F.A.Kadirov et al. / ANAS Transactions, Earth Sciences 1 / 2023, 11-16; DOI: 10.33677/ggianas20230100089

ANAS Transactions **Earth Sciences** **1 / 2023**

http://www.journalesgia.com

BOUGUER GRAVITY DATA AND SATELLITE GRAVITY TRANSFORMATION INTEGRATION IN THE CASPIAN REGION: AN INTRODUCTION

Kadirov F.A.[1,2], Klokočník J.[3], Eppelbaum L.V.[4,5], Kostelecký J.[6,7], Bezděk A.[3]
[1]*Ministry of Science and Education of the Republic of Azerbaijan,*
Institute of Geology and Geophysics, Azerbaijan
119, H.Javid Ave. Baku, AZ1143: kadirovf@gmail.com
[2]*Ministry of Science and Education of the Republic of Azerbaijan,*
Institute of Oil and Gas, Azerbaijan
9, F.Amirov ave., Baku, AZ1000: kadirovf@gmail.com
[3]*Astronomical Institute, Academy of Sciences of the Czech Republic, Prague*
[4]*Dept. of Geophysics, Tel Aviv University, Israel*
Ramat Aviv 6997801, Tel Aviv
[5]*Azerbaijan State Oil and Industry University*
20 Azadlig Ave., Baku, AZ1010, Azerbaijan
[6]*Research Institute of Geodesy, Topography and Cartography, Zdiby, Czech Republic*
[7]*Faculty of Mining and Geology, VSB-TU Ostrava, Czech Republic*

Keywords: *Bouguer gravity map, satellite gravity measurements, gravity aspects, combed strike angles, dilatation, compression*

Summary. Earth's surface gravity measurements are essential (as close to the investigation targets) but insufficient. These measurements were carried out at different years, with various scales and accuracy and numerous white spots. The present epoch makes it possible to utilize various satellite gravity missions that have accomplished a great number of repetitions, the same grids, and the same accuracy. This paper considers satellite-derived data retracked to the Earth's surface and transformed by various mathematical apparatuses. These data can be derived from the global Earth's satellite data, mainly from the GRACE and GRACE-FO missions. The gravity gradient tensor $\mathbf{\Gamma}$ (the *Marussi tensor*) is a tensor of the second derivatives of the disturbing potential T of the gravity field model. This tensor was considered the centerpiece of traditional differential geodesy. It is analogous to the tidal deformation from geodesy and geophysics; one can imagine the direction of such a deformation due to "erosion" brought about solely by gravity. The strike angles usually show chaotic directions. We aim to detect where they are oriented dominantly in one prevailing direction (linearly or creating a halo around the object). Another applied gravitational parameter allows us to obtain the distribution of compressions and dilatations. The values may be used for detecting mainly subsurface structures: oil-gas fields, groundwater, and paleolakes. Integrating the conventional Bouguer gravity maps with satellite-derived gravity transformations will enable the generation of crucial physical-geodynamical and geological conclusions.

Introduction

The gravity field analysis is a comprehensive instrument for studying gravity anomalies of different orders (e.g., Kadirov, 2000; Kadirov et al., 2012; Klokočník et al., 2014, 2017, 2020; Eppelbaum et al., 2018; Eppelbaum, 2019). The studied regions of the Caspian Sea and surrounding areas display the mosaic distribution of the Earth's surface (water) observed Bouguer gravity anomalies (Figure 1), not all of which are explained geologically.

At present, the variable gravity data can be derived from the global Earth's satellite data, mainly from the GRACE and GRACE-FO missions. The combination of Earth's surface registered data with the non-conventional satellite-derived gravity field transformations is of great interest.

