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ИЗВЕСТИЯ

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Қазақстан Республикасы Ұлттық ғылым академиясы «ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы» ғылыми журналының Web of Science-тің жаңаланған нұсқасы Emerging Sources Citation Index-те индекстелуге қабылданғанын хабарлайды. Бұл индекстелу барысында Clarivate Analytics компаниясы журналды одан әрі the Science Citation Index Expanded, the Social Sciences Citation Index және the Arts & Humanities Citation Index-ке қабылдау мәселесін қарастыруда. Webof Science зерттеушілер, авторлар, баспашылар мен мекемелерге контент тереңдігі мен сапасын ұсынады. ҚР ҰҒА Хабарлары. Геология және техникалық ғылымдар сериясы Emerging Sources Citation Index-ке енуі біздің қоғамдастық үшін ең өзекті және беделді геология және техникалық ғылымдар бойынша контентке адалдығымызды білдіреді.

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GEOPHYSICAL DATA COMPLEX INTERPRETATION TECHNIQUES FOR STUDIES OF THE EARTH CRUST DEEP HORIZONS IN THE NORTH CASPIAN REGION

Abstract. Comprehensive interpretation of geophysical data for studies of the Earth crust deep horizons in the Caspian oil and gas bearing region is based on analysis of regional seismic section wave fields as per reference geotravers and gravity anomalies' interpretation results received by posing direct and inverse problems with use of specialized geoinformation systems. Gravity exploration data in the form of consolidated medium- and small-scale maps and the observed travel time graphs of DSS and Reflection Wave/DSS refraction waves taken in separate regional profiles serve as the factual basis for construction of deep geological-geophysical sections. Physical models of density and structural-velocity proved to be effective and allowed identifying vertical and lateral heterogeneities in the crust and upper mantle structure. The models for upper horizons of the Earth crust are most reliable, as they are provided with a large amount of factual material, including geological data. Structural-velocity sections built on regional seismic profiles revealed heterogeneous structure of the North-Caspian region's lithosphere. Negative and positive velocity anomalies characterize the lower horizon blocks of the Earth crust and the upper mantle of different material composition and structure. The gravity models of deep structures and density distribution in the Earth crust allowed to reveal the vertical and sub-vertical boundaries of deep blocks, to predict the material composition of deep structures and to determine the peculiarities of their formation and tectonic development. Given the poorly explored territory and incomplete geophysical information, the proposed method of the complex interpretation of seismic gravimetric data enables to construct reliable density and velocity models of complex geological situation. The obtained models of the region's deep structure can be effectively used both for reconstruction of Paleozoic geodynamic conditions and identification of the modern structural features of the Earth crust and upper mantle.

Key words: seismic surveys, gravimetry, P-wave velocity, density, modelling, deep structure, Caspian Sea region.

Introduction. The Caspian region is one of the world's best known hydrocarbon provinces, characterised today by highly dense regional detailed geophysical observations, not yet covered by regional summaries on a unified methodological basis which would contribute to a wide range of tasks assessing its oil and gas potential [1].

Modern geophysical methods applied today to solve regional geological problems have their advantages and disadvantages, technical and methodological limitations. Analysis of gravitational and magnetic fields, results of investigation of petrophysical parameters of geological complexes provide an opportunity to obtain reliable information about geological heterogeneity of the Earth crust upper part (sedimentary complex and crystalline basement). When studying structural heterogeneity of deep horizons of the Earth crust and upper mantle, data of deep seismic survey and magnetotelluric sounding play the major role. The methodical and complex interpretation of geophysical, structural-geological and petrophysical data allow physical-geological modelling of the tectonic structures of the Earth crust on the geodynamic basis and linking the heterogeneity of the upper layers with minerals embedded in deep horizons of the Earth crust [2,3,4,5].

Regional geophysical materials are sufficient for complex interpretation to construct deep sections of lower horizons of the Earth crust and upper mantle of the Caspian region. The area is provided with high degree of geophysical data: gravimetric survey materials, a large number of DSS and RW/DSS profiles, data generated by rapidly developing seismic tomography which illuminates the structure of the mantle to a depth of 200 km. Constructing the deep geological-geophysical sections was actually based on the gravity survey data in the form of consolidated medium- and small-scale maps and observed travel time graphs of refracted waves obtained by DSS, EWS and RW/DSS methods from selected regional profiles [6].

