ГЕОЛОГІЯ

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IMITATION MODELLING TECHNOLOGY FOR GRAVITY INVERSION CASES

С. Г. Анікеєв, С. М. Багрій, Б. Б. Габльовський. ТЕХНОЛОГІЯ ІМІТАЦІЙНОГО МОДЕЛЮВАННЯ ОБЕРНЕНИХ ЗАДАЧ ГРАВІРОЗВІДКИ. *Гравірозвідку спрямовано на пошуки і розвідку корисних копалин на тлі досліджень будови геологічного розрізу. Завданням кількісної інтерпретації гравіметричних матеріалів, у якій використовуються методи рішення прямих та обернених задач, є моделювання гравітаційного поля (пряма задача) та моделювання густинної будови геологічних середовищ (обернена задача). Важливими ознаками методів моделювання густинної будови складних геологічних середовищ є геологічна змістовність, узгодженість з апріорними матеріалами та підпорядкованість моделювання геологічним гіпотезам. Для аналізу методів моделювання за цими ознаками пропонується імітаційне моделювання. У статті викладено методику імітаційного гравіметричного моделювання, яку засновано на побудові неформальної послідовності еквівалентних рішень. Призначенням імітаційного моделювання є дослідження властивостей обернених задач гравірозвідки у загальній постановці, а також оцінювання ступені детальності і достовірності методики та технологій гравітаційного моделювання, що претендують на ефективне вирішення геологічних завдань. На прикладах густинного і структурного імітаційного випробування методики неформальної послідовності еквівалентних рішень та її комп'ютерних технологій показано, що комплексна інтерпретація даних буріння, сейсморозвідки та гравірозвідки надає можливість детального відтворення будови геологічних середовищ у геогустинних моделях. Досліджено шляхи підвищення достовірності гравітаційного моделювання. Зокрема визначено, що кращим наближенням регіонального фону є нахилена площина, яка апроксимує спостережене поле сили тяжіння на ділянках площі досліджень, які більш детально вивчено. Підвищення достовірності результатів моделювання можна досягти за рахунок перебудови ближніх бокових зон у моделях структурного типу в інтерактивному процесі рішення структурних обернених задач гравірозвідки. Змістовність моделювання залежить від досвіду інтерпретатора, оскільки комп'ютерні технології рішення прямих та обернених задач гравірозвідки є лише інструментом інтерпретації.*

Ключові слова: *геологічний розріз, гравірозвідка, методика інтерпретації, обернена задача гравірозвідки, гравітаційне поле, моделювання, апріорна модель, еквівалентна модель, сейсмогеологічна модель, геогустинна модель.*

С. Г. Аникеев, С. М. Багрий, Б. Б. Габлевский. ТЕХНОЛОГИЯ ИМИТАЦИОННОГО МОДЕЛИРОВАНИЯ ОБРАТНЫХ ЗАДАЧ ГРАВИРАЗВЕДКИ. *Гравиразведка предназначена для поисков и разведки полезных ископаемых на основе исследований строения геологического разреза. Заданием количественной интерпретации гравиметрических материалов, при которой используются методы решения прямых и обратных задач гравиразведки, является моделирование гравитационного поля (прямая задача) и моделирование плотностного строения геологических сред (обратная задача). Важными признаками методов моделирования плотностного строения сложных геологических сред являются геологическая содержательность, согласованность с априорными данными и подчиненность моделирования геологическим гипотезам. Для анализа методов моделирования по этим признакам предлагается имитационное моделирование. В статье изложена методика имитационного гравиметрического моделирования, которая основана на построении неформальной последовательности эквивалентных решений. Предназначением имитационного моделирования является исследование свойств обратных задач гравиразведки в общей постановке, а также оценка степени детальности и достоверности методики и технологий гравитационного моделирования, которые претендуют на эффективное решение геологических задач. На примерах плотностного и структурного имитационного опробования методики неформальной последовательности эквивалентных решений и ее компьютерных технологий показано, что комплексная интерпретация данных бурения, сейсморазведки и гравиразведки обеспечивает возможность построения детальных плотностных моделей геологических сред. Исследованы пути повышения достоверности гравитационного моделирования. В частности, выявлено, что лучшим приближением регионального фона является наклонная плоскость, которая аппроксимирует наблюденное поле силы тяжести на участках площади исследований, которые более детально изучены. Повышение достоверности результатов моделирования можно достичь за счет перестроения ближних боковых зон в моделях структурного типа в интерактивном процессе решения структурных обратных задач гравиразведки. Содержательность моделирования зависит от опыта интерпретатора,*

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поскольку компьютерные технологии решения прямых и обратных задач гравиразведки являются лишь инструментом интерпретации.

Ключевые слова: *геологический разрез, гравиразведка, методика интерпретации, обратная задача гравиразведки, гравитационное поле, моделирование, априорная модель, эквивалентная модель, сейсмологическая модель, плотностная модель.*

Problem statement. The geophysical interpretation methodology effectiveness should be evaluated on test cases that are as close as possible to the real conditions of specific geological tasks solutions. Testing of the computer interpretation technologies on physical and geological models was called an imitation modelling by V. M. Strakhov. These models are close to real rocks properties distribution in the geological environment and physical fields. The meaningfulness and evaluation reliability degree of the geophysical method interpretation capabilities by imitation modeling depends on models proximity to the real geological situations and complexity of test tasks.

The maximum using of imitation modeling is the *methodological principle* of the theory and practice of geological interpretation of potential fields according to V.M. Strakhov. The imitation modeling must provide the correct work organization and the required volume of observations at the design stage; the evaluation of the interpretation result reliability and accuracy at the final stage.

Recent researches and publications analysis. Nowadays, the imitation modeling is used in insufficient scope in gravity prospecting, especially in substantiating of efficiency of gravity field interpretation technologies and modeling techniques, which are usually represented by straight sequence of steps or procedures (for example [1]). In the vast majority of cases, the technologies feasibility is confirmed by tests on simplified models [2 - 5 and others], or by demonstration of practical modelling results. Tests can be complicated by inputting of errors into the output data (potential fields) to confirm the solution stability of gravity inversion. But stability is an obvious consequence of the correct use of regularization. Experience shows that regularization has another, more significant purpose – achievement of geological meaningfulness solutions. A positive description example of the modeling method (in the frame of selection methods) is the work of Ye. H. Bulakh. It depends on the completeness of the initial data and geological tasks character [6].

Density modeling is an important tool for research the deep structure of geological environments [7-15 and others]. Modeling technologies are based on methods of solving direct and inverse gravity problems and are aimed at constructing geodensity models by optimal coordination of drilling, seismic data and other geological and geophysical materials with the Bouguer anomalies.

Principle differences in test modelling from imitation modeling are:

1. Models inadequacy (simplicity) to the geological situation.

2. Absence of correction on effect of regional fields and lateral zones.

3. Limitation on the complexity of geological tasks.

An important difference of imitation modeling is the adaptation and testing of approaching methods to the best results that is methods of managing of solving inverse problems process.

The research tasks and formulation of the purpose. The purpose of this work is to test gravimetric modelling technology, which aims to create the most reliable models of subsurface and density structure of geological environments or their changes in time. Testing is based on imitation modelling. Thus the following tasks are solved:

1. Analysis of the imitation gravimetric modelling method.
2. Evaluation of the reliability degree of gravimetric prediction method of the underground sulfur smelting dynamics.
3. Substantiation of high-precision gravity monitoring (detection and monitoring) of dangerous post-technogenic karst formations.
4. Possibility of gravimetric control of gas-water contact level on the hydrocarbons field.
5. Modelling of salt dome type structural section and subsalt reef formation study.

Purpose and Method of Imitation Gravity Modelling.

1. General Study of the Gravity Inversion (GI) Properties (on the Class of Continuous Functions). Due to the computer technologies development of GI solutions, pertaining to modeling of difficult-built geological environments, testing their capabilities should be implemented on a broad class - a class of densities or density borders geometry as coordinate functions.

2. Testing of Gravimetric Materials Interpretation Methods and Technologies as Tools for Building of Density Models of Geological Environments. The following questions are relevant: the conformity degree of their approximation constructions to the universality requirements and sufficient detailed of real geological environments description; limitation on dimension and speed; geological content and the reliability degree of GI solutions. Computer technologies of geophysical materials complex (integrated) interpretation should be different by approx-

imation constructions universality and possibility to process detailed (large dimension) models of geological environments, especially small sizes, which is relevant for the study of dynamics of the near-surface post-technogenic phenomena.

3. Gaining of the experience in modeling and studying of a link between geological section parameters and local field anomalies, also between objects parameters variation and spatial-temporal anomalies.

4. Substantiation of the method of gravity data interpretation and evaluation of its reliability degree in the specific geological problems solving.

5. Substantiation of the field gravimetric observation method.

Imitation modelling gives us the possibility to analyze the dependences between GI properties and geological content of its solutions. So, the traditional definition of the regularization parameters of the inverse tasks instability was putted into question, as well as the small number of iterations to achieve the necessary solution, as the "a priori positive" characteristic of the technologies. An interesting example of the formal imitation modelling is studies results of the linear operator core content influence of O. I. Kobrunov criterion approach on GI solution.

The imitation modelling methodology of geological environments density structure or changes in its structure over time reflect the experience of long-term geological tasks solutions [16 - 20]. The modelling is as follows (fig. 1).

