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THE THREE-DIMENSIONAL GEOELECTRIC MODEL OF EARTH CRUST AND UPPER MANTLE OF THE DOBRUDGA REGION

Purpose. The purpose of researches is to build a three-dimensional geoelectric model of the crust and upper mantle and to answer some questions of the deep structure and geodynamics of the North Dobrudga and PeriDobrudga depression. **Methodology.** The methodology includes a detailed analysis of the deep structure of the region based on the results of 3D modeling of electromagnetic experimental data and to search for the interrelation between conductivity anomalies in the Earth's crust and upper mantle and foci of seismic events. **Results.** Anomalies of high electric conductivity from the surface of the Earth crust to the upper mantle are identified. Stretched for hundreds of kilometers conductors are associated with deep conductive fractures of different fractures: Frunze, Saratsky, Bolgrad, Cahul-Izmail, Chadyrlungsk and others. A highly conductive layer is identified on the southern side of PeriDobrudga depression which lies at the depth corresponding to the lower crust and the top part of upper mantle. North side of PeriDobrudga depression is characterized by the distribution of electrical conductivity in the upper mantle which is the same as that of EEP, while presence of conductive structure at the depths of 110 to 160 km differs the southern slope from the northern one. Earthquake sources as well as anomalies of high electric conductivity are mainly correlated with active deep tectonic fractures and juncture zones of geological structures such as different age zones of Precambrian EEP and Cimmerian Scythian plate on the territory of PeriDobrudga depression and North Dobrudga. **Originality.** Three-dimensional deep geoelectric model built on experimental results of modern MTS and MVP data reflects inhomogeneous distribution of electric conductivity in the depth on the territory of PeriDobrudga depression and North Dobrudga. **Practical significance.** The results will make it possible to estimate more reliably the peculiarities of seismic hazard for the Dobrudga region of Ukraine and certain seismically active zones and structures.

Key words: 3D-geoelectric model; conductivity anomalies; seismicity; Dobrudga.

Introduction

One of the striking manifestations of geodynamic processes of the Earth is seismicity. The works of the last decade on the seismicity are increasingly linked to issues of degassing of the Earth and, as a consequence, to the manifestation of the deep and ultradeep fluid processes in the crust and mantle of the Earth. The studied region presented, as well as all northern branch of the Eurasian belt – Dobrudga-Crimean-Caucasian, is accompanied by electrical anomalies in the crust and upper mantle [Kulik, 2009] and influences on seismicity of territory of Ukraine. Electrical resistivity is a sensitive indicator of any inner-melting or fluids processes under natural conditions which present deep in the Earth.

Tectonically the studied region belongs to the western part of the Black Sea depression [Chekunov et al, 1976], which is related to the junction of the ancient East European Platform (EEP) and a young Scythian plate (see Fig. 1). Within its boundaries there are three main zones: the North side, located on the ancient Precambrian foundation, the Southern side – on a young folded-metamorphosed Hercynian-Cimmerian foundation of the Scythian plate and the axial part of the grabens at the junction zone of platform of different ages. EEP Precambrian foundation in the axial part of the Black Sea depression connects with the pre-Black Sea suture graben, which is a deep sublatitudinally streched depression. Formation of the suture zone began in the Triassic – Jurassic period. It is a layer of Meso-Cenozoic sediments with a thickness of up to 8000 m. Suture zone includes PeriDobrudga Paleozoic (Moldovan Graben) and the North-Crimean depressions: Krylov, Odessa (Karkinitsky), Sivash. It is well known that tectonic boundaries and foundation boundaries of EEP do not coincide with each other [Hain, 2001].

One of the components of the western part of the axial zone – PeriDobrudga depression – is a complex graben-like structure made of platformal Paleozoic and Triassic-Jurassic sediments. It connects to the folded structures of Dobrudga along a series of large northwest stretching fractures.

The distribution of electrical conductivity in the depths of the North Dobrudga and PeriDobrudga depression

