‌سنجی تعیین کرد. برای بارز سازی توزیع جرمی از روش‌های ژئوفیزیکی مختلفی به‌ویژه روش گرانی‌سنجی می‌توان استفاده کرد. روش گرانی‌سنجی همانند سایر روش‌ها دارای یک سری معایب و مشکلاتی بوده و به‌تنهایی همیشه در تشخیص و تفکیک ساختارهای زیرسطحی موفق نیست. کیفیت عملکرد این روش با به‌کارگیری همزمان و ترکیبی با دیگر روش‌های ژئوفیزیکی و استفاده از اطلاعات جانبی می‌تواند افزایش یابد. در این تحقیق از ارتباط موجود بین داده‌های لرزه‌ای و گرانی‌سنجی یعنی رابطه بین توزیع جرمی و سرعت سیر موج در یک محیط برای وضوح بهتر و مناسب‌تر ساختارهای زیرسطحی مثل گل‌فشان‌های منطقه جنوب شرق دریای خزر استفاده شد. بعد از تهیه یک مدل اولیه به روش مستقیم، توزیع جرمی و آنالیز سرعت موج لرزه‌ای در یک فضای دوبعدی محاسبه و نقشه آن تهیه و ترسیم گردید. پس از تصحیح و پردازش داده‌های گرانی و تهیه نقشه آنومالی بوگه، با توجه به اختلاف چگالی منفی بین گل‌فشان و محیط اطراف آن، آنومالی‌های منفی و کمینه مشخص شدند که می‌تواند نشانه‌ای از وجود گلفشان باشد. از داده‌های یک خط لرزه‌ای که از بالای یکی از این گل‌فشان‌ها عبور کرده است به‌عنوان داده جانبی برای مدل‌سازی مستقیم بهره گرفته شد. برای تخمین توزیع سرعت موج از مقادیر چگالی رابطه گاردنر بکار رفته است. سپس این مدل سرعت با مدل تهیه‌شده از داده‌های لرزه‌ای مقایسه و مورد ارزیابی قرار گرفته است. نتایج بررسی‌ها نشان می‌دهد که مدل‌سازی چگالی و استفاده از مدل سرعت لرزه‌ای سبب افزایش قدرت تفکیک ساختارهای زیرسطحی می‌شود. تفکیک و بارز سازی لایه‌های زیرسطحی با دقت مناسبی در مدل سرعت حاصل از داده‌های گرانی دیده می‌شود و همچنین ناپیوستگی‌های زیرسطحی در این حالت بهتر از پیش شناسایی شده است.

کلمات کلیدی: رابطه گاردنر، تصویرسازی لرزه‌ای، آنالیز سرعت، آنومالی گرانی، گل‌فشان.