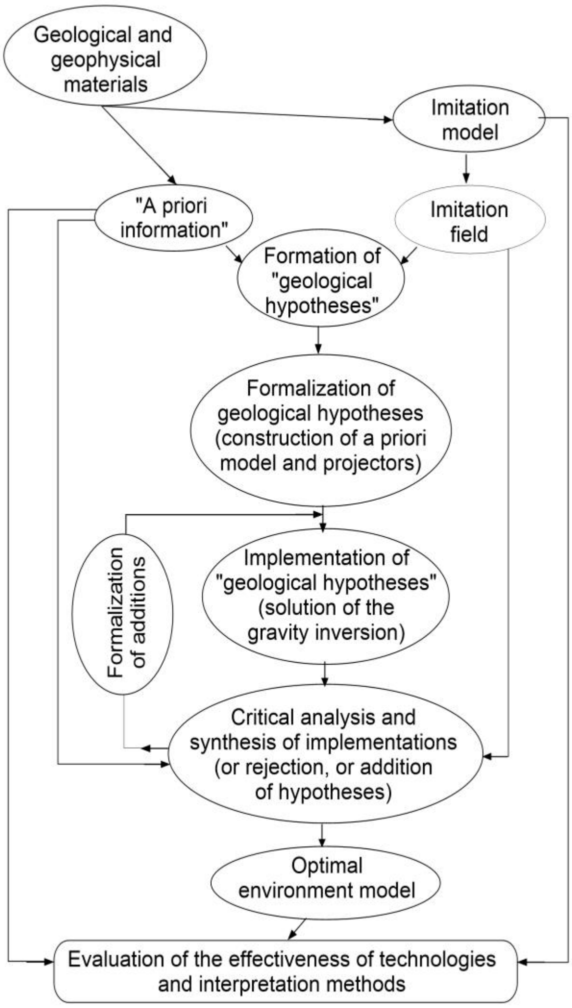


Fig. 1. Imitation modelling scheme

1. Creating the imitation («real») environment model (IEM).

2. Solving the gravity direct problem for the IEM and selecting the calculated theoretical field as «observed field» (imitation).

3. Forming «a priori» data, namely the definition of changes in the IEM which are conditional information about the IEM structure, and the formalization of these a priori data in the form of the primary a priori environment model (AEM).

4. The «geological task» formulation about the IEM structure reconstruction.

5. The «geological hypotheses» formation about the probable IEM structure.

6. The hypotheses formalization in the form of probable additions AEM.

7. The hypotheses realization by constructing equivalent environment models (EEM) using the technologies of gravity inversion (GI) solution being tested.

8. Comparative analysis of the AEM and an EEMs in order to choose the optimal environment model (OEM), or the new hypotheses formation.

9. Comparison of OEM and IEM; evaluation of probability and accuracy of IEM elements reconstruction into the OEM.

10. Conclusions about the interpretation possibilities of the modelling method.

Geological hypotheses are formed on the basis of geological problems analysis, a priori data and gravity anomalous field. Hypotheses are formalized in the form of AEM and projectors, which are constraints on the properties of the GI future solution and formed on the data on the AEM elements probability and accuracy.

The geological hypothesis realization is an interactive process of approximation to EMM when the initial (zero) approximation is the AEM. The imitation modelling technologies should be as close as possible to the conditions of a real interpretation process. They should be complicated by the influence of lateral zones, regional background, a detailed description of the geological situation. Also they should be fast to build a number of EEM technologies.

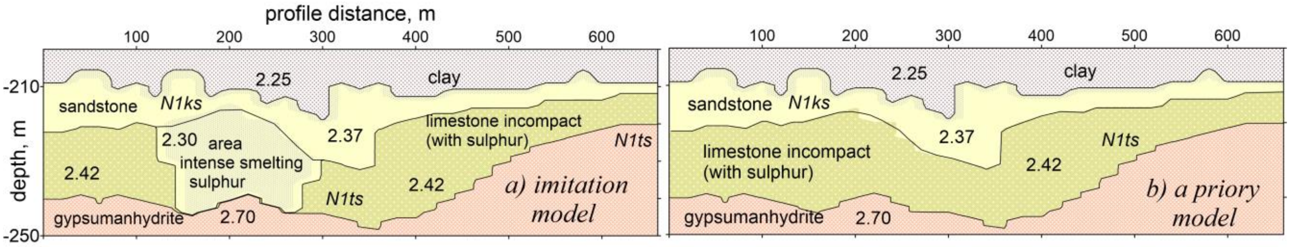
The authors perform the gravimetric data interpretation according to the informal sequence method of equivalent solutions, [20] using the computer technology "Complex.Gravity" of solving 2D / 3D direct and inverse problems. The imitation modelling was performed in order to evaluation the content and reliability of the modelling method, as well as the computer technologies testing.

Imitation modelling of underground sulfur smelting consequences on Nemyriv field example. In the gravity prospecting the prediction of dynamics is the task of spatial-temporal changes detecting in density structure of the local part of geological section.

During the native sulfur deposits exploitation by the underground sulfur smelting (USS) method the area is covered with a dense wells network (for example, 20 × 20 m), that is, the boundaries geometry in the geological section above sulfur is known with high accuracy. The efficiency of sulfur deposit re-exploitation can be controlled by geological and geophysical monitoring [17, 21 - 22].

The imitation model (IEM-1, fig. 2a) reproduces the real longitudinal section of Grushiv area on Nemyriv native sulfur deposit. The zone of intensive sulfur smelting is highlighted by the contour of a significant reduction in density. The layer that lies above and below the productive horizon is practically homogeneous.

A-priory model (AEM) is shown on the Fig.2b. Suppose that a high-precision gravity survey was performed after the USS, so, the «observed» field was taken as the theoretically calculated field of IEM. Data on the sulfur smelting character are «absent». That is why the productive horizon in a priori model, based on drilling data before sulfur smelting, is homogeneous.



x-axis 2D-model discretization - 10 m, z-axis - 3 m *2.70 - a priori density of rocks, 10^3 kg/m^3*

Fig. 2. Imitation and a priory model of a section native sulfur deposits

The imitation geological task is to identify and outline zones of intensive sulfur smelting. It is assumed that during sulfur smelting, there are no significant changes in the section, except within the productive horizon. Therefore, the search for GI solution is limited only by the productive layer contour.

Model-1 is performed on assumption that as a result of the USS, either density reduction or density increasing zones were appeared into the layer of the sulfured limestone. Limits on the probable variations in the limestone density are given in the maximum interval $2.20 \div 2.60 \times 10^3$ kg/m^3. The model, which is the result of GI solution and formally ε-equivalent model, is shown in Fig. 3a. The biggest density reduction was obtained in the profile interval of 100÷300 м. It was contoured by isodense $2.35 \cdot 10^3$ kg/m^3. It practically coincides with the imitation zone of intensive sulfur smelting. In addition to the USS consequences confirmation in the profile interval of 420÷500 m, the insignificant pseudo-anomaly of density increasing is noted (up to $+0.02 \cdot 10^3$ kg/m^3).

Modelling-2 was performed on the geological

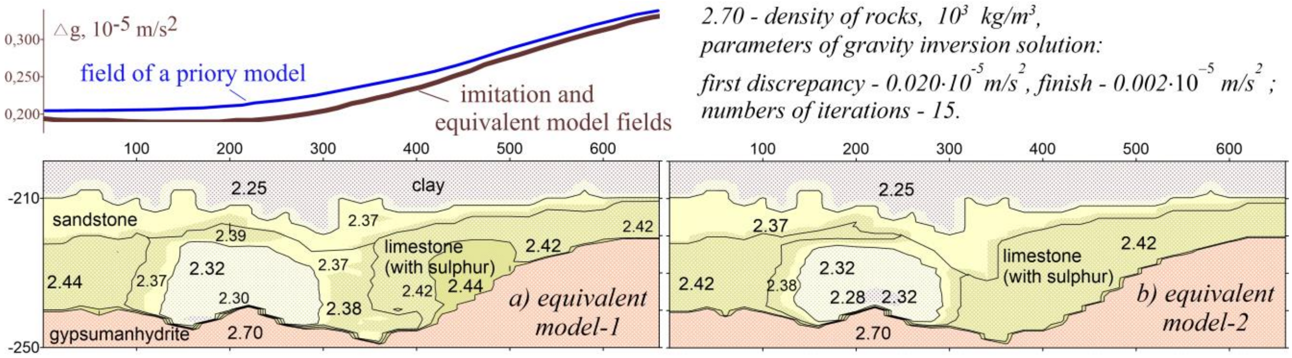


Fig. 3. Equivalent models of a section native sulfur deposits

hypothesis that only zones of density reduction can be the USS result within sulfured limestone layer. That is why limits on the probable densities were taken in the interval 2.20÷2.42×10^3 kg/m^3. As a result of GI solution, zone of density reduction is extracted in the ε-equivalent model (fig. 3b). This zone is close on shape and intensity to the imitation one.

Modelling-3. The study task of density structure changes in a section by the gravity *spatial-temporal anomalies* distribution deserves special attention. In this case, it may be possible to narrow the search area of the GI and, consequently, a significant increase in the gravitational modelling accuracy degree.

Modelling is performed under the conditions that the gravimetric survey was carried out before and after the USS. Imitation modelling of changes in the section structure is based on two imitation “real” models. The first one is the model of the section before the USS (fig. 2b), the second one – after the USS (fig. 2a). Spatial-temporal variations of gravity field, which are the difference between the field after the USS and field before the USS, were used as «observed» field. Spatial-temporal variations are mainly due to changes in the productive layer under the USS influence. Therefore, it is possible to ignore the influence of lateral zones, regional background and structure of the section above and under the productive layer. It is also possible to ignore the data inaccuracy on the density of the intermediate layer (Bouguer density), but take into account the changes in the heights of observation points.

A priori data on the state of the productive formation after the USS is formalized as a model of spatial-temporal changes in the densities distribution. The USS influence is expected only within the productive layer, that is why only non-zero value of excess density is given to this layer with small variation of 0.001·10^3 kg/m^3. Density is equal zero for other parts of the section and for lateral zones. Limits on all possible spatial-temporal variations of excess density in the productive layers are taken in all possible intervals - ±0.3×10^3 kg/m^3. The result of GI solution (EEM-3) is shown on fig. 4. All imitation EEM-1÷3 (fig. 3, 4) contain practically the same by sizes and intensity the local zones of density reduction corresponding to the imitation «real» zone of sulfur smelting. The disadvantage of the first and the third EEMs is the small size and intensity of pseudoanomaly.

Modelling-4 was performed according to the predictions that it is possible to appear of both zones of density reduction and rocks of density increasing in the contour of the productive layer during the underground sulfur smelting.