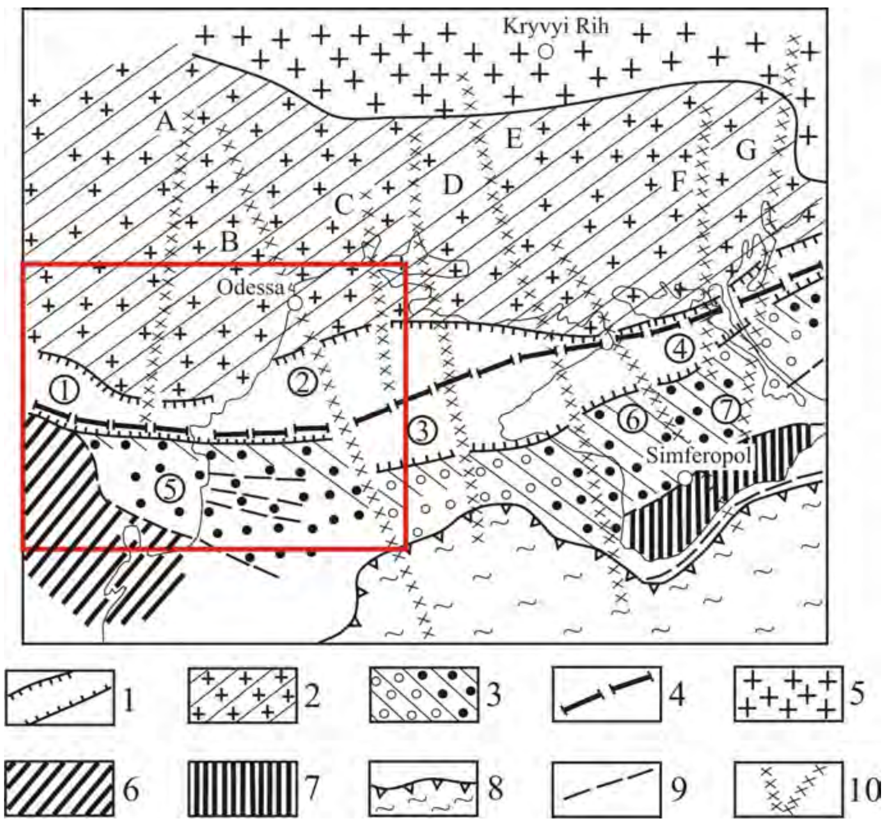
In experimental magneto-variation studies this anomalous region in bay similar geomagnetic variations was first discovered by the authors [Rokityansky et al, 1979], and further confirmed by magnetotelluric studies in 0,1-2000 s range along geotraverse Kealia – Krivoy Rog – Kharkov [Ingerov et al, 1988]. According to the analysis of transverse MTS curves in the neighborhood of PeriDobrudga depression it was suggested an existence of a conductive layer in the mantle at a depth of 80 km, with a total conductivity of 1500 S stretching in the longitudinal direction as an extension of the Carpathian crustal conductive anomaly in the south. In [Rokityansky et al, 1979] it was also suggested an existence of the so-called Black Sea branch of the Carpathian conductivity anomaly.

The result of the two-dimensional simulation of the profile Laz – Byrlad [Kulik et al, 1995] showed that the conductive structure of the Volcanic ridge serves as the southern end of intracrustal Carpathian conductivity anomaly related to the Vygorlat-Gutinsk volcanic ridge. This conclusion is confirmed by experimental magneto-variation observations [Pinna et al, 1982].

Geoelectric study of the Southern Carpathians found that under the structure of the Southern Carpathians in the earth's crust there is an isolated elongated region of high electrical conductivity [Stănică et al, 1999]. Carpathian arc (with the Carpathian conductivity anomaly) separates the entire system from the North Dobrudga (with PeriDobrudga conductivity anomaly), in particular, Petsenega – Kamenka faults zone.

Deep magneto-telluric sounding (MTS) and magneto-variation profiling (MVP) in a wide range of periods of geomagnetic variations field were carried out in the south-western part of Ukraine on PeriDobrudga depression [Burakhovich et al, 1995]. Analysis of a series of 2D models and their comparison with the observed values of apparent resistivity and magneto-variation induced fields points to the existence in the South (as opposed to the North) of "asthenosphere" – a conductive layer in the range of 110-160 km with a total longitudinal conductivity (S) of 700 Sm and two objects of high electrical conductivity at a depth of 10-20 km (S=200 Sm) and 40–80 km (S=1000 Sm).

Using MVP data a quasi-3D thin sheet models of Carpathian region [Burakhovich, 2004] were built, where a junction region of Scythian, Moesian plates and Dobrudga is represented as a separate object with S = 5000 Sm at a depth of 10 km. One can suggest that there several main anomalous bodies of high electrical conductivity exist possibly not galvanically connected to each other: Carpathian conductivity anomaly [Zhdanov et al, 1986] related to the flysch Carpathians and the Pennine belt, the anomaly of Pre-Carpathian depression of Eastern Carpathians, the anomaly of the Southern Carpathians and Dobrudga conductivity anomaly. It is absolutely obvious that in the studied region there is no universal and homogeneous asthenosphere.



