Identifying diapiric bodies with potential field methods

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Abstract

This paper shows some aspects about the gravimetric and magnetic response of diapiric bodies, and it intends to elucidate the way to recognize and modeling these geologic features by using potential field methods.

Theoretical 2D models have been used to represent some geologic scenarios and evaluate the response of the structures in terms of amplitude and frequency of the calculated anomalies. Using 2D models, it is possible to evidence how changes in depth, morphology, density and volume respond in terms of the gravimetric and magnetic anomalies. All these observations help to characterize the signature variations of the diapiric bodies.

Introduction

Seismic data is the most used geophysical method in petroleum exploration, because of the high-quality response of structures and lithologic changes. However, some geological contexts create pitfalls to this method, like volcanic layers, reefs, carbonate formations and shale or salt diapirs, for example. The use of other procedures, such as potential field methods, combined with available geological and other geophysical data, allows an integrated view of the geological context of the studied area. The result is a low risk interpretation.

The potential field methods can also be used in situations where seismic method is not recommended, such as remote areas and areas protected by environmental laws. Because of the low cost of these methods, it can be used in studies to optimize seismic acquisition.

Areas containing diapiric structures are very interesting to petroleum exploration, because their tectonics cause several ductile and fragile deformations in the sedimentary rocks, such as, peripheral diapir synclinals (Mohriak & Szatmari, 2008a), characteristic fault families, and collapse anticlinal structures. Therefore, the knowledge about this tectonics is essential to make a migration description, as well as to predict oil and gas traps. There are many examples of studies in diapiric areas using potential fields, such as Prieto *et al.* (1993) and Rowan *et al.* (1999), for instance.

Diapirism

The geostatic pressure and the density and viscosity contrasts in some low density rocks can induce the movement of these rocks. This phenomenon is called diapirism, and it is related to the buoyancy concept: the floatage of a low density material into a relatively high-density material (*in* Mohriak & Szatmari, 2008a). The most common rocks that compose the diapiric features are evaporitic rocks and low-density shales. The diapiric bodies are formed by deformation of these rocks due to the low-density material accumulation in many different shapes.

In the salt diapirism, the rock density can be diversified according to the mineral composition, such as exemplified in Table 1.

In comparison with the host rocks, salt doesn't have significant density variability with increasing depth, and will not be compacted such as other sedimentary rocks (Figure 1). This fact provides also an increase in density contrast with depth and intensifies the buoyancy effect.

The shale diapirism is also a target to hydrocarbon exploration. Such as occurs with salt formations, this rock type has its particular tectonics. Besides, shale diapirs can be associated with methane gas (CH_4) escape, which causes, in this case, a decrease in density, producing a higher density contrast with the surrounding rocks (Nettleton, 1962).

Table 1 - Main salt minerals average densities, measured from well data. (Mohriak & Szatmari, 2008b).

Mineral	*Chemical Formula*	*Density (g/cm^3)*
Halite	$NaCl$	2,03
Anidrite	$CaSO_4$	2,98
Gipsum	$CaSO_4.2H_2O$	2,35
Polihalite	$K_2SO_4.MgSO_4.2CaSO_4.2H_2O$	2,79
Carnallite	$KMgCl_3.6H_2O$	1,57
Silvite	KCl	1,86
Kieserite	$MgSO_4.H_2O$	2,55
Kainite	$KMg(SO_4)Cl.3H_2O$	2,12
Langbeinite	$K_2SO_4.2H_2O$	2,82

Potential field methods

Gravity method

Petrographic differences between rock types make spatial density variations, adding irregularities to the geoid. Gravity uses these variations to study geology (Blakely, 1996). Some average density values of common rocks are exemplified in Table 2.

The gravity data will be a summation of all responses from sources nearby the measured point. Moreover, the response will depend on the density contrast between the rock types, rather than the density value. Another point is that gravity anomalies have frequency variation with depth, i. e., if the depth increases, the anomaly frequency will be lower (Prieto, 1996). A method to focus the gravity study on a specific objective is to subtract some frequencies and keep only the frequencies of interest, which represent the target response.