So, there is repositioning of more consolidated limestone of sulfur contents. Imitation of “real” model, where the USS effects are reflected in the form of density reduction and consolidation zones, is represented on Fig. 5a. The geological hypothesis is similar to the previous one, therefore, the a priori model and the limits on the densities variations are the same.

Equivalent model-4 (fig. 5b), like the previous one, is constructed according to a difference imitation fields. It contains density anomalies, which by contour, size and intensity are practically identical to the imitation "real" zones of density reduction and increasing; pseudoanomalies are absent.

Given imitation model confirms the possibility of reliable gravimetric mapping of intensive sulfur smelting zones.

Imitation modeling of karsted rock on the example of Kalush-Golin deposit of potassium salts. Modelling was performed on the profile through the Central kainite slope mine of “Kalush” pit, based on the assumptions that mine openings (cavities) are filled with the dangerous brines deconsolidation, or that in the layer between the cavities and the salt mirror there is a zone of deconsolidation. So, there is a zone of deconsolidation too. For detailed description of models, the step of discretization is selected in one meter (approximation of the section is made by small prisms 1 m×1 m).

Model anomalous gravitational fields are obtained in variants (fig. 6).

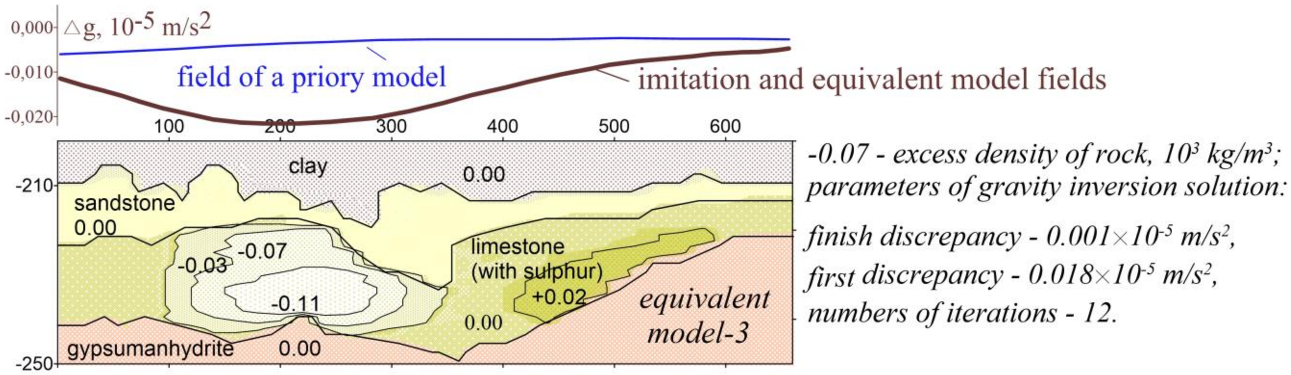


Fig. 4. An equivalent model of changes in the excess dense distribution in the native sulfur deposit section after underground sulfur smelting

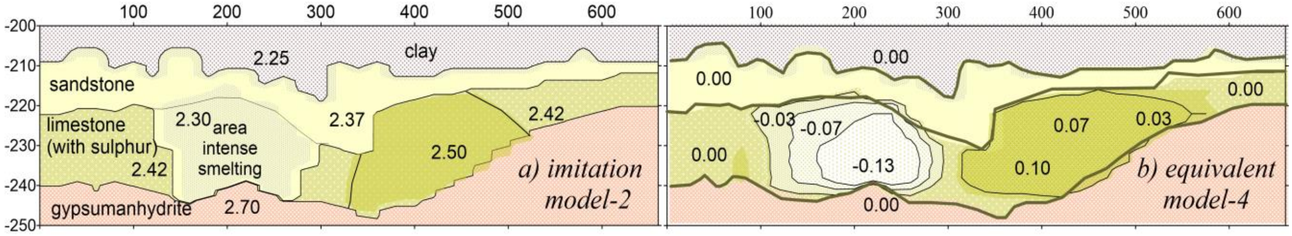


Fig. 5. Imitation and equivalent models of changes in the densities distribution in a native sulfur deposit after underground smelting of sulfur

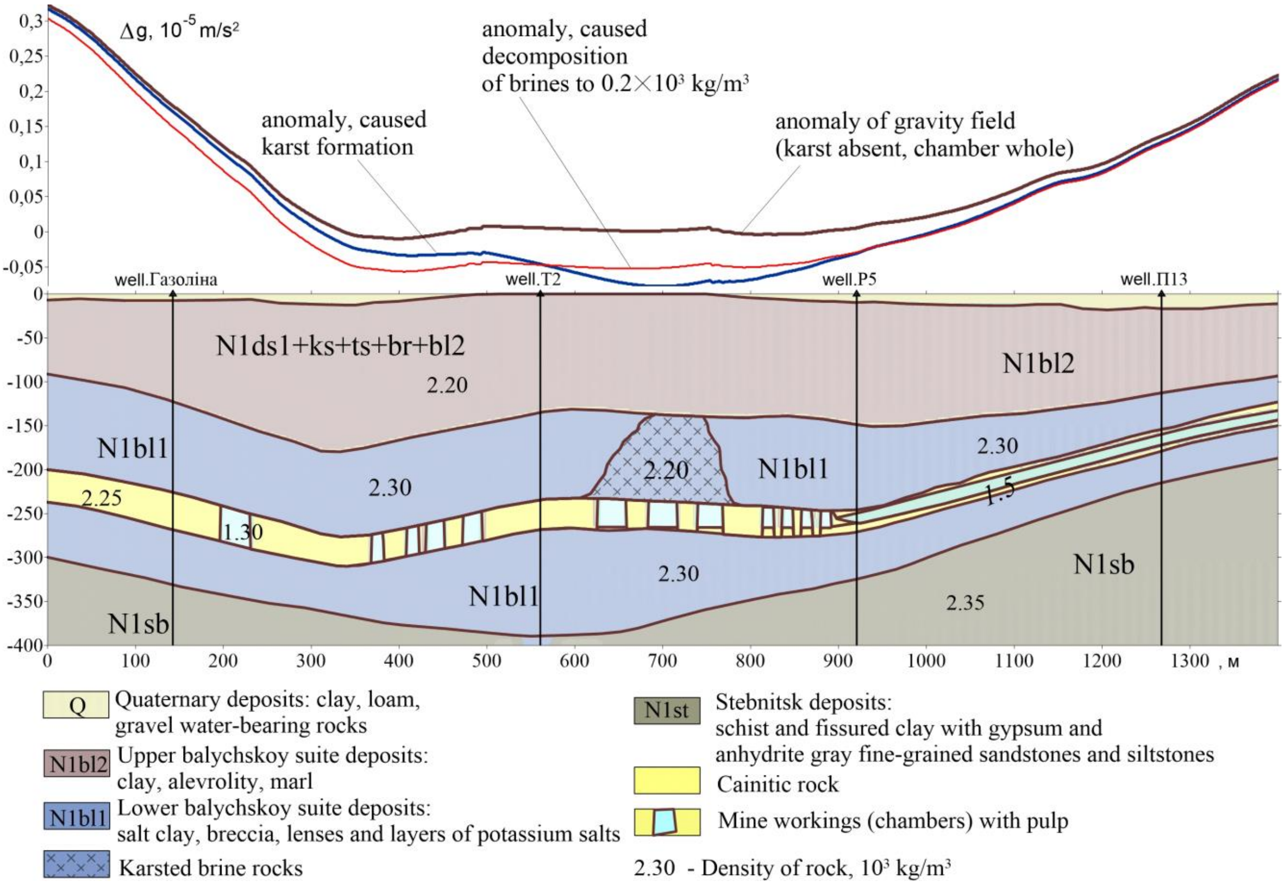


Fig. 6. Imitation models of a potassium salt deposit section

1) the section without karst formations, cavities are saturated by brines with density of $1.30 \cdot 10^3$ kg/m^3;

2) the section with the local zone of karst development over salt; rocks of the zone are deconsolidation on $-0.10 \cdot 10^3$ kg/m^3; the difference anomalous gravitational effect was up to $0.075 \cdot 10^{-5}$ m/s^2;

3) the section with reduced brine density (breakthrough of ground waters) on $-0.2 \cdot 10^3$ kg/m^3; the difference anomalous effect was up to $0.05 \cdot 10^{-5}$ m/s^2.

Post-technological anomalies of a gravitational field (of low intensity, but higher than the possible accuracy of observations) are putted on local anomalies due to the lithofacial features of the geological section, that makes it possible to detect them only with anomalous changes in the field over time. Thus, the modeling proves the requirement of high-precision monitoring observations and the interpretation of spatial-temporal anomalies using a similar methodology, which is considered on the example of changes imitation in sulfur deposits structure.

Imitation modelling of the gas-water contact (GWC) level at the hydrocarbon field. In order to detect changes in the geometry of the geological section, the interpretation of gravimetric monitoring data based on the structural GI solution can be performed only by the methodology of the sequential modelling. It is performed in the modellings 1and 2 for sulfur deposit section, rather than the spatial-temporal anomalies. Models which are obtained as a result of GI solution with the application of limits on the depth intervals of GWC level possible changes are represented on fig. 7.

Modelling of the salt dome type structural section. In the paper [15] a synthetic (imitation) structural model was used to demonstrate the geological efficiency of layer migration of time sections (fig. 8a). The seismic geological model (fig. 8b), generated by the migration of the synthetic time section, differs from the imitation model by the vertical displacement of the borders geometry, which increases with depth up to 500÷800 m, and the horizontal displacement of the over salt mound up to 1000 m.

Seismic modeling results were used to test gravity modelling in the complex interpretation of seismic and gravimetric data. The "geological task" is the geometry refinement of seismic and geological model by the "observed" gravity field. An imitation structural model is accepted as the IEM (fig. 8a). The "observed" field is the calculated field of the IEM.

