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COMPREHENSIVE GRAVITY-MAGNETIC DATA ANALYSIS FOR QUANTITATIVE DETERMINING SALT BODIES IN COMPLEX PHYSICAL-GEOLOGICAL ENVIRONMENTS

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Summary. It is well known that salt bodies in the subsurface are usually unfavorable targets for applying gravity and magnetic methods. It is caused mainly by minor differences in density (salt layers with a density of 2100-2200 kg/m^3 often occur in sediments with a similar density) and magnetic (salt layers with a magnetization of about -10 mA/m frequently occur in low-magnetic media) properties as well as geological-petrophysical variability of the subsurface geological section. Therefore, for gravity-magnetic data processing and interpretation, many advanced procedures from the available methodological arsenal should be applied, beginning with removing different kinds of noise and target visual localization and ending with developing 3D physical-geological models. Although quantitative analysis of gravity-magnetic anomalies from salt objects, usually in thin horizontal plates, is a complicated problem, an interpretation methodology for carefully analyzing observed potential field anomalies has been developed (Eppelbaum, 2019). Integrating gravity and magnetic data between themselves and with other geophysical methods increases the reliability and accuracy of geological-geophysical interpretation. For combined 3D gravity-magnetic modeling, the developed GSFC software is applied, where 3D horizontal polygonal prisms approximate the geological bodies. The application of some qualitative and quantitative interpretation methods is shown in the model and field examples. Besides the land survey, it is proposed to apply a remote-operated vehicle magnetic survey at low altitudes, which will allow not only the delineation of the salt target's disposition but also to monitor the appearance of new karst terranes, which are often associated with salt objects.

Keywords: *salt bodies, gravity, magnetics, quantitative analysis, integrated examination*

Introduction

Most salt targets occur in complex and variable geological media, sometimes in conditions of rugged topography. Gravity and magnetic investigations are the operative, mobile, and low-cost methods tools of geophysical subsurface studying. Available differences in density and magnetization (usually small but detectable) between the desired targets and host media make the salt suitable for careful studies. Besides this, gravity-magnetic methods have a rich (sometimes forgotten) arsenal of interpretation procedures and transformations.

Delineation and quantitative interpretation of gravity-magnetic anomalies from salt bodies are one of the actual problems of modern environmental geophysics (e.g., Sharma, 1997; Rybakov et al., 2005; Eppelbaum et al., 2008; Ezersky et al., 2010, 2013; Silva Dias et al., 2011; Kaufmann, 2014; Eppelbaum, 2019; Paoletti et al., 2020; Wei et al., 2022).

Salt body quantitative characterization plays an essential role in hydrocarbon geophysics. However, the search and localization of salt bodies in environmental mapping play an equally significant role. For instance, in the Dead Sea coastal areas, the salt edge is a significant factor in sinkhole development (Ezersky et al., 2013). Thus, detecting salt targets and their quantitative characterization could be assigned as search criteria for buried sinkhole revealing.

Different kinds of noises arising in potential geophysical field applications for salt body delineation

Modern gravity and magnetic equipment enable the detection of even tiny gravity of 1 microGal (1microGal = 0.001 milliGal (mGal)) and magnetic of 1 picoTesla (1 picoTesla = 0.001 nanoTesla (nT)) and fewer anomalies. However, different kinds of noise (artificial and natural origins) complicate the qualitative and quantitative analyses of the abovementioned fields over salt bodies. These main kinds of noise are presented in Fig. 1 (modified after Eppelbaum (2011a, 2011b)). Let us briefly consider the different kinds of noise.

Artificial (man-made) noise

The industrial noise component mainly comes from surface (e.g., electric power lines) and underground constructions (e.g., water pipe communications, cables), garbage dumps, transportation, and communications lines, etc. The instrumental component is associated with the technical properties of gravimeters (e.g., shift zero) and partially – magnetometers. Human error can accompany geophysical observations at any time. Finally, previous surveys' undocumented (poorly documented) results can distort preliminary Physical-Geological Model (PGM) development.

Natural Disturbances

Nonstationary noise includes, for instance, the known tidal effects in gravity investigations and ionosphere disturbances (temporal variations) – in magnetic studies. Meteorological conditions (rain, lightning, snow, hurricanes, etc.) can also affect gravimeter and magnetometer readings. Corrections for the atmosphere deserve special attention in microgravity investigations since the air layer attraction is different at various levels over and below the mean sea level (MSL). Soil-vegetation factors associated with certain soil types (e.g., swampy soil or loose ground in deserts) and dense vegetation, which sometimes hampers movement along the profile, must also be considered.