Table 2 - Average values of density and magnetic susceptibilities of various rock petrographic types (LCT Gravity and magnetics, 2006; Olhoeft & Johnson, 1989).

Material	*Density (g/cm^3)*	*Magnetic susceptibility (microcgs units)*
Dolomite	2.7	10
Carbonate	2.55	30
Salt	2.2	50 or negative
Sandstone	2.35	40
Shale	2.4	60
Andesite	2.61	16000
Basalt	2.74	800
Diabase	2.91	2500
Diorite	2.85	8500
Gabbro	3.03	7000
Granite	2.64	250
Granodiorite	2.72	500
Peridotite	3.15	15000
Riolite	2.52	1500
Anfibolite	2.96	70
Quartzite	2.6	400
Serpentinite	2.78	600

Magnetic method

This method is based on the magnetic susceptibility of the rocks (Table 2). The magnetic response depends on the amount of magnetic minerals, frequently magnetite, in the rocks (Prieto *et al.*, 1993). However, other factors can affects these rocks, such as the magnetization type (Blakely, 1996), which is the product of the susceptibility by the magnetic induced field.

Using susceptibility values, combined with geological and geophysical available data, it is possible to obtain a first guess about the type of source rock related to the magnetic response (Prieto *et al.*, 1993). However, this property must be used with caution because the same petrographic rock type can present different magnetizations (Blakely, 1996).

The magnetic data analysis is a bit more complicated than gravity interpretation. As stated by Nettleton (1962), gravity method works with a unique variable factor, the density variation, while the magnetic method depends on several parameters, like magnetization, intensity and orientation of magnetic field, for instance (Figure 2).

Modeling

Solutions for some problems in potential fields can be found through the use of 2D or 3D modeling techniques. The 2D models are the most common method of analysis of gravity and/or magnetic anomalies. It can be made by changing a model built based on real data until its response has the same signature of the observed profile. On the other hand, theoretical modeling, without any real potential field data, is interesting to evaluate different geological possibilities and its responses. This procedure is applied in this work.

Model preparation can use constant density for each geologic unit (simplified models) or variable density from increasing depth (Bain *et al.* 1991). In oil exploration, this information is obtained from velocities seismic models or by well data.

Gravity and magnetics for diapiric rocks studies

The magnetic signature of salt diapir is a low-amplitude negative anomaly (Prieto *et al*., 1993), as a result of the diamagnetism. In the diamagnetic materials, an applied magnetic field disturbs the orbital electron motion, so that there is a little induction of magnetization on the opposite direction of the magnetic field. Therefore, the diamagnetism will confer to this rock a slightly negative response (Blakely, 1996). In the case of shale diapir, the response will depend on the mineral composition of the shale and surrounding rocks.

Commonly, the salt response will be negative because of the relative low density and susceptibility in comparison with most common host rocks (Table 2). The visualization of diapir signatures is usually highlighted after regional field removal (Lowrie, 2007). In residual maps, these localized anomalies are characterized by rounded centralized curves located over the diapiric body.

2D Theoretical model analysis

Theoretical 2D models had been created to illustrate different morphologies of diapiric rocks and their gravity and magnetic responses. These models represent a variety of geological settings, keeping the focus on diapiric forms. The geologic settings had been inspired by Prieto *et al.* (1993), Jacques *et al.* (2003), Nettleton (1962) and Mohriak & Szatmari (2008a).

In the 2D salt diapiric models (figures 7 to 10), the salt density was set to 2.2 g/cm^3 (Table 2), and magnetic susceptibility was equal to -0.8 microcgs units (Prieto *et al.*, 1993). For the shale diapir (Figure 11), the shale density is 2.35 g/cm^3 (Jacques *et al.*, 2003), and the magnetic susceptibility is 60 microcgs units (Table 2). The density values of the surrounding rocks were based on Table 2. However, these values are allowed to increase in depth in order to simulate sedimentary overburden.

The analysis of theoretical modeling points out some characteristics of the diapir signatures. In figures 3 to 11, the 2D geological model is shown in the lower panel, the magnetic response (red curve) is in the upper panel, and the gravity response (black curve) is in the middle.