Priory data (AEM) is a seismic geological model (fig. 8b) and known rock densities through the section "according to drilling", error estimation of the structural constructions for limitation of the geometry variations of the AEM boundaries. According to the "geological hypothesis", the possible AEM deviations from the "real model" of the section (IEM) do not exceed before mentioned limitations. The error of the geometry constructing of seismic boundaries in AEM is given in Table 1. Also, the geological hypothesis is supplemented with restrictions on variations in the layer thickness (table 2).

By definition, the imitation modelling is as close as possible to the practical conditions, therefore, the influence of lateral zones and the regional background is taken into account in the model fields. Lateral zones are approximated by the horizontal extension of the boundaries beyond the AEM;

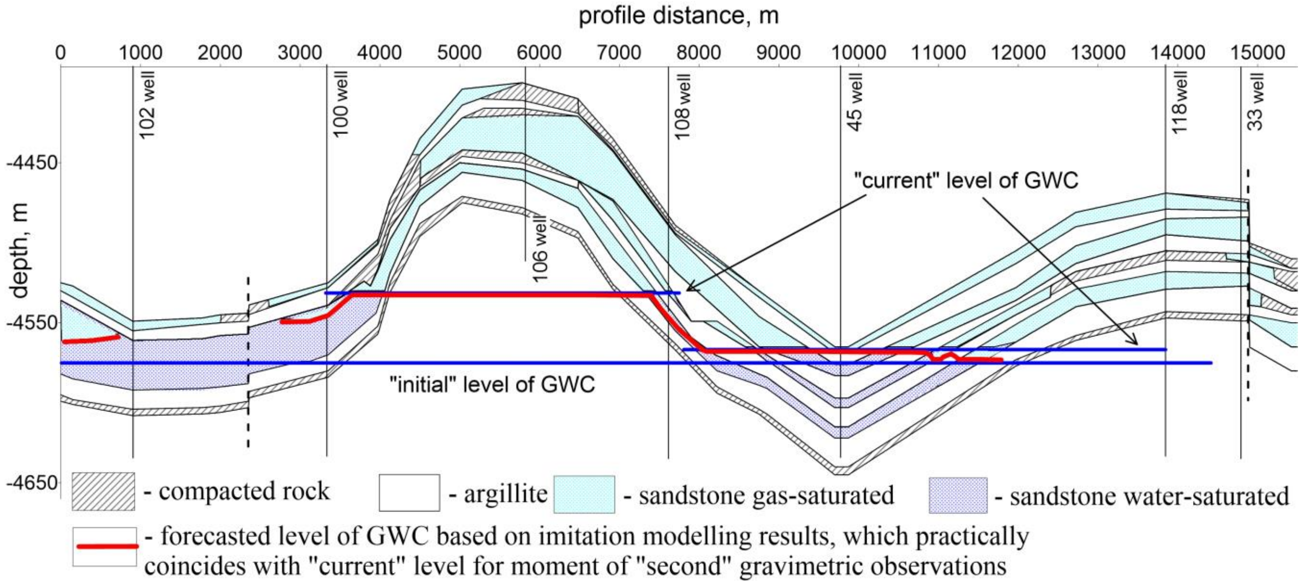


Fig. 7. Detection of the GWC "current" level in a productive horizon of the Berezivsky gas condensate field in the Dnipro-Donetsk depression according to imitation of gravimetric monitoring

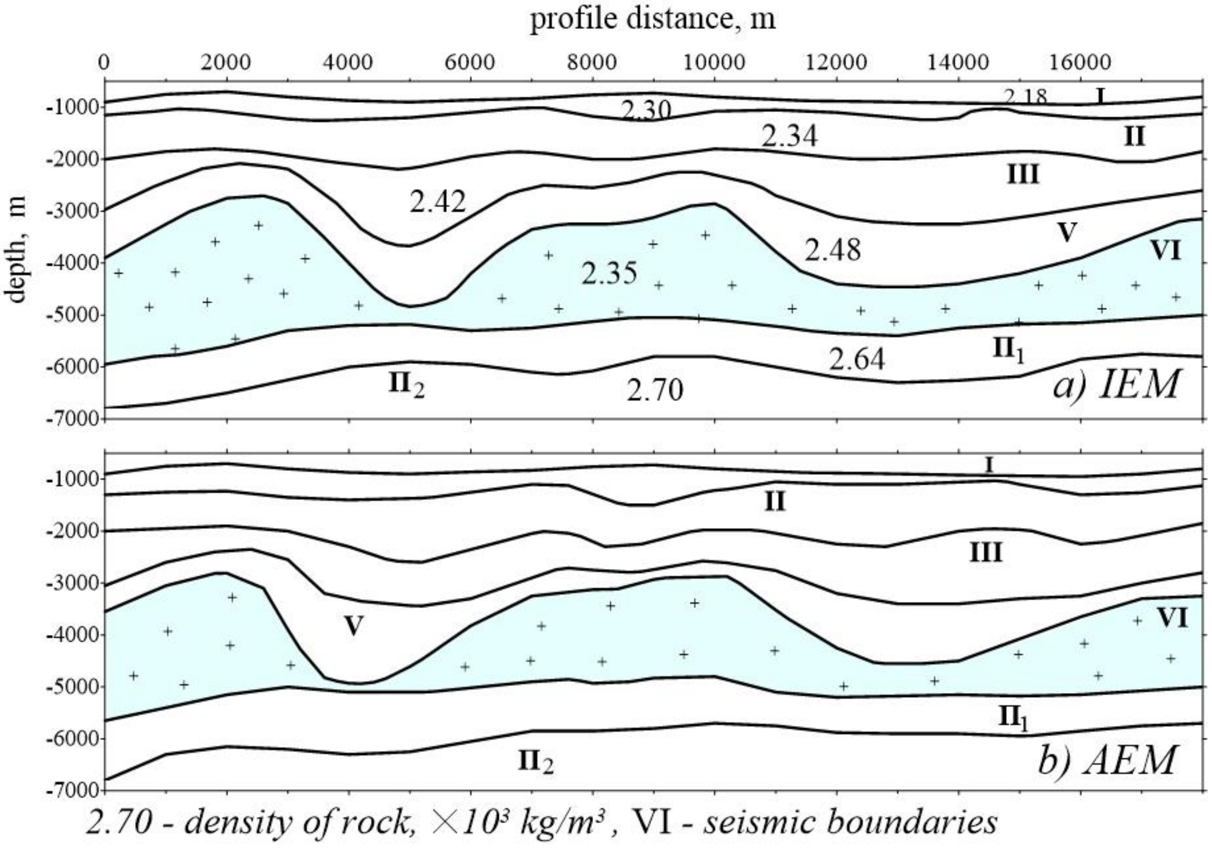


Fig. 8. Imitation (a) and seismic (b) models of structural section

Table 1

Accuracy of the construction of seismic-geological boundaries

II - ±350 м	V - ±700 м	П$_1$ - ±800 м
III - ±600 м	VI - ±1200 м	П$_2$ - ±800 м

Table 2

Permissible thickness of the layers (above the corresponding boundary)

	H_{min}	H_{max}		H_{min}	H_{max}		H_{min}	H_{max}
II	50м	1000	V	50	1600	П$_1$	300	2250
III	50м	1500	VI	500	2000	П$_2$	500	2000

the regional background, that is, the influence of the crust part below the research area is approximated by a linear component.

Modelling-1 (structural GI solution) was performed without using of the strict limits on the possible changes of the boundary geometry in the model. «Regional background» was defined by the plane during modelling. The result is represented on the fig. 9a. The layer's thickness above the salt dome has been increased, and the mould has been displaced towards the "real" position in the central part of the EEM-1a. However, the boundaries geometry in the border zone of the model, especially the gravitational surface of the salt, is significantly different from the IEM. When applying the limits on the thickness of the layers (one of the AEM additions, which are instruments of the equivalent masses redistribution), the EEM-1б is obtained that is closer to the IEM (fig. 9b).

Modelling-2 was performed by the variant of the regional background determining of the inclined plane, but which is brought to the right side of the IEM field (according to the given pickets), assuming that the section boundaries are flat in this part of the profile. Therefore, they are the most reliable based on the reliable principle of seismic constructions. The edge zones suffered the slightest distortion compared to the previous modeling in the EEM-2 (fig. 10).

According to O. K. Malovichko, it is preferably to approximate the regional background only with an inclined plane, which is the reasonable compromise. Imitation modeling allows us to study the effect of the method of the linear background deter-