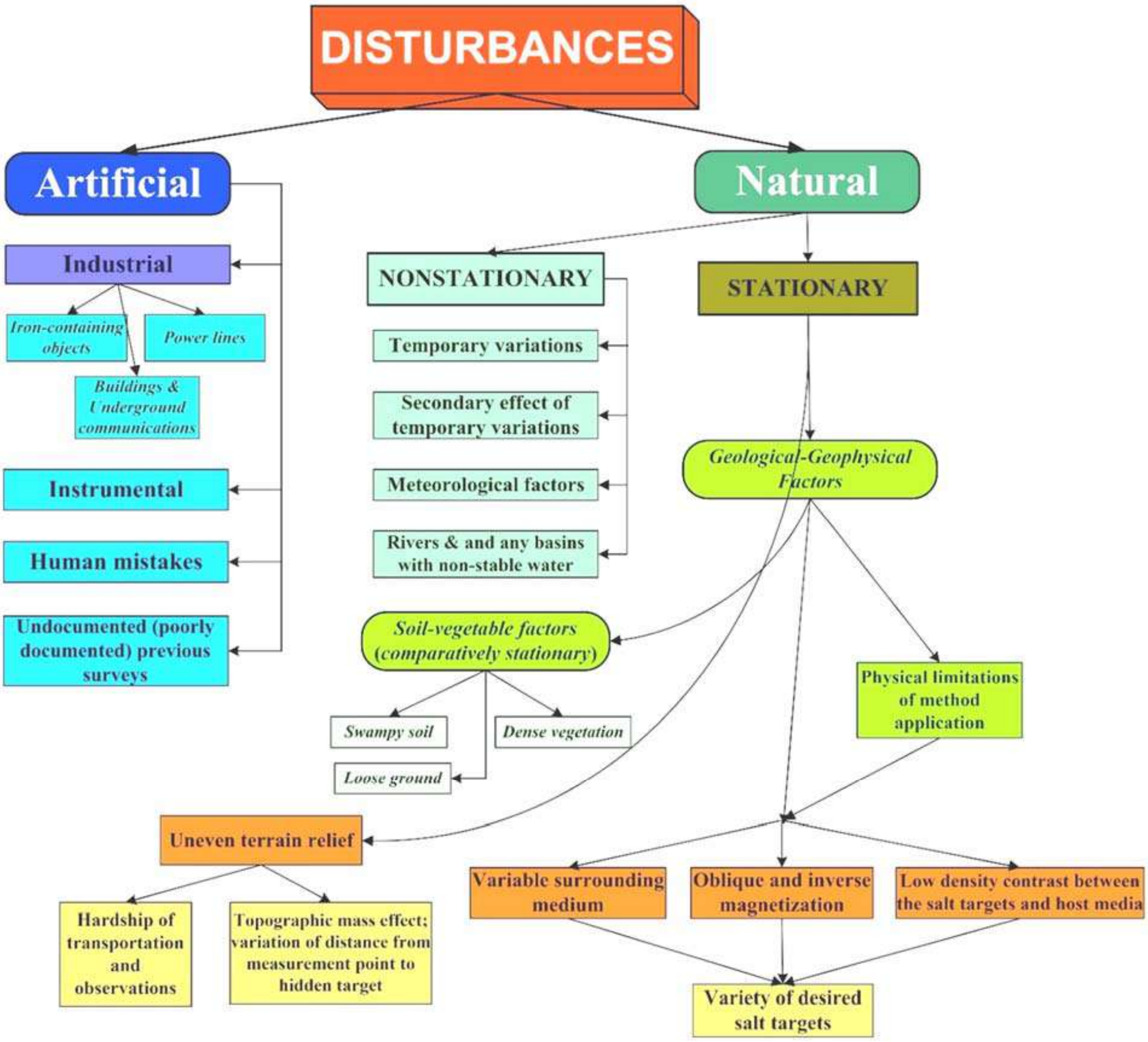

Fig. 1. Different kinds of noise appear in the gravity-magnetic identification of salt bodies

Geological-Geophysical and Environmental Factors

Geological-geophysical and environmental factors constitute the most essential physical-geological disturbances. Applying any geophysical method depends primarily on the existence of physical properties contrast between the objects under study and the surrounding medium. The physical limitation of the method application assesses the measurable density or magnetization contrast properties between the anomalous targets and the host media. In magnetic field analysis, an important role also plays magnetic vector (surrounding medium and anomalous target) orientation.

Spatial Coordinates and Normal Gravity Field Determination

Spatial coordinates and normal gravity field determination are also crucial to precise gravity studies, and any inaccuracies here may lead to significant errors in subsequent analyses. Similar parameters (coordinates and IGRF – International Geomagnetic Reference Field) are essential for introducing necessary corrections to the observed magnetic field (e.g., Sharma, 1997).

Uneven Terrain Relief

Uneven terrain relief can hamper the movement of equipment and restrict gravity and magnetic data acquisition. Physically, the gravity and magnetic fields are affected by the form and density of the topographic features composing the surface relief and variations in the distance from the point of measurement to the hidden target (Eppelbaum, 2019). In gravity prospecting, calculations for the surrounding terrain relief (sometimes for radii up to 200 km) are also very important (Telford et al., 1990; Eppelbaum, Khesin, 2012).

Earthquake Damage

Earthquake damage zones are widely spread over the South Caucasus (Alizadeh et al., 2017) and the Eastern Mediterranean (Eppelbaum, Katz, 2012). These zones may significantly complicate microgravity and magnetic data analysis.

The Variety of Anomalous Sources

The variety of anomalous geological sources at a depth comprises the variable surrounding the medium and the variety of anomalous targets. These factors are crucial and greatly complicate the interpretation of gravity and magnetic data.

Variable Subsurface

In gravity research, variable subsurface can make it difficult to determine the correct densities of bodies occurring close to the Earth's surface, and sometimes depths of hundreds of meters (e.g., Gadirov, Eppelbaum, 2015; Eppelbaum, 2019). In magnetic studies, a special procedure was developed to determine the average magnetization of the medium over day surface relief of any complexity (Eppelbaum, 2010).

Rivers and water basins

Rivers and water basins with non-stable waters can cause certain types of interference with gravity and magnetic measurements ('white' or 'wideband' kinds of noise (e.g., Bashirov et al., 1992).

Inclined and reverse magnetization

In the gravity field, the gravity vector is always oriented vertically (we do not consider here some gravity effects appearing on the complex terrain relief). However, this effect is broadly distributed in magnetized rocks and is crucial. Different effective methodologies were developed to detect and reduce these effects (Eppelbaum, 2019).

Local and Regional Trends

Local and regional trends (linear, parabolic, or other types) often mask the gravity and magnetic effects of the desired target considerably (e.g., Telford et al., 1990; Khesin et al., 1996; Sharma, 1997; Eppelbaum, 2019). Sometimes, regional gravity and magnetic trend effects may exceed local desired anomalies by some tenfold. Several methodologies for regional trend removal are applied by Al-Zoubi et al. (2013) and Eppelbaum (2019).

Interpretation of magnetic and gravity anomalies for salt target delineation and quantitative estimation

Analysis of gravity and magnetic anomalies over salt bodies should include qualitative and quantitative interpretation methods for reliable target classification and quantification. Let us begin with the gravity anomaly examination.

Gravity field interpretation

The model example (Fig. 2) illustrates the known and practical calculation of the second horizontal derivative of gravity potential over a subhorizontal body with contrast density properties.

A simple physical-geological model (PGM) presented in Fig. 2 indicates that from analysis of gravity field behavior (Fig. 2A), it is challenging to recognize where the left end of the salt layer occurs (under conditions of gravity anomaly superposition revealing this point will be some more complicated). Calculating the second horizontal derivative of gravity potential W_{xz} (Fig. 2B) allows determining exactly this point as the projection of $W_{xz(\max)}$ value (Fig. 2C). Besides this, the W_{xz} anomaly could be quantitatively interpreted using methodologies developed for complex environments in magnetic prospecting (Eppelbaum, Khesin, 2012).