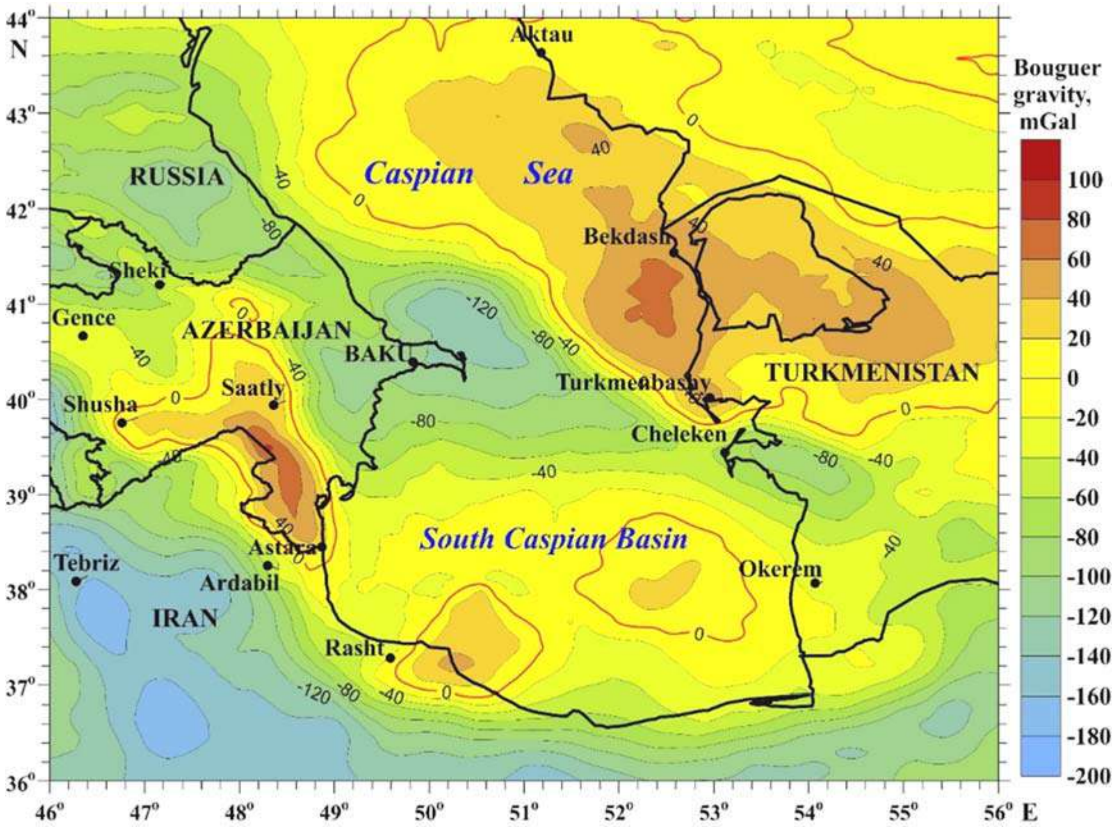

Fig. 1. Bouguer gravity map of the study region (after Kadirov (2000) and Gravity Map (1990))

The disturbing static global gravitational potential outside the masses of a celestial body in the spherical harmonic expansion is given by

$$T(r,\varphi,\lambda)=\frac{GM}{r}\sum_{l=2}^{\infty}\sum_{m=0}^{l}\left(\frac{R}{r}\right)^{l}\left(C'_{l,m}\cos m\lambda+\right. \\ \left.+\,S_{l,m}\sin m\lambda\right)\,P_{l,m}(\sin\varphi), \tag{1}$$

where *GM* is a product of the universal gravitational constant *G* and the mass *M* of the planet (also known from satellite analyses as the geocentric gravitational constant in the case of the Earth), *r* is the radial distance of an external point where *T* is computed, *R* is the radius of the planet (which can be approximated by the semi-major axis of a reference ellipsoid), $P_{l,m}$ *(sin φ)* are the Legendre associated functions, *l* and *m* are the degree and order of the spherical harmonic expansion, the coordinates (*φ*, *λ*) are the planetocentric latitude and longitude, $C'_{l,m}$ and $S_{l,m}$ are the *harmonic geopotential coefficients* (*Stokes parameters*), fully normalized, $C'_{l,m} = C_{l,m} - C^{el}_{l,m}$, where $C^{el}_{l,m}$ belongs to the reference ellipsoid. The word "**disturbing**" here means the difference between the actual body's total gravitational potential and the reference body's gravitational potential, i.e., the reference ellipsoid, usually taken as a rotational ellipsoid with some flattening on the poles due to the rotation of that body. All the gravity transformations of satellite-derived observations provide thorough information about the density anomaly due to the causative body, which is more complete than, for example, the information that the traditional gravity anomalies themselves could yield. The set of gravity aspects informs about location, shape, orientation, a tendency to a 2D or 3D pattern, and some stress tendencies and may also partly simulate "dynamic information" (Klokočník et al., 2017).