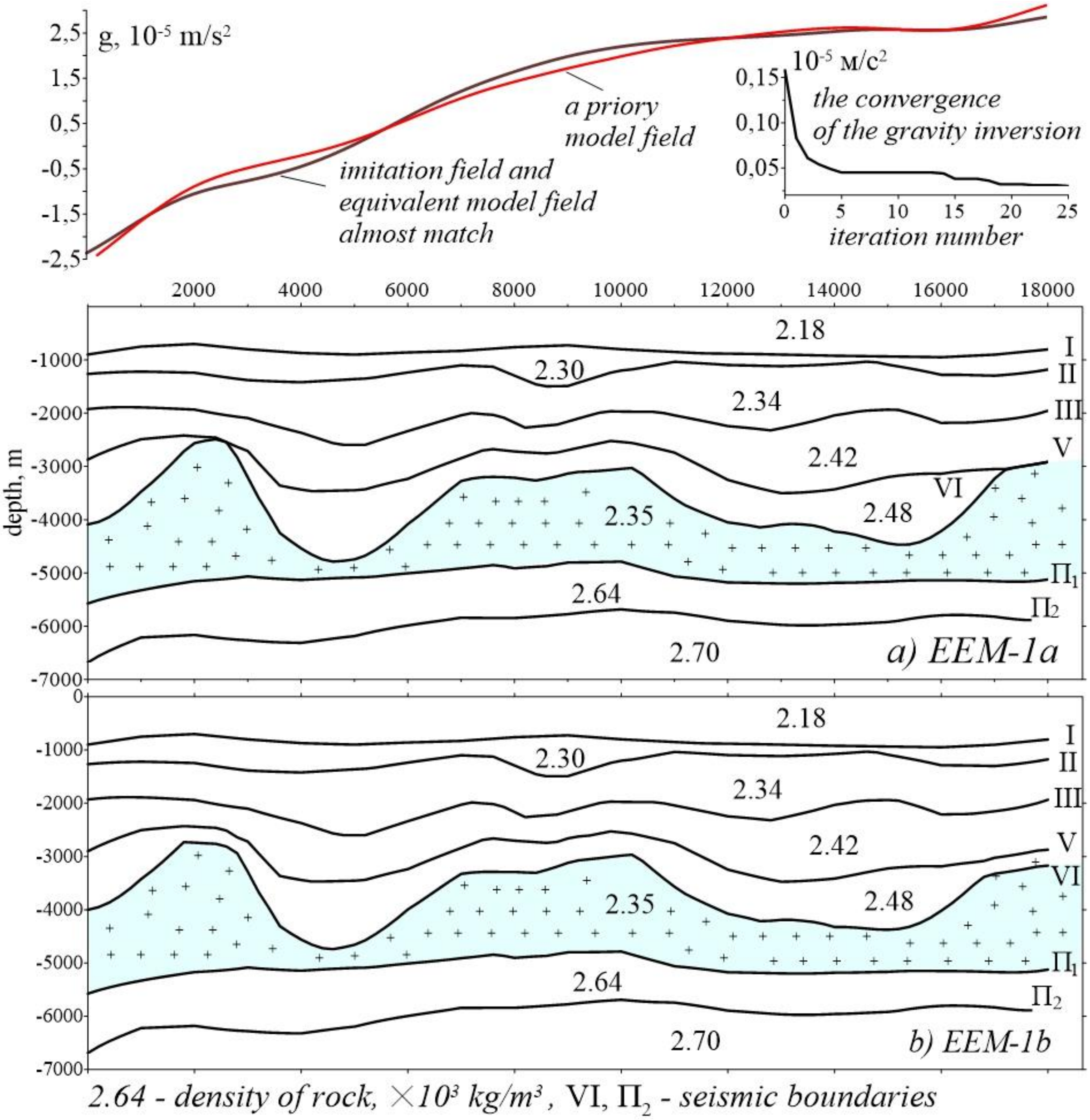


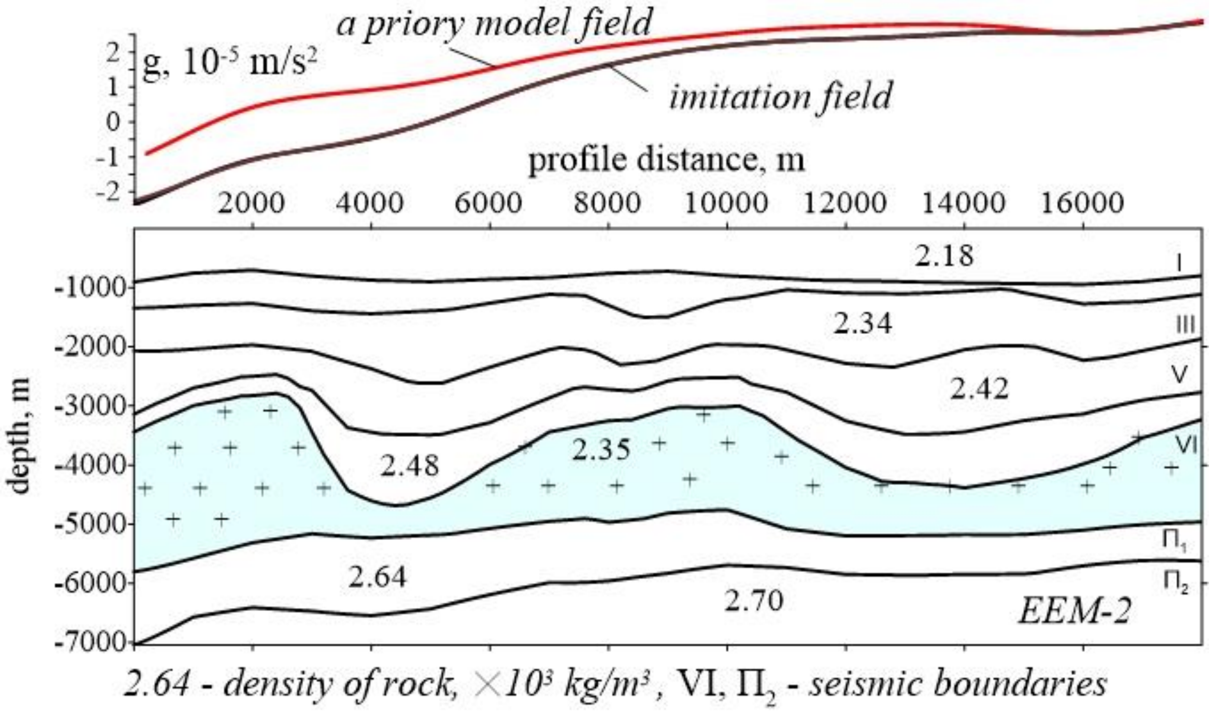
Fig. 9. Equivalent models of structural section

mining on the GI solution. The IEM field that is the "observed" field may not contain a background, but it is calculated during the imitation GI solution. So, it approximates the modeling conditions to practice. The inevitable loss of the linear component part of the observed field and the distorted anomalous field due to the inaccurate consideration of the lateral zones influence reduces the reliability of the GI solutions, especially in the boundary zones, which are approximately estimated of ±2000 m in this modeling.

The middle section part of the EEM-1a,1b, EEM-2 (fig. 9, 10) independently to the linear background variant are compared with AEM closer to IEM. First of all, it concerns the horizons V and VI. The geometry of more damp horizons (and therefore less gravity active) has practically not changed. This is due both to the method of the regional background determination and to the degree of the horizons gravitational activity.

Modelling-3 is performed on the assumption that the salt surface is traced very roughly (horizon VI) by seismic survey but it is known that the geometry of other horizons is presented accurately in the AEM. «A prior data» limits on the boundaries behavior is not taken rigidly (in the regularization parameters of the GI solution): as the degree of probable variations in the boundaries geometry (table 3). The background is defined by the characteristic pickets (selected profile points). The constructed EEM-3 (fig. 11) correlates well with IEM.

Modeling-4 differs by absence of the geometry information about the horizon VI, except for example for three or four wells (fig. 12). Constructed EEM-4



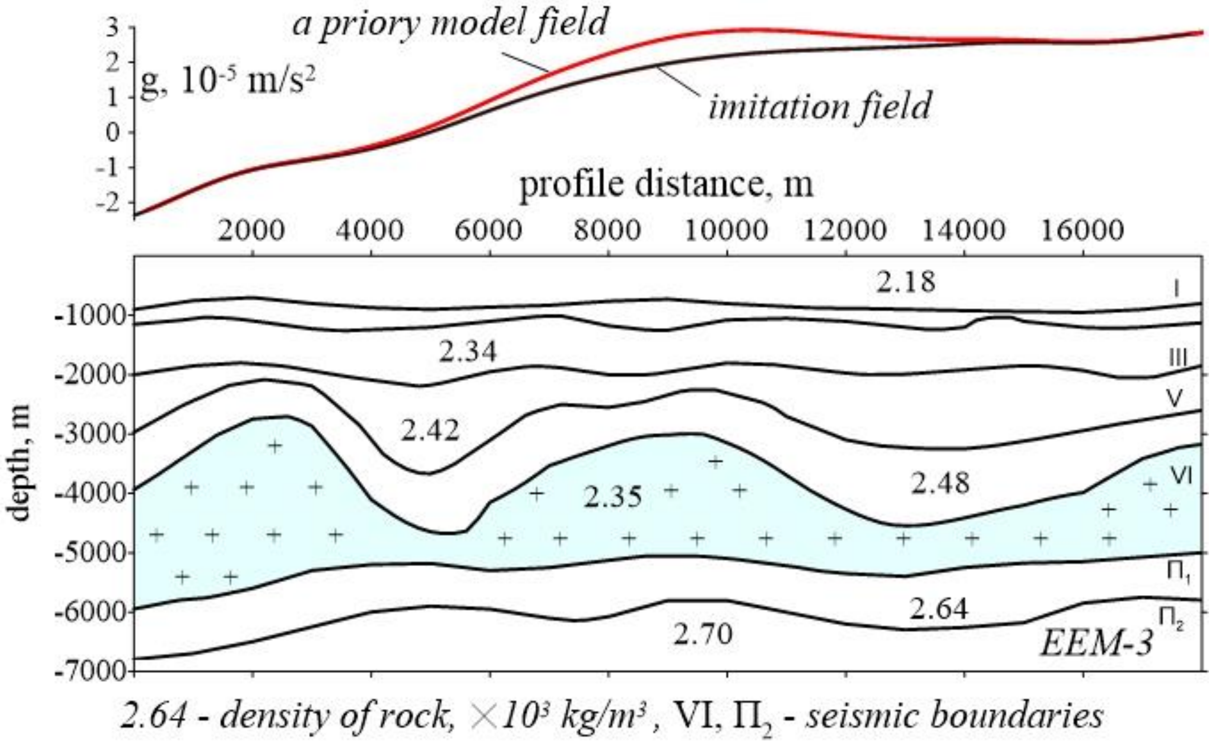
2.64 - density of rock, ×10^3 kg/m^3, VI, $П_2$ - seismic boundaries

Fig. 10. An equivalent model of structural section

Table 3

Accuracy of seismic boundaries

II - ±5м	V - ±5м	$П_1$ - ±5м
III - ±5м	VI - ±60м	$П_2$ - ±5м



2.64 - density of rock, ×10^3 kg/m^3, VI, $П_2$ - seismic boundaries

Fig. 11. An equivalent model of structural section

(fig. 13) with the application of the strict limits on the layer’s thickness (see table 2) and on the geometry variations of the boundaries (table 4), as in the previous modellings, is less reliable in the edge zones.