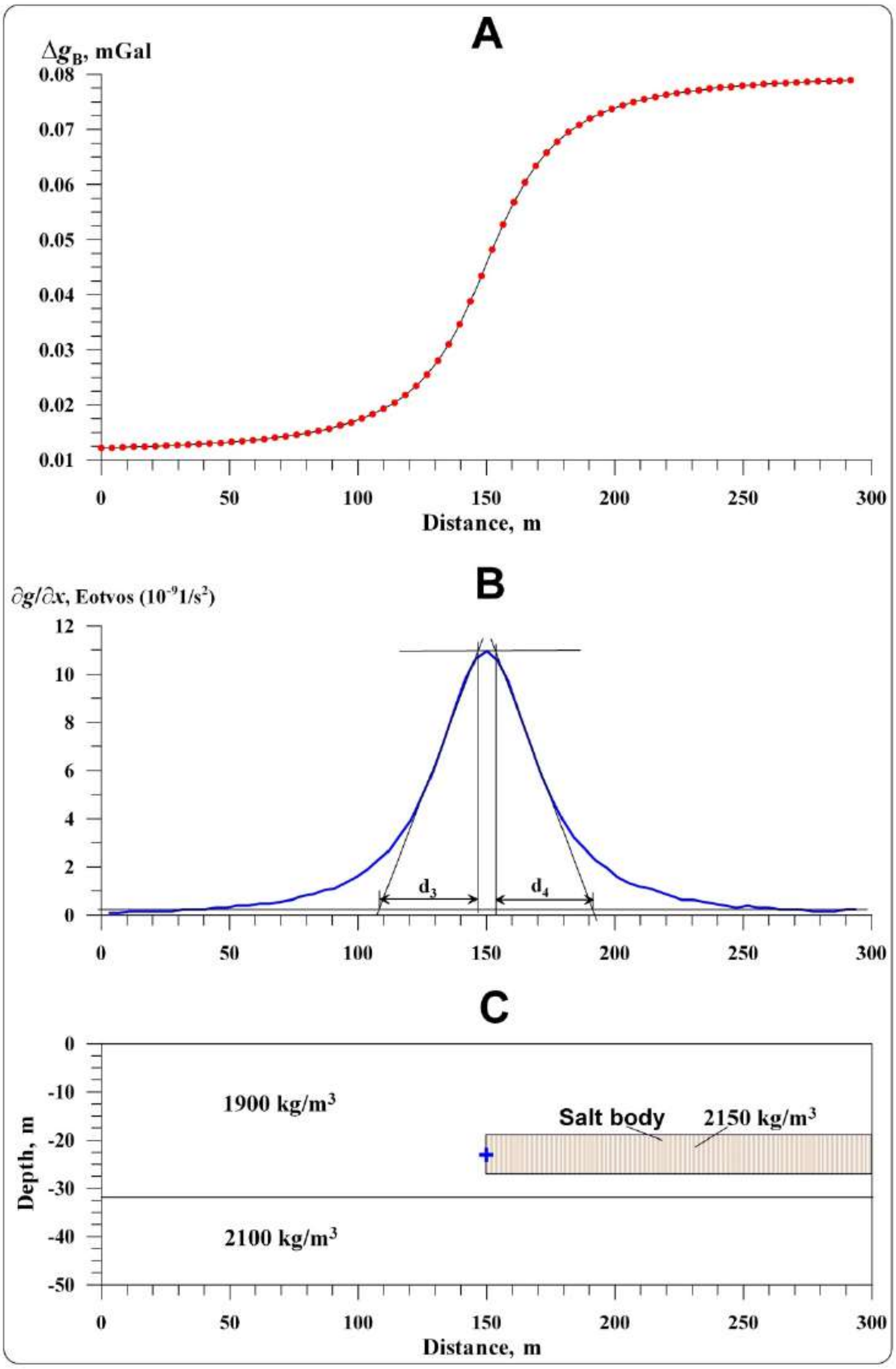

Fig. 2. Computation of the second horizontal derivative of gravity potential ($\mathbf{W}_{xz(\max)}$). **(A)** Computed gravity curve, **(B)** Calculated horizontal derivative of a gravity field, **(C)** Physical-geological model (right end of the salt body was computed as occurring at 700 m). Symbol "+" indicates the determined position of half of the vertical thickness amplitude of the salt body

Determination of the right end of the salt body occurrence is no less important problem. Fig. 3 shows a more complex example of 3D gravity field computations, where the right end of the salt body was computed in five variants: at distances of 300, 350, 400, and 700 m (as in Fig. 2) and in infinity. Thus, the position of the salt body's right end can be estimated by the gravity field behavior over this part of the studied target. The difference between the curves' behavior in the right part of the section is noticeable. At the same, it is fascinating that a significant difference between Δg_B (infinity) and Δg_B (700 m) over the left end of the anomalous body was found (Fig. 3B). Some minor disagreements were discovered, and anomalies between Δg_B (700 m) and Δg_B (300, 350, and 400 m) were found for the differences.

Gravity data examinations were successfully applied to delineate salt layers in several areas in complex conditions of the Dead Sea's eastern coast (Israel) (Eppelbaum et al., 2008; Ezersky et al., 2010, 2013, 2023). Several advanced methodologies for gravity field transformations in complex physical-geological environments were tested on the western Dead Sea coast (Jordan) (Al-Zoubi et al., 2013).