1 – the axial part of the grabens at the junction zone of platform of different ages; 2 – the North side, located on the ancient Precambrian foundation; 3 – the Southern side, located on a young Hercynian-Cimmerian foundation (black and light of circles – raised and lowered with respect to areas the foundation (numbers in circles): Graben: 1 – Moldovan, 2 – Krylov, 3 – Odessa (Karkinitsky), 4 – Sivash; the structure of the Scythian plate: 5 – Kealia zone, 6 – Simferopol-Yevpatoriyskoe raising, 7 – Novotsaritsynsky ledge); 4 – the boundary of the ancient East European Platform and a young Scythian plate; 5 – the Precambrian region of the Ukrainian Shield. Exits to the surface of the folded structures: 6 – Dobrudga; 7 – mountain Crimea; 8 – the Black Sea depression and its contour; 9 – young the faults; 10 – ancient deep the faults: A – Frunze, B – Odessa, C – Ochakov, D – Kirovograd, E – Krivoy Rog, F – Konksky, G – Orehovo-Pavlograd

Fig. 1. Area of research and tectonical units the Black Sea depression according to [Chekunov et al, 1976]

Purpose

The purpose of researches is to build a three-dimensional geoelectric model of the crust and upper mantle and to answer some questions of the deep structure and geodynamics of the North Dobrogea and PeriDobrudga depression.

Methodology

The methodology includes a detailed analysis of the deep structure of the region based on the results of experimental 3D modeling of electromagnetic data and to search for the interrelation between conductivity anomalies in the Earth's crust and upper mantle and foci of seismic events.

Results

Building of a 3D geoelectric model

Currently, the density of observations of natural electromagnetic field of an outer source at low frequencies allows us to build a three-dimensional geoelectric model of the crust and upper mantle and to answer some questions of the deep structure and geodynamics of the North Dobrudga and PeriDobrudga depression.

For calculations we use the software package of three-dimensional simulation of low-frequency electromagnetic fields, which are used in the methods of MTS and MVP – Mtd3fwd [Mackie et al, 1993, 1994]. The 3D modelling algorithm uses the integral form of Maxwell's equations to derive a finite difference approximation for the magnetic field that is second order.

A model is based on the analysis of parameters of MVP and MTS in the range of periods of magnetotelluric field of up to 4000 s [Rokityansky et al, 1979, Ingerov et al, 1988, Burakhovich et al, 1995, Burakhovich et al, 2011] (see Fig. 2).

The important element of the technique of the 3D modeling is the "normal" values of the electrical resistance (ρ_n) of the 1D horizontally-layered section of the earth's crust and upper mantle; it is the background of the three-dimensional geoelectric model. For the Precambrian region of the Ukrainian Shield (USh), it is accepted as:

Depth of the range, km	ρ_n, Ohm·m	Depth of the range, km	ρ_n, Ohm·m
0–160	2000	400–500	20
160–200	600	500–600	10
200–250	250	600–760	5
250–320	100	760–960	1
320–400	50	> 960	0.1

Hercynian-Cimmerian regions are characterized by the other values, that include "asthenosphere" – a layer of high electrical conductivity in upper mantle:

Depth of the range, km	ρ_n, Ohm·m	Depth of the range, km	ρ_n, Ohm·m
0–110	2000	400–500	20
110–160	40	500–600	10
160–200	600	600–760	5
200–250	250	760–960	1
250–320	100	> 960	0.1
320–400	50		

The electromagnetic parameters are significantly affected by the inhomogeneous distribution of the electrical conductivity of the subsurface conductive layer. Its total conductivity mainly corresponds to the thickness of the sedimentary deposits and correlates with the main structural geological units. North Dobrudga is characterized by relatively low values (but abrupt changes) of the total longitudinal conductivity of up to 200 Sm (see Fig. 2). In PeriDobrudga depression where the crystal base is located at a depth of about 9 km, S does not exceed 1000 Sm. On the southern slope of USh value of S reaches 1000 Sm, while on the Moldavian plate - about 100 Sm. In the Black Sea region S of the near-surface conductive layer is set in the model to be between 1000 and 2000 Sm. Distribution of electrical resistivity of the layers and their thickness in 3D model have been taken conditionally and are based on the data value of the total longitudinal conductivity of the sediments and the depths to the consolidated basement.

A great number of models with various spatial parameters of anomalous structures as well as values of electrical resistivity in the Earth's crust and the mantle were calculated. The final version of the distribution of the electrical resistivity in the depths of PeriDobrudga depression and Dobrudga is shown in Fig. 3.