Applied Methods

The gravity gradient tensor **Γ** (the *Marussi tensor* or simply the **gravity tensor**) is a tensor of the second derivatives of the disturbing potential *T* of the gravity field model. The Marussi tensor was considered the centerpiece of traditional differential geodesy. The tensor **Γ** is given in the local north-oriented reference frame (*x*, *y*, *z*), where *z* has the geocentric radial direction, *x* points to the north, and *y* is directed to the west (Pedersen and Rasmussen, 1990):

$$\mathbf{\Gamma}=\begin{bmatrix}T_{xx} & T_{xy} & T_{xz}\\ T_{yx} & T_{yy} & T_{yz}\\ T_{zx} & T_{zy} & T_{zz}\end{bmatrix}=\begin{bmatrix}\frac{\partial^2 V}{\partial x^2} & \frac{\partial^2 V}{\partial x\partial y} & \frac{\partial^2 V}{\partial x\partial z}\\ \frac{\partial^2 V}{\partial y\partial x} & \frac{\partial^2 V}{\partial y^2} & \frac{\partial^2 V}{\partial y\partial z}\\ \frac{\partial^2 V}{\partial z\partial x} & \frac{\partial^2 V}{\partial z\partial y} & \frac{\partial^2 V}{\partial z^2}\end{bmatrix}. \tag{2}$$

The gradient tensor **Γ** contains information about subsurface strike (stress) directions. Pedersen and Rasmussen (1990) defined the *strike angle θ* (strike lineaments, strike direction) as follows:

$$\tan 2\theta_s = 2\frac{T_{xy}\left(T_{xx}+T_{yy}\right)+T_{xz}T_{yz}}{T_{xx}^2-T_{yy}^2+T_{xz}^2-T_{yz}^2} = 2\frac{-T_{xy}T_{zz}+T_{xz}T_{yz}}{T_{xz}^2-T_{yz}^2+T_{zz}\left(T_{xx}-T_{yy}\right)}, \qquad (3)$$

where θ is estimated within a multiple of $\pi/2$; and only one value represents the main direction of $\mathbf{\Gamma}$.

The strike angle may indicate a dominant 2D structure. If one were able to rotate with the structure in such a way that the elements of the first row and first column of $\mathbf{\Gamma}$ were identically equal to zero, then one would reach a "correct" direction of "stress fields" described by θ (Beiki and Pedersen, 2010).

Mathematically, θ is the main direction of $\mathbf{\Gamma}$. Geophysically, it is an important direction for the ground structures; it may indicate areas with a higher porosity or "stress directions" or both (Klokočník et al., 2020).

The strike angles usually show chaotic directions. Sometimes, they are oriented dominantly in one prevailing direction (linearly or creating a halo around the object); they are aligned, we say, "combed". The values may be used for detecting mainly subsurface structures: oil-gas fields, groundwater, paleolakes, or impact craters (e.g., Klokočník et al. 2020, and further references there).

The situation remains, however, not unambiguous when solely using gravity data. The parameter $\boldsymbol{\theta}$ probably relates to changes in porosity, for example, possibly revealing the porosity increase due to an impact pressure deformation. It is evident that we need additional information on the gravity aspects. This means geological or geophysical information, namely drilling data, analysis of seismic data, magnetic anomalies, thermal and other data.