Some aspects were found:

a) A diapiric salt dome that is connected to the original salt layer (Figure 3) has a larger amplitude signature than a detached body ("drop shape" in Figure 4). There is an amplitude decreasing in the second case because of the lower volume of low-density material along the vertical axis.

b) If the dome has a lateral development on the top (Figure 5), the resulting anomaly is a merge of two responses. The first one is from the deeper diapiric mass, whose response is similar to that of Figure 3. The second is from the top lateral extension, which has a lower amplitude response than the main dome because of the lower volume of salt. In addition, it has a higher frequency response due to the fact that it is a shallower source. If the salt dome or salt walls have lateral extensions in both directions (Figure 6), the same shallow effects seen in

Figure 5 will be present on both edges of the anomaly curve.

c) In figures 7 and 8, the peaks of the magnetic and gravity calculated curves are related to the sediment cores that are inside the salt mass. These cores are also called mini-basins. Canopies structures, formed by amalgamated salt walls or mushrooms, can give similar responses such as in Figure 7.

d) An amplitude decreases in both gravity and magnetic profiles can be observed comparing figures 9 and 10. This effect is caused by the connection of the salt tongue with the main salt layer that increases the amount of low density/susceptibility material (Figure 9). Also, in these two models, it is possible to see additional high-frequencies on the anomaly, which is caused by shape irregularities on the top of the salt tongue.

e) Despite the density values of shale in Table 2, in general, the shale diapir provides a negative gravity signature (Figure 11), similar to the shape of salt dome responses in figures 3 and 4. The Figure 11 shows a model of low-density shale diapir, based on models showed in Jacques *et al.* (2003). In this case, the anomaly is a bit shifted, with the peaks over the center of gravity of the diapir. The magnetic response of this diapir is positive because the shale has a positive susceptibility contrast to the surrounding rocks. Another possibility is to consider the diapir composed by gas bearing shale. In this case, the estimate of an average value strongly depends on the hydrocarbon concentration.

The mineral composition is the main factor that changes the salt density, because different types give different densities (Table1). The salt density can reach very high values. The anhydrite value (Table 1), for example, has density comparable to mafic rocks (Table 2). Thus, for gravity interpretation, it is fundamental to determine the type of salt before finding a final solution.

In some cases, salt domes exhibit a thin high-density layer on the top called “cap rock”. This layer is composed by three or four monomineralic rocks, usually anhydrite, gypsum, calcite and, rarely, celestite. Although it often occurs in shallow salt domes, it can also be found on top of the deep ones (Walker, 1976).

Because the cap rock is a shallow high-density source, it creates a positive low-amplitude feature on the expected negative response of salt diapir (Figure 12). Such feature can disturb the correct determination of the salt body geometry. This positive anomaly can be removed by filtering, and the diapir model will be constructed by a regular negative anomaly (Nettleton, 1962).

Various shale diapiric structures are similar to salt diapirism, and sometimes, the discrimination between the two types can be not easy. Solving this question is not simple even when using potential field studies because, in general, low-density shales and salt have similar responses. Therefore, using only density, magnetic susceptibility and the geometry of the body, it is difficult to identify the type of rock that compounds the diapir.

A plausible solution to this problem is to evaluate other physical properties to complement the research. As an example, Sandsberg *et al.* (2008) suggest to use resistivity measured by the magnetotelluric method to recognize salt cores.

Conclusions

Many aspects of the potential fields anomalies can be observed through 2D theoretical models. There are some important factors that compound the signature of diapiric bodies, such as density contrast, depth, shape and volume of diapiric rock. These parameters modify the amplitude and shape of the calculated anomalies.

As it was already expected for gravity and magnetic methods, considerable changes in the anomalies come from lateral shape variations in the bodies. These changes may create a superposition effect, characterized by the appearance of high-frequency features in the anomaly, such as those presented in domes with lateral top development (the mushroom shape, for instance). The vertical variation in shape only influences in the amplitude of the anomaly.