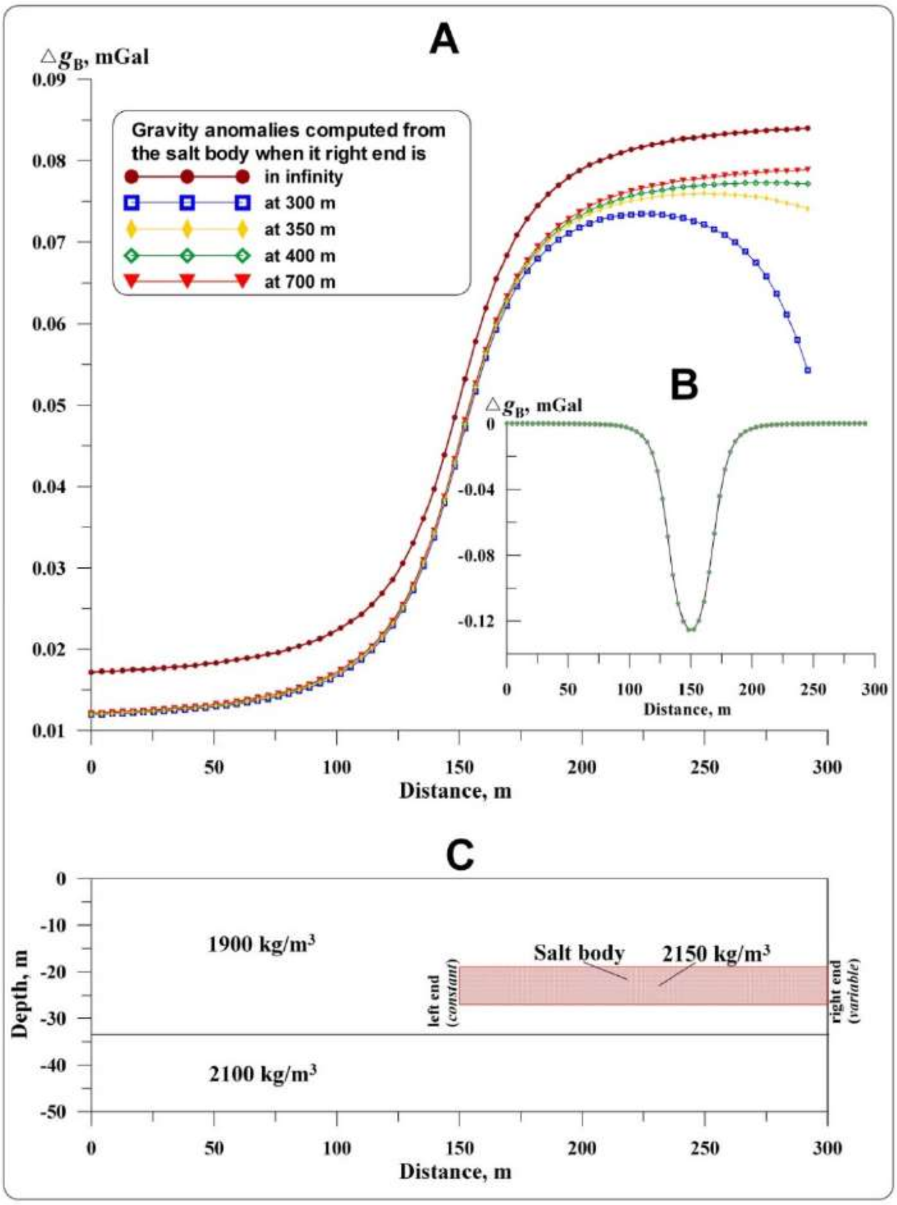

Fig. 3. Computing gravity effects from the model of the salt body by different positions of the right end of the body. **(A)** Computed gravity curves for different positions of the salt body right end, **(B)** Computed difference between Δg_B (infinity) and Δg_B (700 m), **(C)** Physical-geological model

Of course, 3D modeling of real PGM is a more powerful tool for gravity field examination. The results of 3D gravity field modeling along a profile crossing the Ein Gedi area (western Dead Sea coast, Israel) are shown in Fig. 4.

For advanced 3D gravity modeling, the *GSFC* software (3D horizontal polygonal prisms approximate geological bodies) (Khesin et al., 1996; Eppelbaum, 2011b, 2019) was applied. This program has been intended for computing the field of Δg (Bouguer, free-air or observed value anomalies), magnetic components ΔZ, ΔX, ΔY, and total magnetic field ΔT, and second derivatives of the gravitational potential under conditions of rugged relief and inclined magnetization. Each geological body can be approximated up to 50 characteristic points; the number of bodies practically is not limited; the software enables calculating the influence of geological bodies outside the geological section.

It should be noted that the initial PGM was composed of an analysis of samples from drilling boreholes, results of geological mapping, and other geophysical method examination (seismic methods, continuous vertical electric sounding (CVES), and electric resistivity tomography (ERT) analysis (Ezersky et al., 2013). A salt layer with a density of 2200 kg/m^3 (yellow colored in Fig. 4) is an essential feature of this PGM.

Magnetic field interpretation

An effective and reliable interpreting system has been developed for magnetic anomaly quantitative analysis in complex environments (inclined magnetization, rugged terrain relief, and unknown level of the normal field) (Khesin et al., 1996; Eppelbaum et al., 2001; Eppelbaum, 2011a, 2011b; Eppelbaum, Mishne, 2011; Eppelbaum, 2019). Some developed methodologies can be employed (with the necessary modifications) to interpret gravity anomalies (Eppelbaum, 2011b).

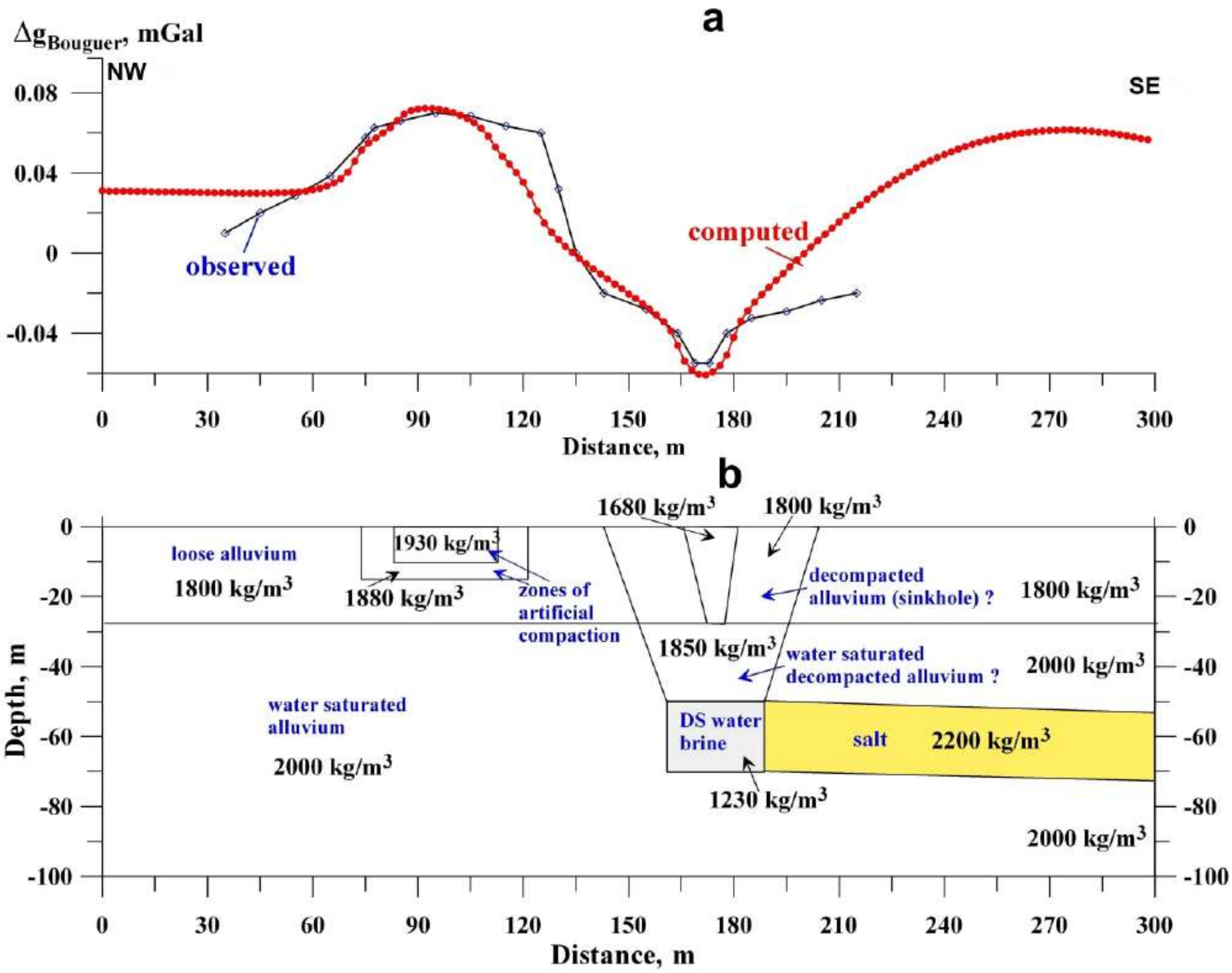

Fig. 4. 3D gravity modeling over a complex geological section in the Ein Gedi area (eastern Dead Sea coast, Israel), **a**: observed and computed gravity fields, **b**: physical-geological model (after Ezersky et al., 2013, with modifications)

3D magnetic field computations indicate that salt bodies (paramagnetic matter) occurring at different depths create distinguishable anomalies (Fig. 5). Magnetic anomaly from body 1 has a more detectable magnetic anomaly (~ 9 nT), but an anomaly from body 2 (~ 4.5 nT) is quite detectable (when we have no high noise level). These anomalies could be interpreted by the methodology developed to analyze anomalies produced by thick bed bodies (Eppelbaum, 2013, 2015a, 2015b, 2019). However, it is the subject of a separate investigation.