Let us define the parameter of "virtual deformation" (Kalvoda et al., 2013). It is analogous to the tidal deformation from geodesy and geophysics; one can imagine the directions of such a deformation due to "erosion" brought about solely by gravity.

If there were a tidal potential, represented as in our case by the gravity potential T, then horizontal shifts (deformations) would exist due to this, and they could be expressed in the north-south direction (latitude direction) as

$$u_\Phi = l_S\,\frac{1}{g}\,\frac{\partial T}{\partial \varphi}, \qquad (4)$$

and in the east-west direction (longitudinal direction) as

$$u_\Lambda = l_S\,\frac{1}{g\cos\varphi}\,\frac{\partial T}{\partial \lambda}, \qquad (5)$$

where g is the gravity acceleration (9.81 $\mathrm{m\cdot s^{-2}}$), l_S is the elastic coefficient (called the Shida number) expressing the elastic properties of the Earth as a planet (generally $l_S = 0.08$), φ and λ are the geocentric latitude and longitude of the point P where we measure T; and the potential T is expressed in [$\mathrm{m^2\cdot s^{-2}}$].

Results and discussion

Here are presented only two examples from a wide variety of transformations: parameter **Q** (Figure 2), one of the variants of virtual deformations (Figure 3) and "combed" image accompanied by hydrocarbon deposit location (Figure 4). As clearly seen from Figure 1, from one side, and Figures 2, 3 and 4, from another side, despite a visible correlation between these figures, variety of noticeable anomalies wait for their careful physical-geological interpretation.

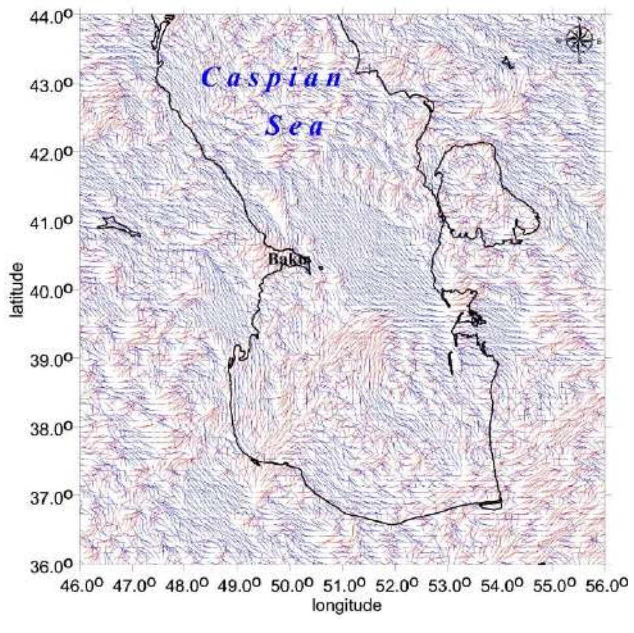

Fig. 2. Map of the strike angles (the main direction of the tensor Γ)

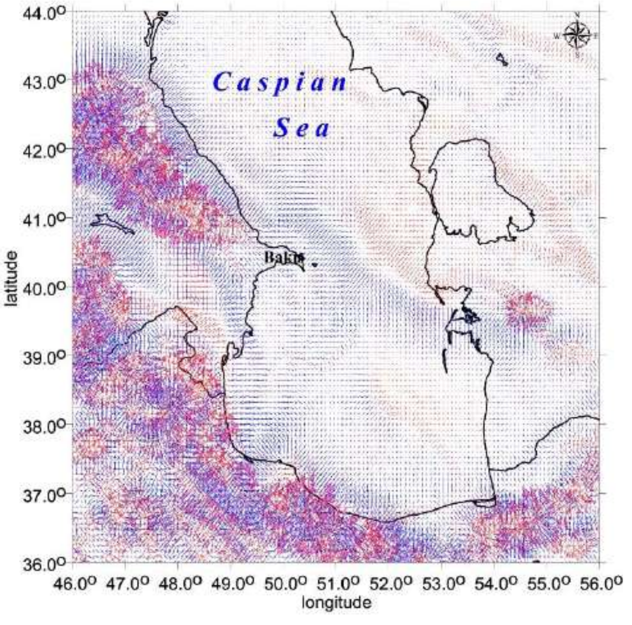

Fig. 3. Map of the virtual deformation parameter. Blue color reflects areas of compression, and red color – areas of dilation