Another important factor is that the volume variation of the diapiric rock is directly proportional to the anomalous amplitude. In other words, if the volume decreases, the amplitude also decreases. This fact gives importance to gravity modeling of diapiric units mapped on seismic sections because it helps to confirm the volume of rock interpreted.

Changes in the anomaly caused by modifications in the diapiric body are easier to visualize if the body is shallow. Similarly, the deeper part of a body will produce lower amplitude response than its shallow portion.

Analysis of the differences in the responses for similar geological settings, demonstrates the importance of the use of potential fields as a complementary tool to solve some questions in seismic interpretations.

This paper presents some common situations, based on scenarios from Campos and Santos basins, in Brazil, as well as from Gulf of Mexico. However, additional models should be analyzed in order to assist some specific problems. Besides, these analyses can be enhanced by using density variation with depth. Also, 3D modeling could be a complementary approach to study the effects of diapiric structures.

Acknowledgements

The author would like to thank Petrobras S/A for the permission to publish this work. A special thank is due to the Petrobras’ Potential Fields Team for their support and revision.

References

Bain, J. E; Weyand, J.; Weber, M. (1991). Resolving Complex Salt Features Using Gravity and Magnetics. AAPG Invited Lecture Series.

Blakely, R. J. (1996). Potential Theory in Gravity and Magnetics Applications. Cambridge University Press. Cap. 5.3, p87-91.

LCT Gravity and magnetics, version 2006 for Linux: modeling software. Fugro Robertson Inc, 2006.

Jacques, J.; **Parsons, M. E.**; **Price, A. D.**; **Schwartz, D. M.**, 2003, Improving geologic understanding with gravity and magnetic data: Examples from Gabon, Nigeria and the Gulf of Mexico. First Break, EAGE. Special Topic, 21, 57-62.

Lowrie, W., 2007, Fundamentals of Geophysics. Cambridge University Press. 2nd Edition, 2.6, 84-91.

Moriak, W. & Szatmari, P., 2008a, Introdução às propriedades químicas e físicas dos evaporitos. Livro: Sal: Geologia e Tectônica / organizers: Mohriak, W.; Szatmari, P.; Anjos, S. São Paulo: Beca Edições Ltda, 1, 18-41.

Moriak, W. & Szatmari, P., 2008b, Tectônica de sal. Livro: Sal: Geologia e Tectônica / organizers: Mohriak, W.; Szatmari, P.; Anjos, S. São Paulo: Beca Edições Ltda, 4, 90-163.

Nettleton, L. L., 1962, Gravity and magnetics for geologists and seismologists. AAPG Bulletin 46, 10, 1815-1838.

Olhoeft, G.R., and Johnson, G.R., 1989, Densities of Rocks and Minerals. *In* CRC Practical Handbook of Physical Properties of Rocks and Minerals. *Edited by* R.S. Carmichael. CRC Press, 139–176.

Prieto, C., 1996, Gravity / Magnetic signatures of various geologic models – an exercise in pattern recognition. Integrated Geophysics Corporation (IGC) - Footnotes Series. October 1993, 1, Number 1.

Prieto, C., Grow, T., Curtis, C. (1993). Understanding the magnetic response due to the salt intrusion. Integrated Geophysics Corporation (IGC) - Footnotes Series. October 1993, 1, Number 1.

Sandberg, S. K., Wu, S., Roper, T., 2008, Salt mapping in the Gulf of Mexico using marine magnetotellurics. First Break, 26, 91-94.

Rowan, M.G., Jackson, M.P.A., Trudgill, B.D, 1999, Salt-related fault families and fault welds in the Northern Gulf of Mexico. AAPG Bulletin, 83, number 9, 1454-1484. .

Walker, C.W.,1976, Origin of Gulf Coast salt-dome cap rock. AAPG Bulletin, 60, number 12, 2162-2166.