A small deviation between the imitation field and the EEM-4 field ($<0.01\cdot10^{-5}$ m/s^2) indicates on the high formal accuracy of the GI solution. But the comparison of the geometry of the salt domes of the IEM and the EEM-4 is not in favor of the last one and this despite the fact that the task of geometry finding of one boundary was actually solved. One from the reasons that causes the negative properties of the EEM-4 is the distortion in the field, which is due to the way of the background removing.

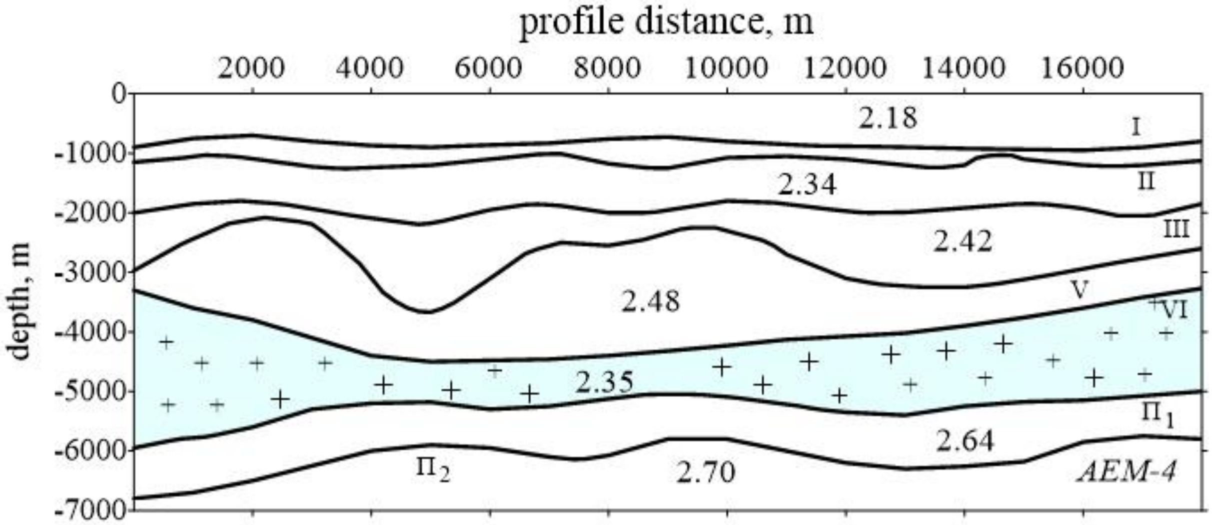


Fig. 12. A priory model of structural section for modelling-4

Table 4

Accuracy of seismic boundaries

II - ±1м	V - ±1м	$П_1$ - ±1м
III - ±1м	VI - ±1200м	$П_2$ - ±1м

Modelling-5 is connected with trying to find ways to increase the reliability of the EEM construction due to lateral zones and regional background reconstructions.

From the predictions that the EEM is more reliable than the AEM, it follows that the background allocation based on the confidence principle of the EEM will be even more reliable too. In this case, the lateral zones should be rebuilt, so the EEM edge zones have changed relatively the AEM. Consequently, after replacing the EEM→ AEM, the lateral zones reconstruction and the updated field separation, it is possible to update the iterative process of the GI solution. The criterion for stopping the solutions search by registered complicated iterations is satisfactory fields’ deviation of the "updated" AEM in the final cycle and the IEM ("observed" field). The EEM-5 (fig. 14) was built as a result of this GI method (the initial conditions are the same as in the previous modelling). EEM-5 is essentially close to the IEM within the entire section.

The EEM → AEM replacement was carried out in the first steps of the interactive cycle when reaching 1/4 ÷ 1/5 of the fields misfit relatively to the initial one which is compared with the final misfit of the previous cycle, as a rule, grows up on 10÷20%. But termination of a cycle at reaching ~ 1/2 of the misfit from the initial one leads to a sharp drop of the initial misfit in the next cycle and even below the level of the final misfit of the previous cycle. This regularity is saved during GI solution in different regimes. The EEM, which was constructed on the last cycles, did not defer one for another (final misfits level is $\leq 0.01\cdot10^{-5}$ m/s^2). So, the method of more reliable EEM finding which is stable to the background and lateral zones reconstruction is created by the way of interactive cycles.

In attempts to refine the structure of seismic geological sections, it was detected that reliability increasing of the modeling results can be achieved by the regional background approaching to an inclined plane. It is approximates the fields by characteristic pickets over the areas with the most reliable seismic constructions, as well as by the near-lateral zones rebuilding in the interactive process of the structural GI solving.

Study of Tengiz structure. A large structure was detected by seismic and gravity survey within

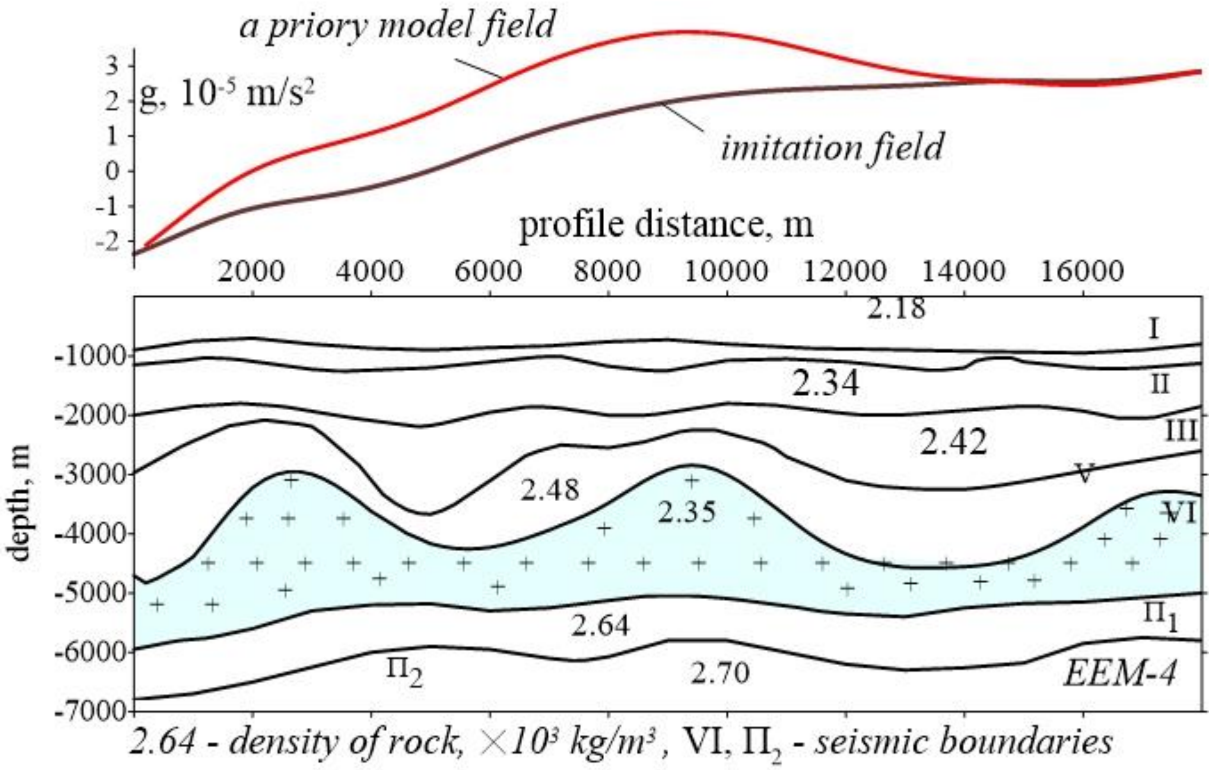


Fig. 13. An equivalent model of structural section

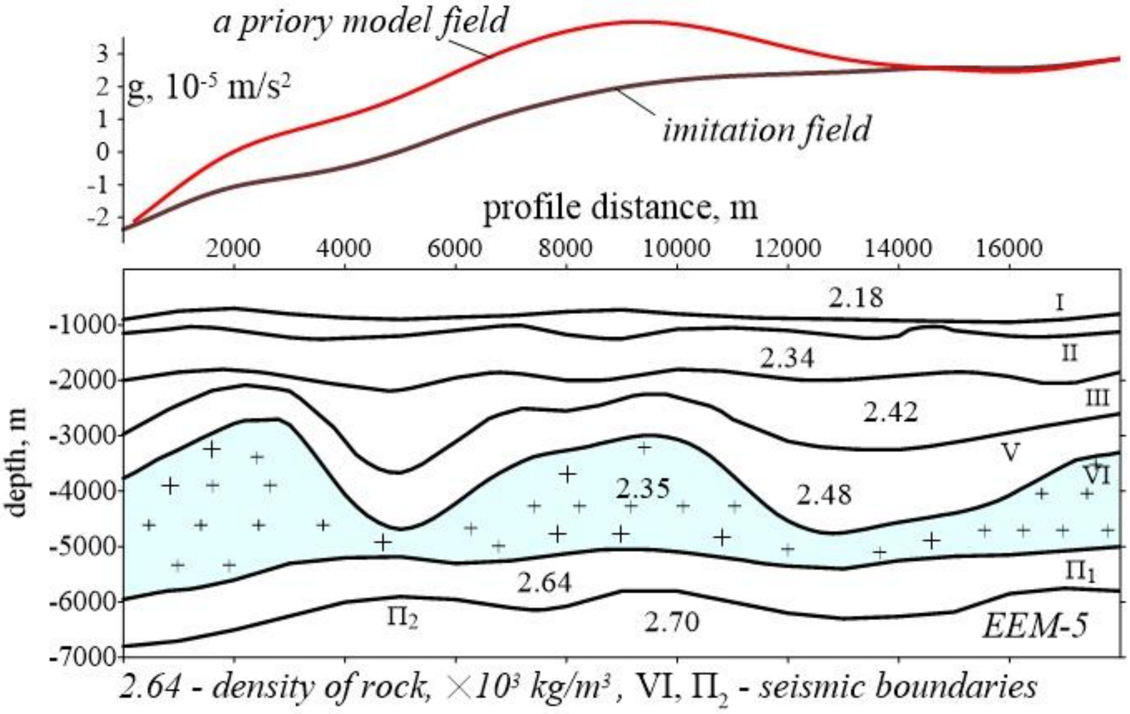


Fig. 14. An equivalent model of structural section

the Southern Emba (Pre-Caspian Foredeep, Kazakhstan). Under salt rocks deposits, including the salt surface, have been studied in detail by drilling and seismic survey.