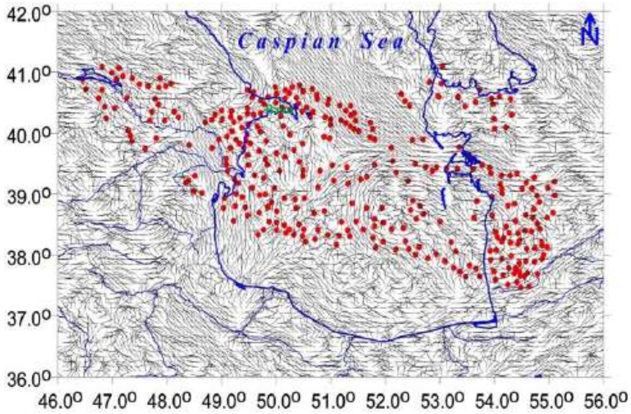

Fig. 4. The "combed" strike angles (black dashes) in the South Caspian Basin accompanied by the hydrocarbon deposit location (red dots) (last – after Alizadeh et al., 2017)

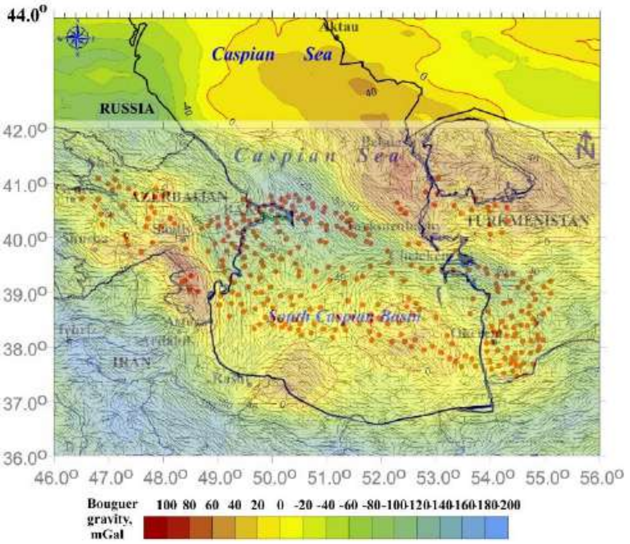

Fig. 5. Comparison of the Bouguer gravity map (Fig. 1) and the "combed" strike angles (Fig. 4)

The tectonic-geodynamic significance of Figures 2, 3, and 4 is obvious, but their further study demands an integrated geological-geophysical examination with attracting the available borehole data.

The comparison of the Bouguer gravity map (Figure 1) and the "combed" strike angles are displayed in Figure 5. Evidently, a careful analysis of the borehole columns and the attraction of other data are necessary.

Conclusions

Combining conventional gravity measurements with the calculation of advanced satellite-derived gravity transformations will enable us to obtain novel physical-tectonic characteristics, for example, locating subsurface inhomogeneities and detecting deep faults, zones of compression, and dilatation.

REFERENCES

Alizadeh A.A., Guliyev I.S., Kadirov F.A., Eppelbaum, L.V. Geosciences in Azerbaijan. Volume II: Economic Minerals and Applied Geophysics. Springer. Heidelberg – N.Y., 2017, 340 p.

Eppelbaum L.V. Geophysical Potential Fields: Geological and Environmental Applications. Elsevier. Amsterdam – N.Y., 2019, 476 p.

Eppelbaum L., Katz Yu., Klokočník J., Kosteletský J., Zheludev V., Ben-Avraham Z. (2018). Tectonic insights into the Arabian-African Region inferred from a comprehensive examination of Satellite Gravity Big Data. Global and Planetary Change, Vol.171, pp. 65-87.