The authors believe that the currently available regional geophysical database supports identification of the major deep geotectonic heterogeneities (rises, troughs, tectonic faults, thrusts along the crust's deep horizons, the basement surface and overlapping strata, etc.) at a higher qualitative level, which is necessary for further, more profound, study of the deep structure and geodynamic evolution of the Caspian region's lithosphere.

Research methodology. Comprehensive interpretation of geophysical data in the study of the Earth crust deep horizons in the Caspian oil and gas bearing region is based on analysis of wave fields of regional seismic sections and results of quantitative calculations of gravity anomalies based on methods of direct and inverse problems with extensive use of specialized geoinformation systems.

In this study, materials of deep seismic sounding (DSS, EWS-DSS) along geotraverse lines crossing the Kazakhstan part of the North Caspian region were employed. In addition, when studying the structure of the Earth crust and the upper mantle of the Northern Caspian, seismic methods were applied: correlation refraction method, DSS and its combination with the method of earthquake exchange waves (EWS) on individual regional profiles. The lack of traditional deep seismic surveys in some areas was recuperated by profile seismic tomography [7] (Figure 1).

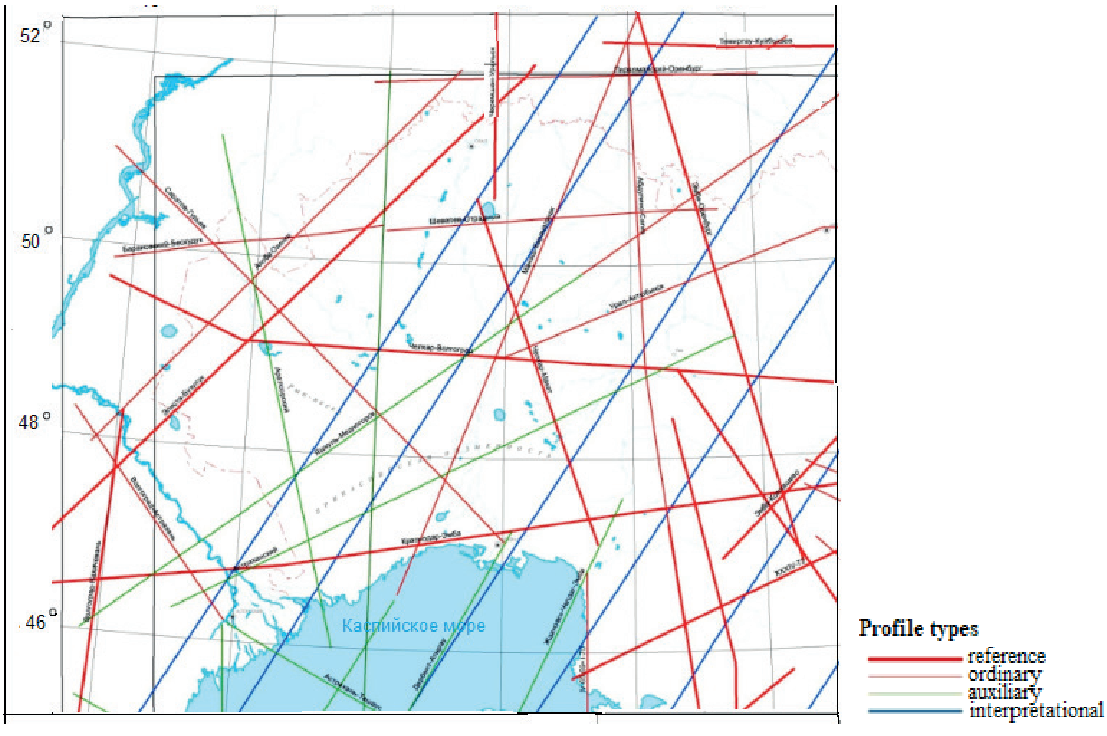
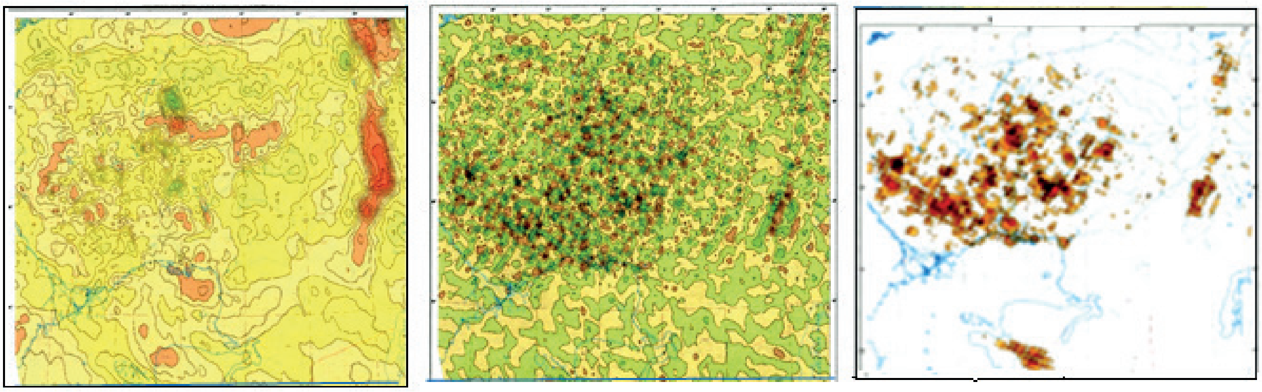