Imitation model reflects the main horizons of geological section, age and rock densities. There is a large oil reservoir in the central part of the IEM in the depth range of 3500÷7000m. This reef structure has an atoll form in plan and significant density reduction in the lateral zones (fig. 15).

Prior information contains data on the structure of the upper section part, the geometry of the salt bottom of the kungur formation and the boundary between the terrigenous rocks of the Devonian and

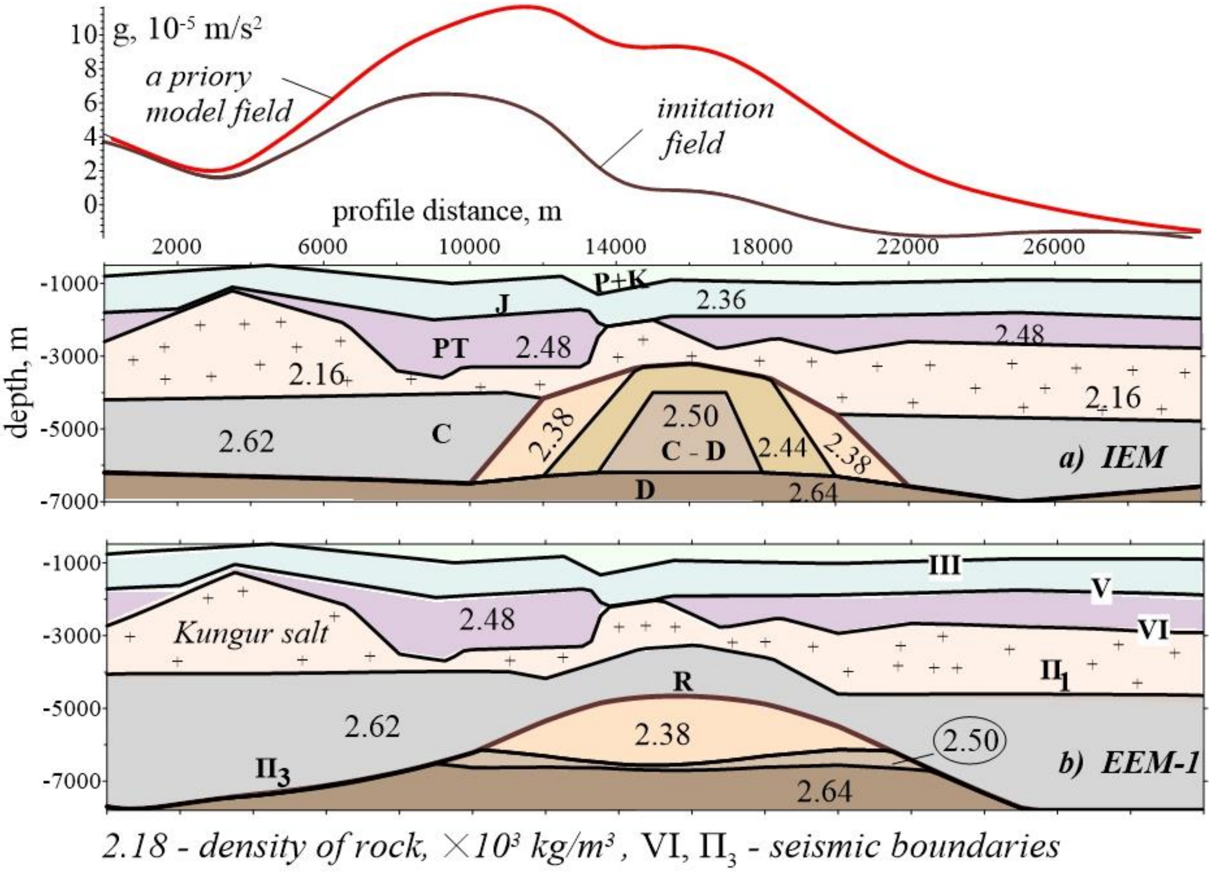


Fig. 15. Imitation (a) and equivalent (b) structural models of the Tengiz section

Carboniferous. Density of rocks is confidently known for the upper part of the section. According to seismic survey and drilling, a large oil deposit is predicted. It is associated with probable subsalt biogermic carbonates. The lateral zones of this possible reef structure are traced uncertain by seismic survey, therefore the a priori model (AEM) contains the upper part of the section including to the salt layer and the lower boundary between the Devonian and Carboniferous rocks (Π_3); reef object is missing.

Geological task: to confirm the existence of a reef structure.

Modelling-1 was performed with using the structural GI by the next conditions. There is no reef structure in AEM (compared to IEM, fig. 15a), but the top of the expected reef formations (boundary R) and possible internal density boundaries are conventionally assigned (coinciding with the surface of the reflection horizon Π_3). As a result of the structural GI solution (the initial error is – $4.64 \cdot 10^{-5}$ m/s^2, the final one is $0.10 \cdot 10^{-5}$ m/s^2, the non-strict limits are applied - table 5), a structural EEM-1 of the Tengiz structure section was obtained (fig. 15b). At the base of the subsalt section, the layer of about 1500 ÷ 2000 m and with rock density of $2.38 \cdot 10^3$ kg/m^3 is plotted by the boundary R. The fact that this density value is close to the limitations for the minimum values for subsalt rocks, and also that the boundary Π_3 within the whole model was below the permissible level, gives us grounds to confidently predict the existence of a reef structure of greater thickness.

Modelling-2 is excellent using of the strict restrictions (table 5), that is, they are used in the regularization of the GI solution process and as limitations on the possible boundaries variations. As a result of the structural GI solution, EEM-2 (fig. 16) was constructed, in which the density reduction zone with a density of $2.38 \cdot 10^3$ kg/m^3 was expanded; the boundary of Π_3 within the structure "deepened", which released the place for a new zone with a density of $2.50 \cdot 10^3$ kg/m^3. However, the density reduction zone although is much larger, but by form is different from the imitation model.

An appropriate question about the correct using of the structural GI for the simultaneous solution of two problems: the detection of anomalous zones and the study of their geometry? The imitation modelling results of density distribution convince that there should be a consistent modelling: the fundamental existence questions, sizes and depths of geological formations occurrence are solved at the beginning. The incorrectness of the EEM-1 and EEM-2 fragments can be explained by the properties of the structural gravimetric tasks, when the field ano-

Table 5

Accuracy of seismic boundaries

III - ± 30 м	VI - ± 50 м	R - ± 3000 м
V - ± 30 м	$П_1$ - ± 30 м	$П_3$ - ± 60 м

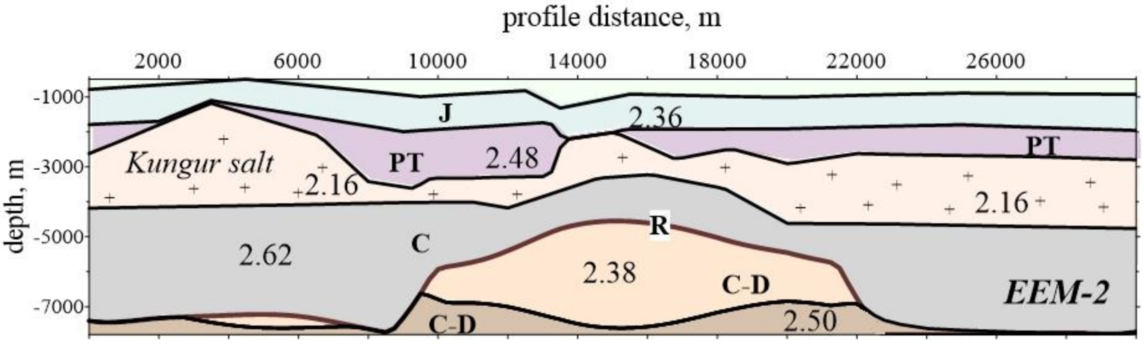


Fig. 16. An equivalent structural model of the Tengiz section

malies are caused by the geometry, the boundaries depth, the sign and the magnitude of the densities changing at the boundary, as well as the direction of the boundaries correction depends on density changing sign and the anomaly sign on the structural GI solving. That is why the internal reef zone with density of $2.44{\cdot}10^3$ kg/m^3 (fig. 15a), which is given in AEM by borders that repeat $П_3$, will not appear in EEM on no condition. But zone with density of $2.50{\cdot}10^3$ kg/m^3 will appear (fig. 16) due to the "deepening" of the boundary $П_3$, but not as a result of the boundary that contoured the top of this zone. The last one, as a top of a zone with density of $2.44{\cdot}10^3$ kg/m^3, by the statement of this problem, can "deepen" in reversely proportional intensity of the densities changing on these boundaries, because the sign of this densities changing is positive.

Modelling-3 was conducted to identify the most probable contours of the reef structure. In the AEM, the reef is also absent, but for the predicted uniform structure the average weighted density is $2.44{\cdot}10^3$ kg/m^3, which is close to the imitation. The EEM was built with using the limitations (table 5). The modelling results (EEM-3) are given on fig. 17.