Gravity map of the USSR. Scale 1:2500000, Ministry of Geology. Moscow, USSR, 1990.

Kadirov F.A. Gravity field and models of Azerbaijan's deep structure. Nafta-Press. Baku, 2000 (in Russian).

Kadirov F., Floyd M., Alizadeh A., Guliyev I., Reilinger R., Kuleli S., King R., Toksoz, M.N. Kinematics of the eastern Caucasus near Baku, Azerbaijan. Natural Hazards, Vol. 63, No. 2, 2012, pp. 997-1006.

Kalvoda J., Klokočník J., Kostelecký J., Bezděk A. Mass distribution of Earth landforms determined by aspects of the geopotential as computed from the global gravity field model EGM 2008. Acta Univ. Carolinae, Geographica XLVIII, 2, Prague, 2013, pp. 17-97.

Klokočník J., Kostelecký J., Bezděk A. Gravitational Atlas of Antarctica. Springer. Dordrecht – N.Y., 2017, 124 p.

Klokočník J., Kostelecký J., Cílek V., Bezděk A. Subglacial and underground structures detected from recent gravito-topography data. Cambridge Univ. Press. Cambridge, 2020.

Klokočník J., Kostelecký J., Eppelbaum L., Bezděk A. Gravity

ЛИТЕРАТУРА

Alizadeh A.A., Guliyev I.S., Kadirov F.A., Eppelbaum, L.V. Geosciences in Azerbaijan. Volume II: Economic Minerals and Applied Geophysics. Springer. Heidelberg – N.Y., 2017, 340 p.

Eppelbaum L.V. Geophysical Potential Fields: Geological and Environmental Applications. Elsevier. Amsterdam – N.Y., 2019, 476 p.

Eppelbaum L., Katz Yu., Klokočník J., Kosteletský J., Zheludev V., Ben-Avraham Z. (2018). Tectonic insights into the Arabian-African Region inferred from a comprehensive examination of Satellite Gravity Big Data. Global and Planetary Change, Vol.171, pp. 65-87.

Gravity map of the USSR. Scale 1:2500000, Ministry of Geology. Moscow, USSR, 1990.

Kadirov F., Floyd M., Alizadeh A., Guliyev I., Reilinger R., Kuleli S., King R., Toksoz, M.N. Kinematics of the eastern Caucasus near Baku, Azerbaijan. Natural Hazards, Vol. 63, No. 2, 2012, pp. 997-1006.

Kalvoda J., Klokočník J., Kostelecký J., Bezděk A. Mass distribution of Earth landforms determined by aspects of the geopotential as computed from the global gravity field model EGM 2008. Acta Univ. Carolinae, Geographica XLVIII, 2, Prague, 2013, pp. 17-97.

Klokočník J., Kostelecký J., Bezděk A. Gravitational Atlas of Antarctica. Springer. Dordrecht – N.Y., 2017, 124 p.

Klokočník J., Kostelecký J., Cílek V., Bezděk A. Subglacial and underground structures detected from recent gravito-topography data. Cambridge Univ. Press. Cambridge, 2020.

Klokočník J., Kostelecký J., Eppelbaum L., Bezděk A. Gravity disturbances, the Marussi tensor, invariants and other functions of the geopotential represented by EGM 2008. Journal disturbances, the Marussi tensor, invariants and other functions of the geopotential represented by EGM 2008. Journal of Earth Science Research, Vol. 2, No. 3, 2014, pp. 88-101.

Pedersen B.D., Rasmussen T.M. The gradient tensor of potential field anomalies: Some implications on data collection and data processing of maps. Geophysics, Vol. 55, No. 12, 1990, pp. 1558-1566.

of Earth Science Research, Vol. 2, No. 3, 2014, pp. 88-101.

Pedersen B.D., Rasmussen T.M. The gradient tensor of potential field anomalies: Some implications on data collection and data processing of maps. Geophysics, Vol. 55, No. 12, 1990, pp. 1558-1566.