Figure 1 - Diagram of regional seismic profiles (DSS), the Caspian Depression.

At present, the entire territory of the Caspian sedimentary basin is covered by gravity surveys of various scales and accuracy (1:500,000-1:200,000), and high precision detailed surveys have been carried out for individual perspective areas with high-performance modern gravimeters (1:50,000-1:25,000). The results of gravimetric work were summarised and presented in the form of consolidated maps (Figure 2).

Traditionally, seismometry (DSS and seismology) provides basic information on the structure of the Earth crust and upper mantle. The data are mainly used to delineate horizontal boundaries. Gravimetry is more sensitive to the block heterogeneity of the crust and the entire tectonosphere, but is poorly suited to detecting extended subhorizontal interfaces. In other words, an important feature of gravity survey is that it cannot study smooth horizontal and subhorizontal interfaces and is most effective when studying local bodies (separate structures, blocks, massifs, lenses, dikes, etc.) and vertical and sub-vertical boundaries [8,9].



Gravity field intracrustal component

Gravity field local component

Gradients of gravity field local component

Figure 2 - Gravity field transformations. Caspian Basin. Scale 1:2 500 000
(edited by Nussipov E., 2005).

The authors widely used traditional methods of geophysical data interpretation, namely: analysis of physical properties of rocks and evaluation of their area and depth differentiation degree, sectional modelling of deep structure by quantitative calculations and selection of parameters of geological section. The calculated petrophysical models of the lithosphere (velocity and density) were linked to results of lithological and formation analyses of geological complexes, petrochemical composition of rocks, etc. [10].

The following general principles guided the authors in their attempts to improve efficacy of geophysical data integration while constructing the deep geological and geophysical models:

1. Seismic section is assumed to be the main information source on deep structure of an area. Results of profile seismic tomography (Shatsilov V.I., Saipbekova A.M., 1994) were used for velocity characteristics of the Earth crust and the upper mantle, and volumetric seismic tomography for deeper (up to 500 km) mantle horizons (Saipbekova A.M., 2003; Shatsilov V.I., 2003; Xu Yi, 1994).
2. Gravity field is a link in interpreting materials of other geophysical methods. The complex analysis of gravimetric, seismic tomographic and seismological investigations allowed to reveal the density stratification of the crust and upper mantle and thereby to develop the data obtained earlier by seismological methods on the deep structure of the region.
3. Interpretation of geophysical fields is oriented towards the areal variant to enable the construction of a volumetric model of a deep structure.
4. In the process of interpretation, computer technologies were widely used to develop a unified information base of initial data.

The method developed by V.I. Shatsilov, based on the method of transformation of observed travel time graphs of refracted waves into a field of true velocity values in the section plane was applied for construction of structural-velocity models of the region. Using the most productive of existing methods of transformation of travel time graphs of refracted waves into velocity models, the expert team of the Institute of Seismology at the RK Ministry of Education and Science processed more than 200 DSS, DSS-EWS and correlation refraction profiles, obtained in different years in Kazakhstan and the adjacent areas [7,11].

The structural-velocity sections obtained along regional profiles enabled the typification of crustal blocks based on mutual correlation of its layers and zoning of the territory by crustal types (continental, relict paleoceanic, transitional crust). Figure of sectional velocity isolines confidently fixes such structures as deep thrusts, sialic blocks submerged into the lower crust, blocks of intense basification and abrupt accretion of the lower crust, tops of mantle asthenoliths, and other [2, 7].