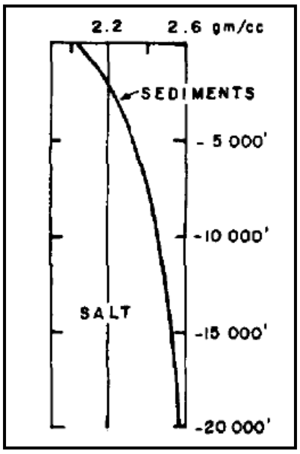

Figure 1: Density variation rate by depth increasing (in meters) for salt and sedimentary rocks (Nettleton, 1962).

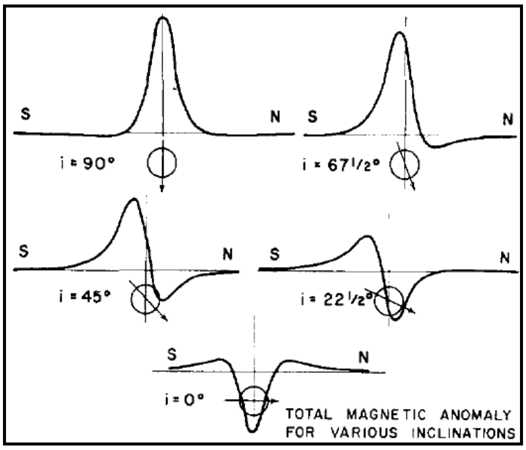

Figure 2: Total field anomalies for a single body and the variation by the assorted positions on different latitudes, when *i* is the Earth magnetic field inclination (Nettleton, 1962).

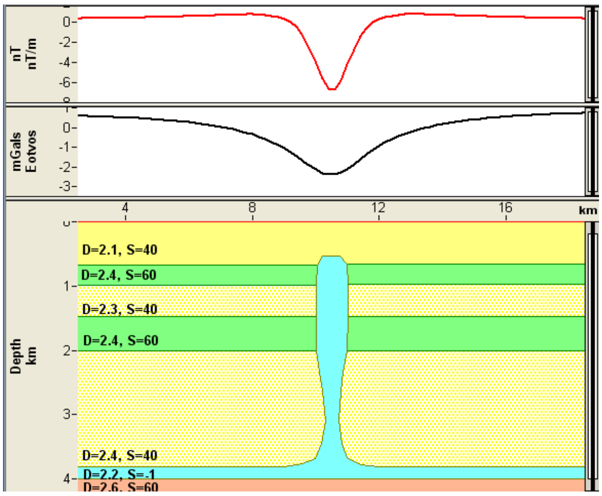

Figure 3: Theoretical 2D Model – diapiric body connected to original salt layer.

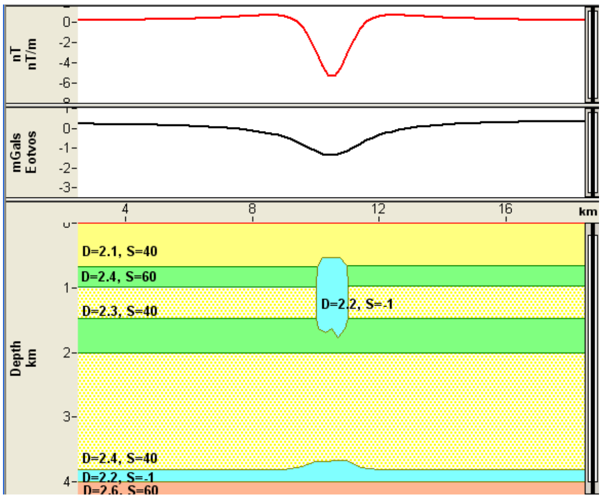

Figure 4: Theoretical 2D Model – diapiric body disconnected to original salt layer.

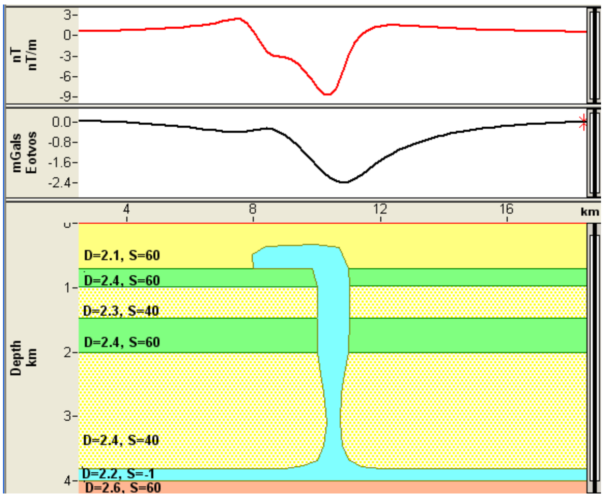

Figure 5: Theoretical 2D Model – diapiric body, which has a lateral top development.