Кадиров Ф.А. Гравитационное поле и модели глубокого строения Азербайджана. Нафта-Пресс. Баку, 2000.

КОМПЛЕКСИРОВАНИЕ ГРАВИМЕТРИЧЕСКИХ ДАННЫХ В РЕДУКЦИИ БУГЕ И ТРАНСФОРМАЦИЙ СПУТНИКОВЫХ ГРАВИМЕТРИЧЕСКИХ ДАННЫХ В КАСПИЙСКОМ РЕГИОНЕ: ВВЕДЕНИЕ

Кадиров Ф.А.[1,2], Клокочник Я.[3], Эппелбаум Л.В.[4,5], Костелески Я.[6,7], Бездек А.[3]
[1]Министерство науки и образования Азербайджанской Республики, Институт геологии и геофизики, Азербайджан
AZ1143, Баку, просп. Г.Джавида, 119: kadirovf@gmail.com
[2]Министерство науки и образования Азербайджанской Республики, Институт нефти и газа, Азербайджан
AZ1000, Баку, ул. Ф.Амирова, 9: kadirovf@gmail.com
[3]Астрономический Институт, Академия наук Чешской Республики, Прага
[4]Отдел геофизики, Тель-Авивский университет, Израиль
Рамат-Авив 6997801, Тель-Авив
[5]Азербайджанский государственный университет нефти и промышленности, Баку, Азербайджан
AZ1010, Баку, просп. Азадлыг, 20
[6]Научно-исследовательский институт геодезии, топографии и картографии, Здиби, Чехия
[7]Факультет горного дела и геологии, Остравский технический университет, Острава, Чехия

Резюме. Анализ гравитационного поля является одним из мощных методов изучения как региональных, так и локальных особенностей строения Земли. Гравитационные измерения на поверхности Земли необходимы (поскольку находятся ближе к объектам исследования), но недостаточны. Данные измерения проводились в различные годы, с разным масштабом и точностью и многочисленными «белыми пятнами» в тех областях, где невозможно было провести измерения по тем или иным причинам. Нынешняя эпоха позволяет использовать многократно повторенные спутниковые гравитационные измерения, наблюдаемые по одинаковой сети и с одинаковой точностью. В этой статье рассматриваются особенности спутниковых гравитационных данных, пересчитанных к поверхности Земли и трансформированных с использованием различных алгоритмов. В настоящее время эти данные могут быть получены из глобальных спутниковых данных, в основном из миссий GRACE и GRACE-FO. Тензор градиента гравитации Г (Марусси тензор) представляет собой тензор вторых производных возмущающего потенциала *T* модели гравитационного поля. Данный тензор считается центральным элементом традиционной дифференциальной геодезии, аналогичным приливной деформации в геодезии и геофизики. Это позволяет представить направления такой деформации за счет «эрозии», вызванной исключительно силой тяжести. Углы простирания обычно показывают хаотические направления. Нашей целью является определение тех площадей, где углы простирания ориентированы преимущественно в одном преобладающем направлении (линейно или создавая некий ореол вокруг объекта исследований). Другой применяемый гравитационный параметр позволяет получить распределение сжатий и растяжений. Полученные карты могут быть использованы для выявления погребенных структур: нефтегазовых месторождений, подземных вод и палеоозер. Комплексирование конвенциональных карт силы тяжести в редукции Буге с преобразованными спутниковыми гравитационными данными позволяет сделать выводы, имеющие существенные физико-геодинамические и геологические аспекты.