Let us consider the magnetic effect from the "classic" thin horizontal plate characterized by large horizontal thickness 2*b*, small vertical thickness ($2b >> h_1$ and h_2; h_1 and h_2 are the depths to upper and lower surfaces of the horizontal plate, respectively) and near-surface occurrence (Fig. 6).

Of course, this concrete model cannot be interpreted as a "quasi-thick" model. We observe two independent magnetic anomalies if parameter 2*b* is sufficiently large. These anomalies can be interpreted using methodologies developed for the model of thin beds for complex physical-geological conditions (Eppelbaum et al., 2001). In this case, we assume that the magnetization of the *L.H.* bed is positive and the *R.H.* bed is negative (in this case, a determination of magnetization is not possible). As shown in Fig 6, the results of the interpretation indicate the position of the center of the upper edges of two "fictitious" thin beds on the left (positive anomaly) and right (negative anomaly) of the considered thin horizontal plate model.

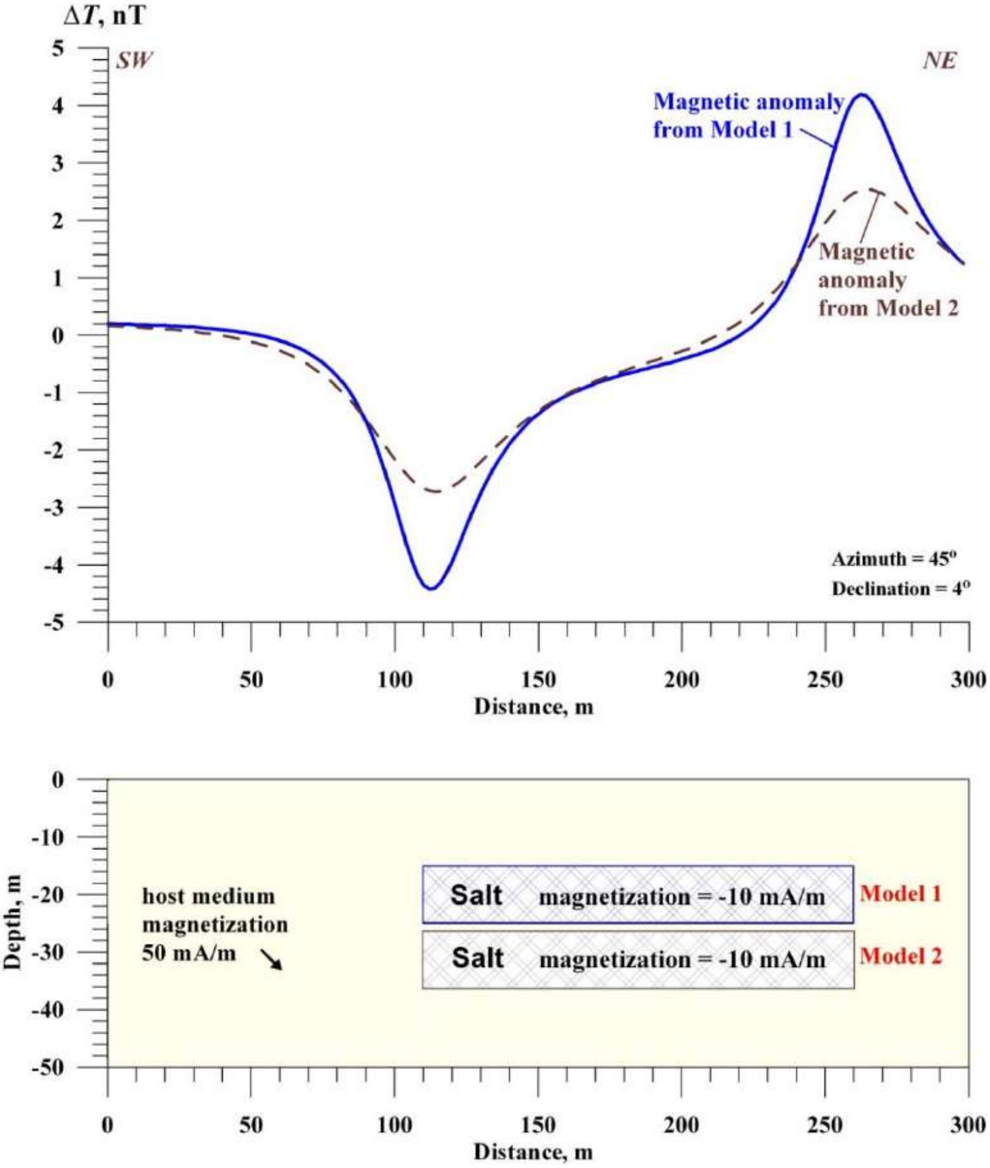

Fig. 5. Magnetic field modeling over two salt bodies occurring at different depths