Development of the 2D density models of the Earth crust in the Caspian region profited from main provisions of the methodology of deep geological modelling formulated at the RK MES Institute of Seismology for studies aimed at laying the deep geological and geophysical grounds for solving seismological problems in Kazakhstan [12,13,14].

In case of the Caspian region, the authors applied the technique of iterative construction of density gradient-layer models of complex environments based on numerous velocity sections obtained in recent years and the identified features of the $\sigma = f(Vp)$ relation for various rock types. With help of developed deep structure gravity models along a number of geotraverses crossing the south of the Caspian Basin and adjacent regions, both velocity features and density distributions were established for different blocks. These results together with other geological and geophysical materials enable us to predict the material composition of individual deep blocks and assess the peculiarities of their formation and tectonic development.

Construction of density models was carried out in three stages: at first, the observed gravity field was split into orthogonal components reflecting the gravity effect of crustal and mantle density objects; secondly, density of the layered environment's vertical section was determined by gravity field and P-velocity data to reveal the structure and properties of the section; thirdly, links were established between the lithosphere's identified features of density structure with tectonics and geodynamics of its most critical elements. A uniform law of transition from velocity to density was observed [15].

Transformations of the observed gravity field obtained by the principal component method produced three orthogonal components: regional, residual and local (Figure 2). The process of gravity field modelling began with selection of the regional component of the field, which manifests the inhomogeneity of the structure of the entire thickness of the Earth crust. Then, inhomogeneity models of deep crustal layers (granulite-basite and granite-metamorphic) were built by selecting the intracrustal field effect Δg. In the last stage, local Δg anomalies indicated the near-surface structures characterizing geological heterogeneities in the sedimentary layer. The zero approximation of the section was carried out in strict accordance with the P-velocity section. Using the latter, bodies were "coded" separately for the main crustal layers and the mantle material inhomogeneities. The calculations were iterated until the theoretical and observed gravity fields, representing the regional, intracrustal, and near-surface models were in complete agreement. The final model is the result of summation of quantitatively consistent models: mantle, crustal, intracrustal and the near-surface one.

Accordingly, we obtained the following layer densities: 2.4g/cc for the suprasalt layer, 2.2g/cc for the salt layer, 2.65g/cc for the sedimentary layer (further separation of the sedimentary layer into two sub-layers with density values of 2. 55g/cc and 2.65g/cc), 2.75g/cc for the granite-gneiss bed, 2.85g/cc for the granulite-gneiss bed, 2.95g/cc for the granulite-basite bed, 3.05g/cc for the crust inclusions in the active mantle (coromantle mixture). Density of the active mantle below the Mojo surface is 3.25g/cc. As the Caspian mantle is characterized by lower density, rocks of normal mantle with density 3.29g/cc are assumed as host medium for crustal objects. In addition, fragmentary inclusions with increased density of 3.31 g/cc were individuated in the mantle. Anomaly-forming bodies complicating the structure of the main crustal layers were used for constructing the density model of intracrustal objects. Quality of results of petrophysical modelling depends on the choice of technique for dividing the gravity field into components anomalies of which reflect the velocity and density inhomogeneities of the geological section.

Research results. The authors analyzed the 2D density and structural-velocity models along regional profile lines (geotraverses) located in the Northern Caspian, namely, Atrek-Abdulino-Sagiz, Volgograd-Chelkar-Turgai, Emba-Kolpashevo, Meridian 500, provided with velocity models as per the DSS data (Figure 1). The modelling results are shown in the 2D density sections accompanied by the original P-velocity models (Figure 3).

For example, re-interpretation of the primary DSS travel time graphs for the Volgograd-Chelkar profile and of the regional CRM for the Turgai profile allowed us to obtain a velocity model for the Volgograd-Chelkar-Turgai profile with a total length of 1500 km. The P-velocity model prominently reflects the sophisticate structure of the lithosphere of the unique Caspian Basin: an abnormally large thickness of the platform cover; a complex shape of the transition zone from the sialic layer of the consolidated crust to the basaltic layer expressed in frequent alternation of high-speed protrusions and low-speed deflections in the depth interval of 10-35 km; and in the mantle, below the centre of the basin, a high-speed block is clearly marked with significantly increased lateral dimensions as compared to intracrustal ones [16].