Ключевые слова*: гравитационная карта в редукции Буге, спутниковая гравиметрия, гравитационные параметры, сглаженные углы простираний, растяжение, сжатие*

XƏZƏR REGİONU QRAVİTASİYA SAHƏSİNİN BUQE REDUKSİYASININ VƏ PEYK QRAVİTASİYA MƏLUMATLARININ TRANSFORMASİYALARI İLƏ İNTEQRASİYASI: GİRİŞ

Qədirov F.Ə.[1,2], Klokoçnik Ya.[3], Eppelbaum L.V.[4,5], Kosteleski Ya.[6,7], Bezdek A.[3]
[1]Azərbaycan Respublikası Elm və Təhsil Nazirliyi, Geologiya və Geofizika Institutu, Azərbaycan
AZ1143, Bakı, H.Cavid prospekti, 119: kadirovf@gmail.com
[2]Azərbaycan Respublikası Elm və Təhsil Nazirliyi, Neft və Qaz Institutu, Azərbaycan
AZ1000, Bakı, F.Əmirov küçəsi, 9: kadirovf@gmail.com
[3]Astronomiya Institutu, Çexiya Respublikası Elmlər Akademiyası, Praqa
[4]Geofizika şöbəsi, Tel-Əviv Universiteti, Israil
Ramat-Əviv 6997801, Tel-Əviv
[5]Azərbaycan Dövlət Neft və Sənaye Universiteti, Bakı, Azərbaycan
AZ1010, Bakı, Azadlıq prospekti, 20
[6]Elmi-Tədqiqat Geodeziya, Topoqrafiya və Kartoqrafiya Institutu, Zdibi, Çexiya
[7]Dağ işi və geologiya fakulteti, Ostrava Texniki Universiteti, Çexiya, Ostrava

Xülasə. Qravitasiya sahəsinin təhlili Yerin strukturunun həm regional, həm də lokal xüsusiyyətlərini öyrənmək üçün güclü üsullardan biridir. Yer səthində qravitasiya ölçmələri zəruri olsada (çünki onlar öyrənilən obyektlərə daha yaxındır) kifayət deyil. Bu ölçmələr müxtəlif illərdə müxtəlif miqyasda və dəqiqliklə aparılıb, bu və ya digər səbəbdən ölçmə aparılması mümkün olmayan çoxsaylı yerlər (“ağ ləkələr”) mövcuddur. Hazırkı dövr eyni şəbəkə üzərində və eyni dəqiqliklə müşahidə edilən dəfələrlə təkrarlanan peyk qravitasiya ölçmələrindən istifadə etməyə imkan verir. Bu məqalədə müxtəlif alqoritmlər istifadə edilərək Yer səthinə hesablanmış peyk qravitasiya məlumatlarının xüsusiyyətləri müzakirə edilir. Hazırda bu məlumatlar əsasən GRACE və GRACE-FO qlobal peyk məlumatlarından, əldə edilə bilər. Qravitasiya qradiyenti tensoru Γ (Maroussi tensoru) qravitasiya sahəsi modelinin həyəcanlaşmış T potensialının ikinci törəmələrinin tenzorudur. Bu tensor geodeziya və geofizikada Yerin qabaran deformasiyasına bənzər ənənəvi diferensial geodeziyanın mərkəzi elementi hesab olunur. Bu, yalnız qravitasiya qüvvəsinin yaratdığı "eroziya" səbəbindən belə deformasiyanın istiqamətlərini təmsil etməyə imkan verir. Uzanım bucaqları adətən xaotik istiqamətləri göstərir. Məqsədimiz uzanım bucaqlarının əsasən bir üstünlük təşkil edən istiqamətə yönəldildiyi sahələri müəyyən etməkdir (xətti və ya tədqiqat obyekti ətrafında bir növ areol yaratmaqla). Digər tətbiq olunan qravitasiya parametri sıxılmaların və gərginliklərin paylanmasını əldə etməyə imkan verir. Alınan xəritələr kömülmüş strukturları (neft və qaz yataqları, yeraltı sular və paleolaklar) müəyyən etmək üçün istifadə edilə bilər. Buqe reduksiyasında məlum qravitasiya xəritələrinin çevrilmiş peyk qravitasiya məlumatları ilə inteqrasiyası əhəmiyyətli fiziki, geodinamik və geoloji aspektləri olan nəticələr çıxarmağa imkan verir.

***Açar sözlər**: Buqe qravitasiya xəritəsi, peyk qravimetriyası, qravitasiya parametrləri, uzanmanın hamarlanmış bucaqları, genişlənmə, sıxılma*