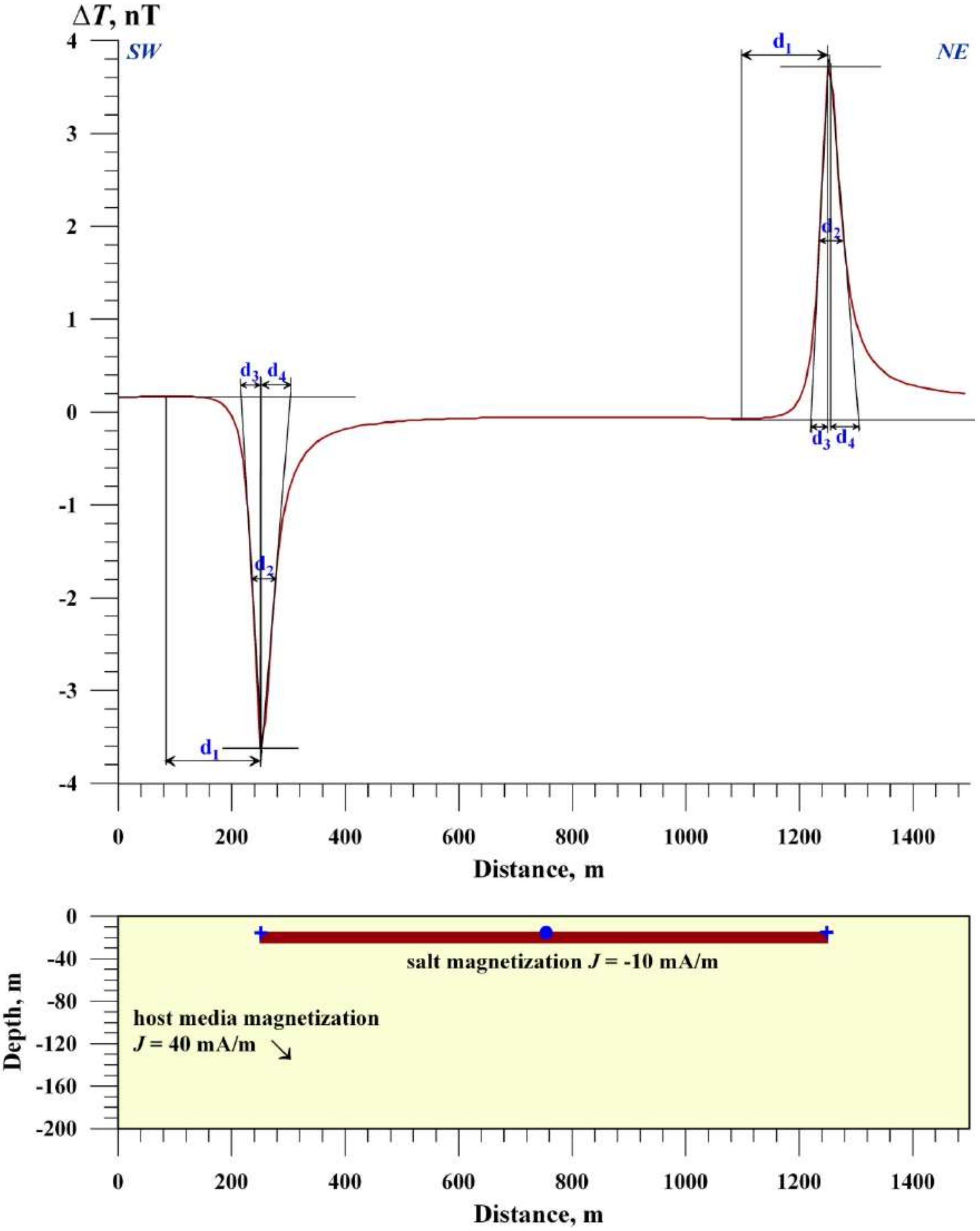

Fig. 6. Quantitative analysis of magnetic anomalies produced by the model of the expanded salt bed. Here, blue crosses show determined positions of the left and right ends of the body, and the blue-filled circle – the position of the body's center

Fig. 7 shows a quantitative analysis of magnetic anomaly produced by a salt layer approximated by a thick bed model. Since salt is a paramagnetic matter with a small magnetization (-10 mA/m) usually occurring in host media with a very low magnetization (here, a magnetization of 30 mA/m was assumed), the amplitude of the modeled anomaly is only about three nT. The characteristic peculiarity of this model is the presence of rugged terrain relief disturbing the magnetic anomaly. Results of the quantitative analysis (the interpretation methodology for such bodies were presented in detail in Eppelbaum (2015a, 2015b) do not ideally coincide with this PGM but demonstrate sufficient accuracy (Fig. 7). The calculated *Je* value was about -7 mA/m.

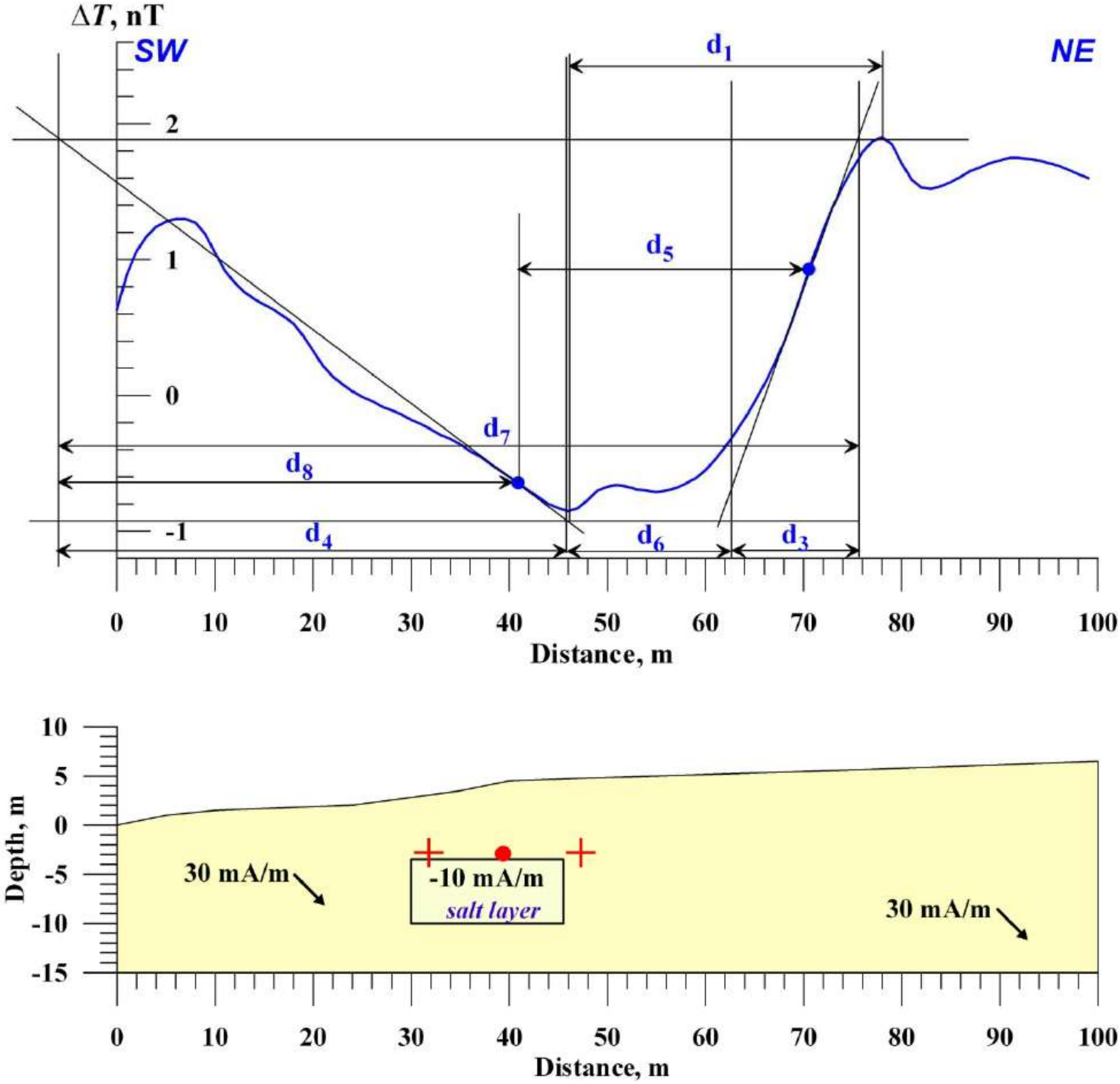

Fig. 7. Quantitative analysis of magnetic anomaly over the model of salt thick bed computed for the conditions of rugged terrain relief. The red crosses show the determined positions of the left and right ends of the body, and the red-filled circle – the position of the body's center