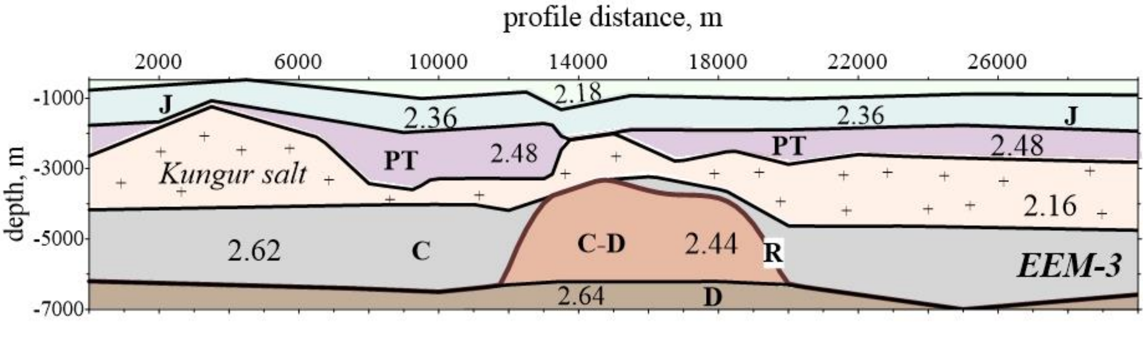


Fig. 17. An equivalent structural model of the Tengiz section

The reef structure contours of the IEM are satisfactorily represented in the EEM-3, however, the reef zone is less than the imitation one. The modelling results show that the shape and size of the object should be predicted after the reliable estimation of the average weighted densities onto the section.

The following modellings are a test of computer technology for the linear GI solving. The imitation model (fig. 18 a) and a priori data are identical to the previous modellings. The geological task is complicated by confirming of a reef body existence and predicting of high porosity zones in subsalt deposits.

The hypothesis that there is no reef structure and intensive density decrease zone under the salt in the carbonate-terrigenous sediments, and the density of deposits is in the range of $2.62 \div 2.64{\cdot}10^3$ kg/m^3, is realized in the EEM form (not shown here), which contains a zone of significant density decreasing under the salt, but which is substantially different from the imitation model; its presence confirms the existence of a reef body.

The next hypothesis: the depth interval of the reef development is 3500÷7000 m, the average reef density is significantly low - up to $2.30{\cdot}10^3$ kg/m^3; the hypothesis is implemented by the EEM-4 (fig. 18 b).

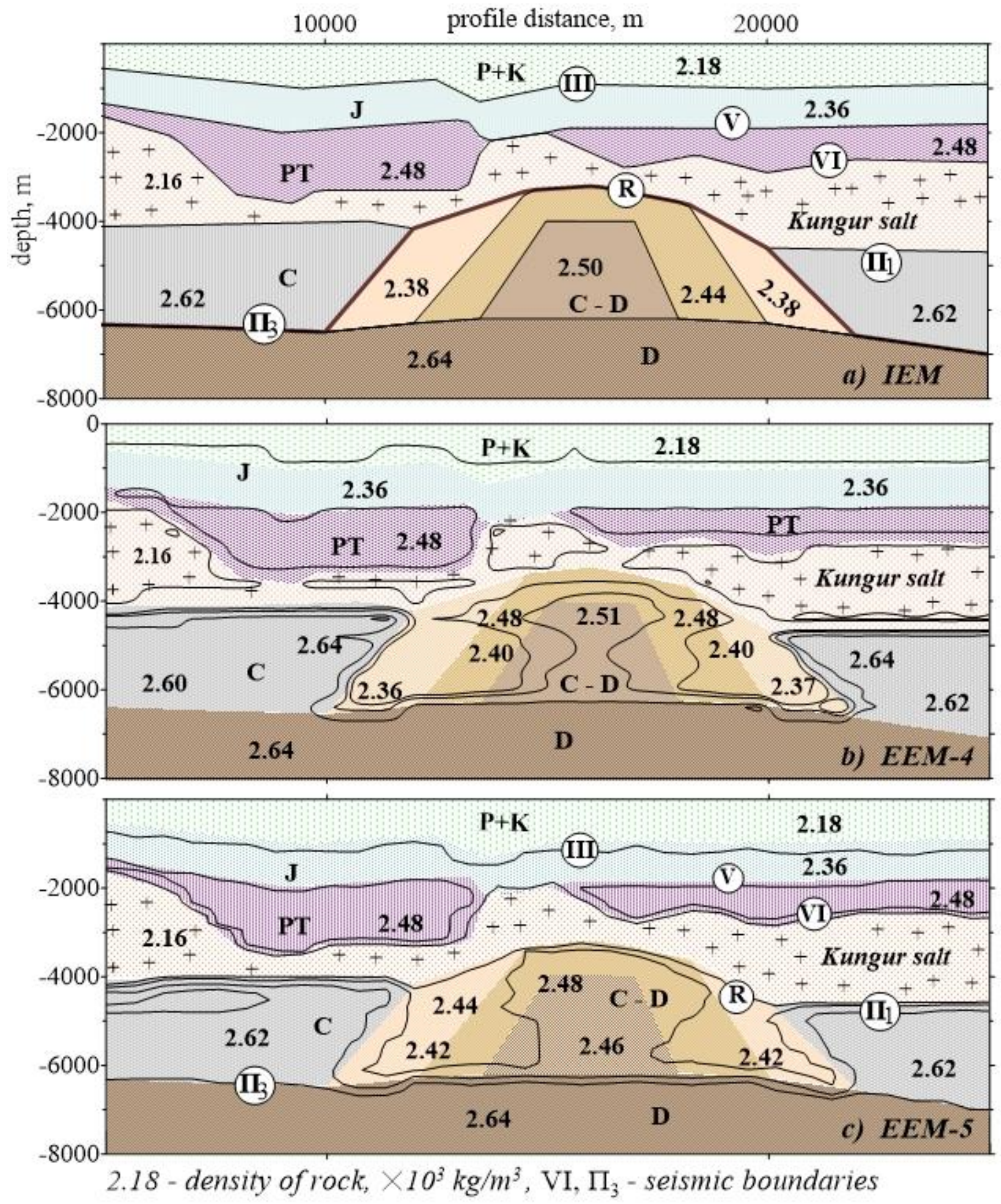


Fig. 18. Density models of the Tengiz structure

Comparison of the EEM and the AEM allows to constrict the predicted estimation of the carbonate rocks average density to the limit of $2.42 \div 2.48 \cdot 10^3$ kg/m^3 (a very wide range of possible densities of $2.34 \div 2.62 \cdot 10^3$ kg/m^3 is given according to a priori data), which approximates the densities of the imitation model.

Thus, the most probable hypothesis is that under the salt there is a large reef body like the atoll. The density decreased zones frame the central part (lagoon?) of dense rocks within the reef. Check it on the opposite hypothesis: the reef body is homogeneous; the average weighted density of carbonate rocks that form the body is close to $2.44 \cdot 10^3$ kg/m^3. Figure 18в shows EEM-5. This implementation contradicts the last hypothesis. Thus, the result of imitation modelling is the confirmation of the reef existence and its heterogeneous atoll structure.

Conclusions. Comparison analyses of the imitation models (IEM) and the most reliable equivalent models (EEM) lead to the following conclusions:

1. In the structural GI solutions, the direction of geometry changes in the density boundaries is determined not only by the sign of the anomalies, but also by the sign of the dangling of the rocks densities on these boundaries.

2. Absolute values of rock density in density EEMs or boundaries geometry in the structural EEMs will not accurately match the imitation one.

3. EEM are qualitatively probable models of density distribution or boundaries geometry, which reflect the general, fundamental nature of the section structure. The achievement of a small final field

misfit and the rapid convergence of the iterative process of the GI convergence solution are not critical: they have a tangible relation for the evaluation of the EEM proximity degree to real environments.

4. The imitation modelling is based on the methodology geological efficiency of the informal sequence of equivalent solutions, which bases on the formation of hypotheses, their formalization in the AEM form and the EEM construction, further in the comparative analysis of the EEM with the subsequent definition of the most reliable hypothesis and corresponding optimal model of the section (OMS).

5. The degree of modeling reliability depends on the completeness of the use of a priori data, the possibility of the near-lateral zones including in the AEM structure. The GI solution reliability also depends on mastering of the GI methodology and techniques and on the properties understanding degree by the interpreter of the wide equivalence of GI solutions in its general formulation.

6. The thoroughness of the EEM series analysis, which is aimed at choosing one model or series generalizing in the form of OEM, first of all depends on the interpreter's experience, because computer technology of 2D/3D direct and inverse problems solving is just an interpretative tool.

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IMITATION MODELLING TECHNOLOGY FOR GRAVITY INVERSION CASES

Formulation of the problem. A gravity method is aimed at prospecting and exploration of mineral resources which are based on the study of the geological section structure. The task of quantitative interpretation of the gravimetric materials, which uses methods for solving direct and inverse gravity problems, is the modelling of a gravity field (direct problem) and geological media's density structure (inverse problem). The important features of methods for density structure modelling of complex geological media are geological content, consistency with a priori data and its subordination to geological hypotheses. It is proposed to analyze these properties by a imitation technique.

The purpose of the article is to describe the imitation gravimetric modelling method, based on the construction of an informal sequence of equivalent solutions. The purpose of imitation modelling is to study the properties of gravity inversion in general formulation as well as to assess the degree of detail and reliability of the methodology and technologies of gravity modelling, which is claimed to be an effective solution to geological problems.

Methods. Imitation modelling technology and methods of solving gravity direct and inverse problems for geodensity model of complex geological environment.

Results. The examples of density and structural simulation testing of the informal sequence of equivalent solutions and its computer technologies show that complex interpretation of wells, seismic and gravity data enables to create detailed density models of geological medium. Studies have also been conducted of ways to increase the reliability of gravitational modelling.

Scientific novelty and practical significance. It is revealed that the best approximation of the regional background is an inclined plane, which approximates the observed gravity field along characteristic pickets over the research areas that are better studied. Also, an increase in the reliability of modelling can be achieved by rebuilding near side zones in structural type models in an interactive process of solving structural inverse gravity problems. Substantive modelling depends primarily on the experience of the interpreter, since computer technologies for solving direct and inverse gravity problems are only an interpretation tool.

Keywords: geological section, gravity prospecting, interpretation method, gravity inversion, gravity field, modelling, a priori model, equivalent model, seismic model, density model.

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