The density model along this profile agrees with the structural-velocity data of the section, confirming the complex structure of the lithosphere within the Caspian depression, expressed in frequent alternation of high-density protrusions and low-density deflections in the 10-35 km depth interval and in simple character of deep structures of the lower horizons of the crust.

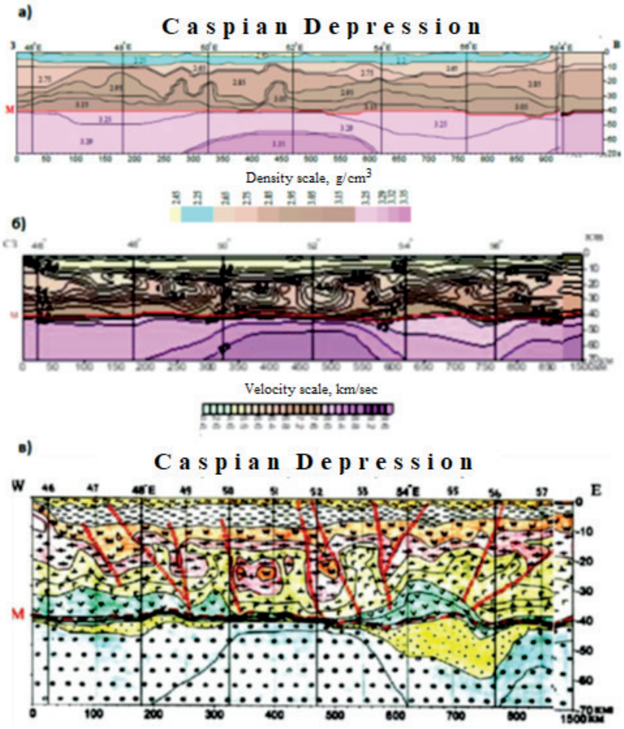


Figure 3 - Seismic gravity modelling along the Volgograd-Chelkar-Turgai profile
Models: a) density model, b) P-velocity model, c) structural-tectonic model (data by Abdulin A.A., Pilifossov V.M., Votsalevsky E.S., 1996).

Conclusions. The seismogravitational modelling allowed obtaining the density and velocity models on regional seismic profiles of the North Caspian region. The character of the velocity section and differentiation of density properties convey an idea on correlation of the Earth crust layers, possibility to conduct typification of the Earth crust blocks on the basis of its layers' correlation and to carry out zoning of the territory by types of the Earth crust. Figure showing the velocity isolines across sections confidently identifies large thrusts, structural heterogeneities of intense basification, sialic blocks embedded into the lower horizons of the crust, sharp increase in thickness of the crust, tops of mantle decompressed magmatic bodies (asthenoliths), etc. Gravity models of deep structures and density distribution in the Earth crust are utilised to identify structural features of individual horizons, vertical and sub-vertical boundaries of deep blocks, and to predict the material composition of deep structures, their formation and tectonic evolution.

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СОЛТҮСТІК КАСПИЙ МАҢЫ ОЙПАТЫНЫҢ ЖЕР ҚЫРТЫСЫНДАҒЫ ТЕРЕҢ ЖАРЫЛЫМДАРДЫ ЗЕРТТЕУ КЕЗІНДЕГІ ГЕОФИЗИКАЛЫҚ МӘЛІМЕТТЕРДІ КЕШЕНДІ ИНТЕРПРЕТАЦИЯЛАУ ӘДІСТЕМЕСІ