An exciting example of the quantitative analysis of the airborne observed magnetic anomaly is presented in Fig. 8. The low-level (about 100 m over the Earth's surface) airborne survey detected a negative magnetic anomaly from the salt dome in the Gulf of Mexico (USA). Despite the significant depth of the salt dome's upper edge's occurrence (4,000 feet ≅ 1,220 meters), the registered anomaly consisted of -9 nT (because of the large salt dome dimensions). Quantitative interpretation of this magnetic anomaly performed by the developed methods for the thin bed interpreting model (e.g., Eppelbaum et al., 2001) showed good agreement with the available geological data.

Integrated analysis of gravity-magnetic fields for salt target delineation

As shown in Eppelbaum (2014a, 2014b), for mapping (ranging) any area, theoretically, two equivalent effective methods applications are sufficient for mapping (ranging) any area. These methods may be, for instance, gravity and magnetics, or gravity and seismics. Due to the complexity of geological sections, some redundancy of geophysical integration is sometimes necessary.

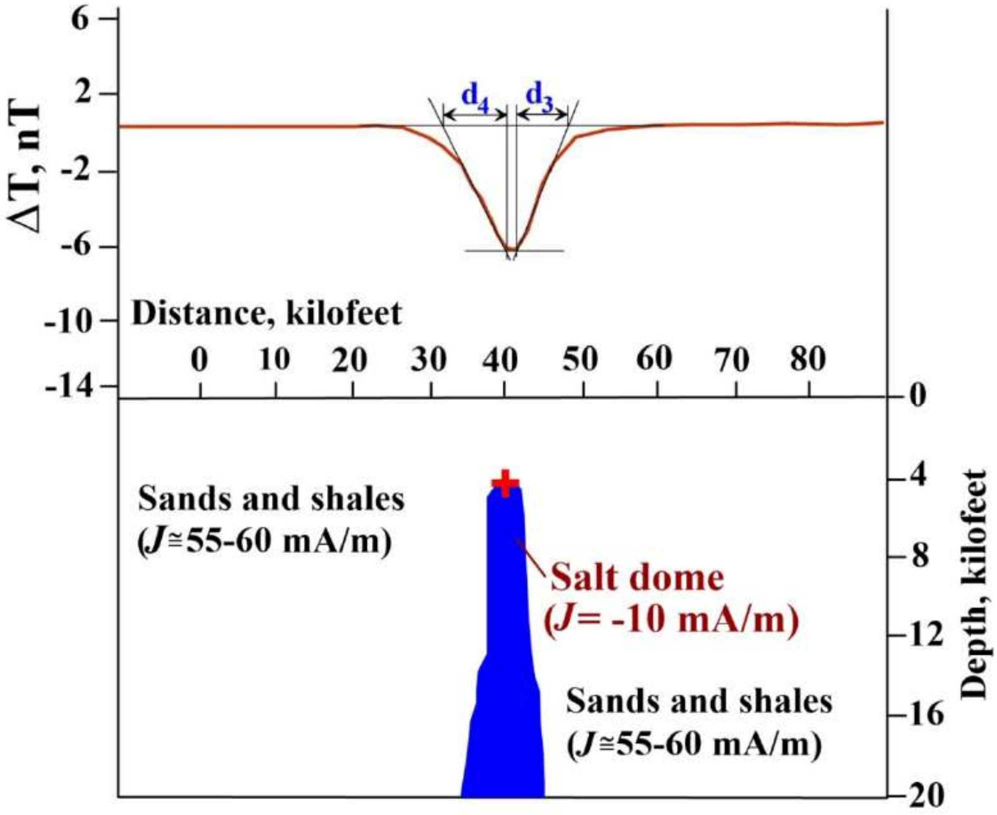

Fig. 8. Quantitative analysis of the airborne observed magnetic data over salt dome (Gulf of Mexico, USA) by the developed methodology (the magnetic survey was flown at a level of 100 meters) (initial data are from Rowe, Prieto, 2002). The red crosses show the determined positions of the center of the upper edge of the salt dome

It is well-known that an integrated examination (sensing) increases the amount and reliability of geophysical-geological information sharply (Eppelbaum, 2020). Theoretically suppose that a set of geophysical (geological, geochemical, geodynamical) methods is focused on investigating independent indicators of equal value. In that case, the anomaly detection reliability γ can be described by an equation:

$$\gamma = F\left(\frac{\sqrt{\sum_i \upsilon_i}}{2}\right),$$

where υ is the ratio of the anomaly squared to the noise dispersion for each i-th method, and F is the probability integral.

Let us assume that three points indicate some natural anomaly and that the mean square of the anomaly for each field is equal to the noise dispersion. For a single investigation method, the reliability of detecting an anomaly of a known form and intensity can be calculated by Kotelnikov's criterion (e.g., Borda, 2011). Hence, the reliability for individual methods is 0.61 and 0.77, and 0.87 for a set of two or three methods, respectively. It means that the q value (risk of an erroneous solution, $q = 1 - \gamma$) decreases when integrating two or three methods by factors of 1.7 and 3.0, respectively. These simple calculations indicate the preferences of different methods of integration. In our subsurface sensing, the number of applied methods with positive estimations in many cases vastly outnumbers the three.

A successive application of integrated information and wavelet methodologies in subsurface geophysics was demonstrated by Eppelbaum et al. (2011). The employment of diffusion maps methodology with gravity and magnetic fields application on an example of karst target delineation was shown in detail in Eppelbaum et al. (2014). The same methodology (with corresponding modifications) could be applied to delineating the subsurface salt bodies. The advanced methodologies obtained in wavelet theory and data mining based on the matching pursuit combined with wavelet packet dictionaries permitted the effective integration of geophysical fields for subsurface examination even in the presence of strongly noised data (Alperovich et al., 2013; Averbuch et al., 2014).