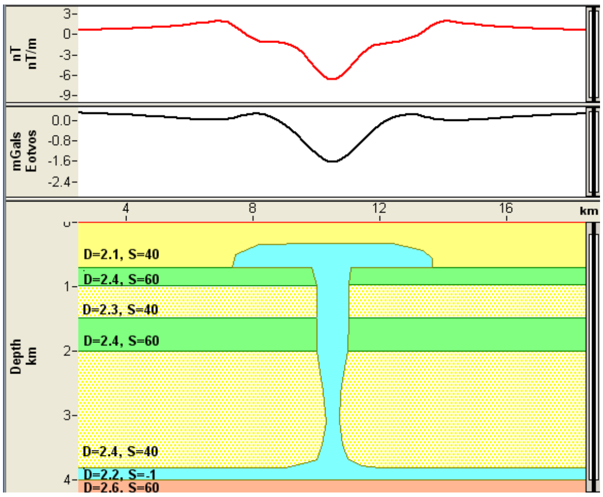

Figure 6: Theoretical 2D Model – diapiric body, which has a lateral top development to both directions.

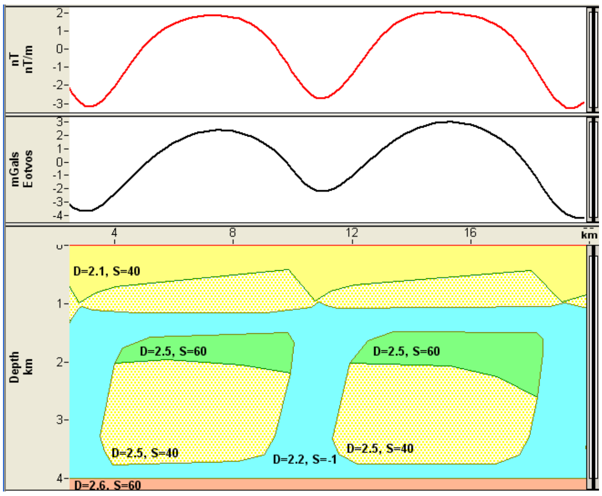

Figure 7: Theoretical 2D Model – sedimentary cores among diapiric salt.

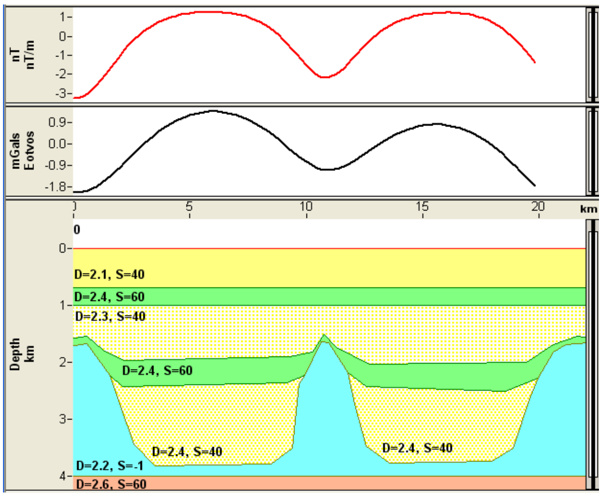

Figure 8: Theoretical 2D Model – sedimentary cores between salt diapirs.