Аннотация. Жаңа компьютерлік технологияларды кеңінен пайдалана отырып тура және кері тапсырмаларды шешу жолдары негізінде нақты гравиметриялық мәліметтерді түзету, қималардың тығыздықтарын есептеу, тіректі сейсмикалық қималарды қолдану арқылы мұнайлы газды Каспий маңы ойпатындағы терең жер қыртыстарын зерттеуде геофизикалық мәліметтерді кешенді интерпретациялау. Жекеленген аймақтық қималар бойынша ГСЗ және МОВ-ГСЗ әдістерімен рефрагмалық толқындарды годографтармен бақылаулар мен жанама орта және кіші масштабты карталар түріндегі гравибарлау материалдары терең жарылымды геологиялық-геофизикалық қималардың негізі болып табылады. Тығыздық және жылдамдық құрылымдарының физикалық моделін құру – аса тиімді болып табылады, демек вертикал мен латерал бойынша жоғарғы мантия мен жер қыртысының біртұтас емес екендігі туралы мәлімет алуға болады. Нақты зерттеу материалдары мен геологиялық мәліметтердің болуынан жер қыртысының жоғарғы горизонтары туралы нақты құрылымдар анықталды. Аумақтық сейсмикалық қималар арқылы алынған құрылымдық-жылдамдық қималары бойынша Солтүстік Каспий маңы ойпатындағы литосфералық қабықтың біртұтас емес құрылымын анықталды. Теріс және оң белгілері бар жылдамдық аномалиялар әртүрлі заттық құрамы мен құрылымы бар мантияның беткі қабаты мен жер қыртысының төменгі горизонт блоктарын сипаттайды. Терең құрылымдардың гравитациялық үлгілерінің көмегімен жер қыртысындағы таралу тығыздықтары мен жекеленген горизонт құрылымдары анықталды, сондай-ақ зерттеу аумағының, вертикалды, субвертикалды терең шекаралық блоктардың шекаралары белгіленді. Жер қыртысының тектоникалық дамуы мен жер қыртысының таужыныстарына сипат берілді. Ұсынылған кешенді сейсмогравиметриялық мәліметтерді интерпретациялау әдістері арқылы күрделі құрылымды геологиялық ортаның жылдамдықтары мен тығыздықтары туралы мәлімет алып, нақты геофизикалық ақпараттар бойынша қоршаған ортаның моделін құруға болады. Аумақтың тереңдік бойынша алынған моделін палеозойдағы палеогелдинамикалық қайта қалыпқа келтіру үшін тиімді түрде пайдалануға болады, өйткені осы әдістермен жер қыртысы мен жоғарғы мантияның қазіргі жаңа құрылымдық ерекшеліктерін анықтай аламыз.

Түйінді сөздер: сейсмикалық зерттеулер, гравиметрия, көлденең толқын жылдамдықтары, модельдеу, терең құрылымдар, Каспий маңы ойпаты, аймағы.

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МЕТОДИКА КОМПЛЕКСНОЙ ИНТЕРПРЕТАЦИИ ГЕОФИЗИЧЕСКИХ ДАННЫХ ПРИ ИЗУЧЕНИИ ГЛУБОКИХ ГОРИЗОНТОВ ЗЕМНОЙ КОРЫ СЕВЕРО-КАСПИЙСКОГО РЕГИОНА

Аннотация. Комплексная интерпретация геофизических данных при изучении глубоких горизонтов земной коры Прикаспийского нефтегазоносного района осуществлена на основе анализа волновых полей региональных сейсмических разрезов по опорным геотраверсам и результатам интерпретации гравитационных аномалий методами решения прямых и обратных задач с применением специализированных геоинформационных систем. Фактической основой построения глубинных геолого-геофизических разрезов явились материалы гравиразведки в виде сводных средне- и мелкомасштабных карт и наблюденные годографы рефрагированных волн методов ГСЗ и МОВ-ГСЗ по отдельным региональным профилям. Построение физических моделей – плотностной и структурно-скоростной – оказалось весьма эффективным и позволило выявить неоднородности строения земной коры и верхней мантии по вертикали и латерали. Наиболее достоверны построения для верхних горизонтов земной коры, поскольку они обеспечены большим количеством фактического материала, в том числе и геологического. Структурно-скоростные разрезы по региональным сейсмическим профилям, позволили установить неоднородное строение литосферы Северо-Каспийского региона. Аномалии скоростей отрицательного и положительного знаков характеризуют блоки нижних горизонтов земной коры и верхней мантии разного вещественного состава и строения. С помощью гравитационных моделей глубинных структур и распределения плотностей в земной коре выявлены вертикальные и субвертикальные границы глубинных блоков, дан прогноз вещественного состава глубинных структур, определены особенности их образования и тектонического развития. Предложенная методика комплексной интерпретации сейсмогравиметрических данных позволяет в условиях слабой изученности территорий, неполноты геофизической информации обеспечить построение достоверных плотностных и скоростных моделей сложнопостроенных геологических сред. Полученные модели глубинного строения региона можно эффективно использовать как для реставрации палеогеодинамических обстановок в палеозое, так и для выявления современных структурных особенностей земной коры и верхней мантии.

Ключевые слова: сейсмические исследования, гравиметрия, скорость продольных волн, плотность, моделирование, глубинное строение, Прикаспийский регион.

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