Remotely operated vehicle geophysical surveys

A broad application of remotely operated vehicle (ROV) geophysical surveys at different altitudes (Eppelbaum, 2008; Eppelbaum, Mishne, 2011; Brooke and Clutterbuck, 2020; Kolster et al., 2022; Ivashov et al., 2023) will significantly increase the effectiveness and reliability of environmental (subsurface) geophysics, especially in areas with various surface measurement limitations. The proposed ROV methodology with different flight trajectories will help to estimate the magnetization of the upper part of the geological section for any surface relief (Eppelbaum, 2010).

Another important factor stimulating the ROV application is the comparative cheapness of such studies. The ROV employment could be applied for salt target identification and delineating an associated dangerous phenomenon – karst (sinkhole) appearing.

Conclusions

As a rule, salt bodies occurring in the upper part of the geological section have small positive density and negative magnetization characteristics compared with the host media that create the necessary precursors for applying detailed gravity-magnetic surveys. The methods developed for analyzing gravity and magnetic anomalies in complicated environments (inclined topography, an unknown level of the normal field, and oblique magnetization) could be successfully applied to delineate and quantitatively characterize salt bodies. Some of these methods may be effectively employed for gravity anomaly interpretation. Testing these procedures on the models and actual data confirms gravity-magnetic data analysis's effectiveness. Some advanced procedures for cooperative gravity and magnetic field analysis are briefly discussed. Advanced 3D gravity-magnetic field modeling is applied at the last stage of physical-geological analysis and enables the creation of the medium's final (enhanced) Physical-Geological Models. It is proposed that the ROV survey will be employed as the main instrument of environmental mapping, including the localization of salt bodies.

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КОМПЛЕКСНЫЙ АНАЛИЗ ГРАВИМАГНИТНЫХ ДАННЫХ ДЛЯ КОЛИЧЕСТВЕННОГО ОПРЕДЕЛЕНИЯ СОЛЯНЫХ ТЕЛ В СЛОЖНЫХ ФИЗИКО-ГЕОЛОГИЧЕСКИХ УСЛОВИЯХ

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Резюме. Хорошо известно, что соляные тела являются обычно неблагоприятными объектами для применения гравитационных и магнитных методов. Это обусловлено главным образом незначительными различиями в плотности (соляные объекты плотностью 2100-2200 кг/м^3 часто залегают в отложениях со схожей плотностью) и намагниченности (слои соли с намагниченностью около -10 мА/м, как правило, залегают в слабомагнитных средах), а также геолого-петрофизической изменчивостью изучаемого геологического разреза. Поэтому для обработки и интерпретации гравимагнитных данных необходимо использовать хорошо разработанные методологии из имеющегося богатого аналитического арсенала, начиная с удаления (уменьшения) различного рода помех и визуальной локализации объектов исследований и заканчивая разработкой трехмерных физико-геологических моделей (ФГМ). Хотя количественный анализ гравимагнитных аномалий от соляных объектов, залегающих обычно в виде тонких горизонтальных пластов, представляет собой сложную задачу, разработанная детальная методика интерпретации потенциальных аномалий (Эппельбаум, 2019) позволяет успешно решать эту проблему.

Комплексирование гравитационных и магнитных данных между собой и с другими геофизическими методами повышает надежность и точность геолого-геофизической интерпретации. Для комплексного трехмерного гравимагнитного моделирования применяется разработанное программное обеспечение GSFC, в котором геологические тела аппроксимируются трехмерными горизонтальными полигональными призмами. Применение ряда качественных и количественных методов интерпретации представлено в статье на модельных и полевых примерах. Помимо наземной съемки предлагается применять магнитную съемку с использованием беспилотных летательных аппаратов на малых высотах, что позволит не только оперативно оконтурить расположение соляных объектов, но и отследить появление карстовых подземных полостей, часто связанных с соляными объектами.

Ключевые слова: *соляные тела, гравитация, магнетизм, количественный анализ, комплексная интерпретация*

MÜRƏKKƏB FİZİKİ-GEOLOJİ ŞƏRAİTDƏ MİQDARCA MÜƏYYƏNLƏŞDİRİLMİŞ DUZLU CİSİMLƏRİN QRAVİMAQNİT GÖSTƏRİCİLƏRİNİN KOMPLEKS ANALİZİ

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Xülasə. Məlumdur ki, duzlu cisimlər qravitasiya və maqnit metodlarının tətbiqi üçün adətən əlverişsiz obyektlər hesab olunur. Bu, əsasən, öyrənilən geoloji kəsilişin sıxlıq (2100-2200 kq/m^3 sıxlığı olan duzlu obyektlər tez-tez oxşar sıxlığa malik çöküntülərdə yerləşirlər) və maqnitləşməsində (maqnitləşmiş duz layları (təxminən -10mA/m), adətən, zəif maqnitləşmiş mühitdə yerləşir) olan cüzi fərqlə həmçinin geoloji-petrofiziki dəyişiklər ilə əlaqədardır.

Buna görə də qravimaqnit göstəricilərin işlənməsi və interpretasiyası üçün müxtəlif növ maneələr və obyektlərin vizual lokallaşdırmasının aradan qaldırılması (azaldırılması) ilə başlayan və ətraf mühitin üçölçülü fiziki-geoloji modellərinin hazırlanması ilə tamamlanan mövcud zəngin analitik arsenalın yaxşı işlənmiş metodologiyasından istifadə etmək lazımdır.

Adətən nazik horizontal təbəqələr şəklində yerləşən duz obyektlərindən qravimaqnit anomaliyaların kəmiyyətcə xeyli çox olan analizi çətin məsələ olsa da, müşahidə olunan potensial anomaliyaların (Eppelbaum, 2009) interpretasiyasının təkmilləşdirilmiş ətraflı metodologiyası bu problemin uğurlu həllinə imkan verir. Qravitasiya və maqnit göstəricilərin bir-biri ilə və digər geofiziki metodlarla kompleksləşməsi geoloji-geofiziki interpretasiyanın etibarliliğını və dəqiqliyini artırır. Üçölçülü qravimaqnit kompleks modelləşdirilmə üçün horizontal poliqonal prizma ilə əvəz olunan geoloji cisimlərə təkmilləşdirilmiş GSFC proqramı tətbiq olunur. İnterpretasiyanın bir sıra keyfiyyət və kəmiyyət metodlarının tətbiq edilməsi məqalədə model və sahə nümunələri ilə göstərilib. Yerüstü çəkilişlərdən başqa kiçik hündürlüklərdə pilotsuz maqnit çəkilişlər aparmaq da təklif olunur bu da duz obyektlərin yerləşməsini nəinki operativ konturlaşdırmağa həmçinin duz obyektləriylə tez-tez bağlı olan karst yeraltı boşluqların yaranmasını izləməyə imkan verər.

Açar sözlər: *duz cisimləri, qravitasiya, maqnetizm, kəmiyyət analizi, kompleks ekspertiza*