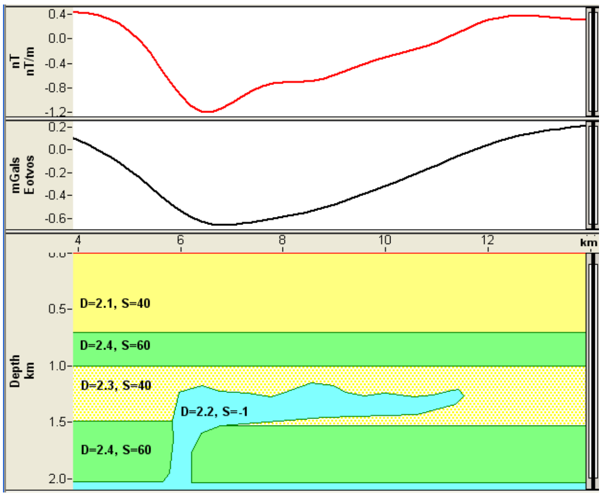

Figure 9: Theoretical 2D Model – Salt tongue connected to original layer.

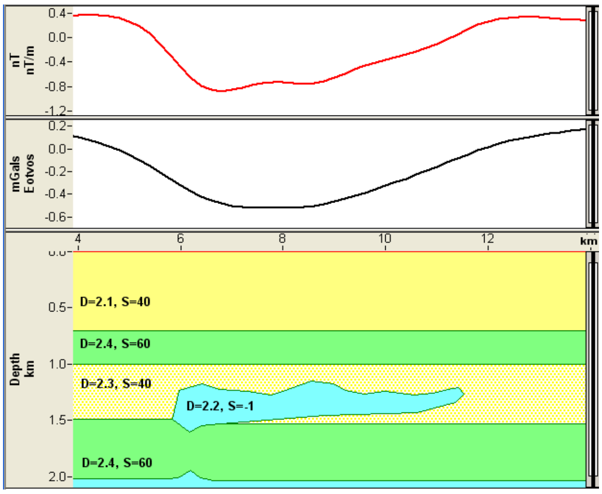

Figure 10: Theoretical 2D Model – Salt tongue disconnected to original layer.

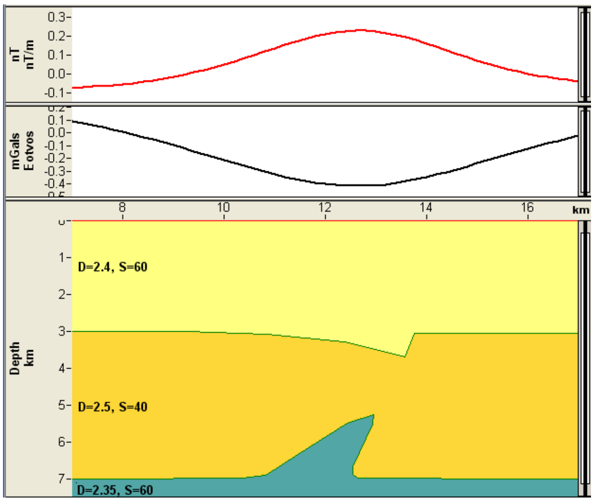

Figure 11: Theoretical 2D Model – Shale diapir in the base of a normal fault.

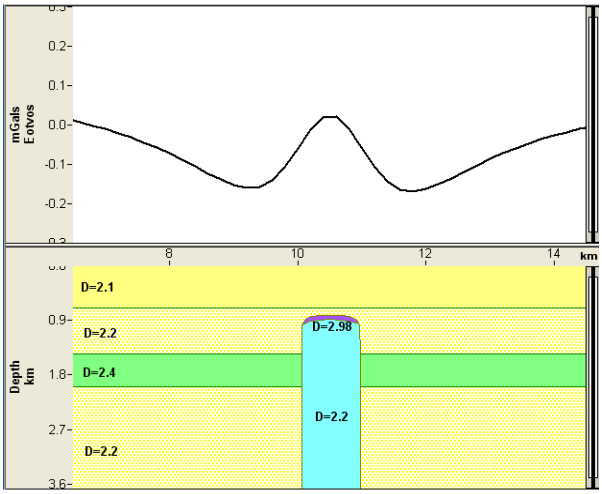

Figure 12: Theoretical 2D Model – Salt dome presenting a cap rock.