Comparison of the observed and calculated induction parameters is shown only for the period of geomagnetic variations of 400 s, and the same for the MTS curves, located in different parts of the map, is shown on Fig. 2.

A three-dimensional geoelectric model

Vertical conductors from the surface to a depth of 10 km form a network of galvanically interconnected, generally elongated structures of different spatial orientations (a width of 5 to 15 km), which corresponds to the fault zones. A turn in the induction parameters space and their values indicate that the most noticeable near-surface conductivity anomalies may be related to Chadyrlung fracture, especial to the region of its intersection with Frunze, Saratsky faults and places of abrupt changes in its direction (see Fig. 2, 3).

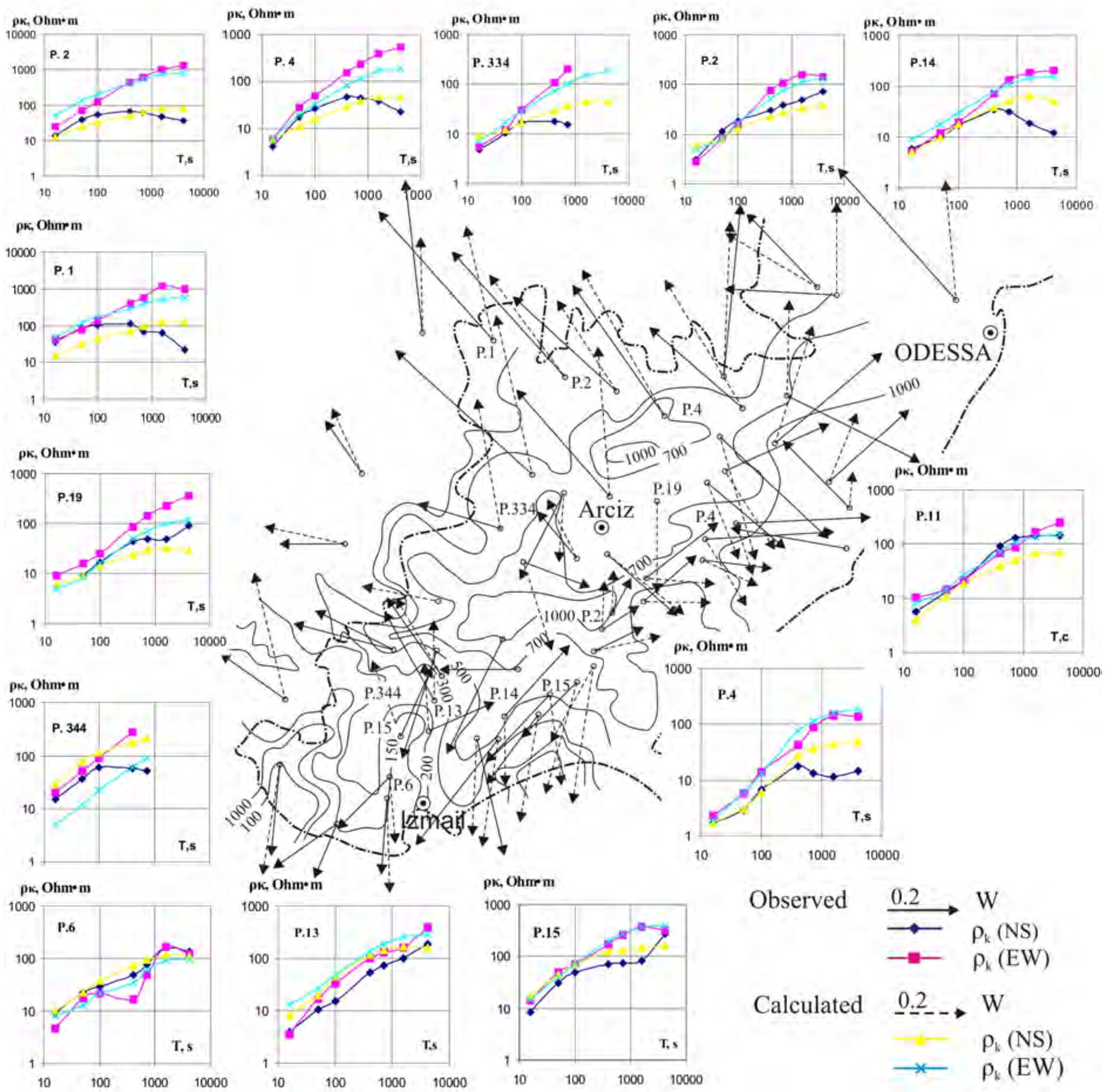
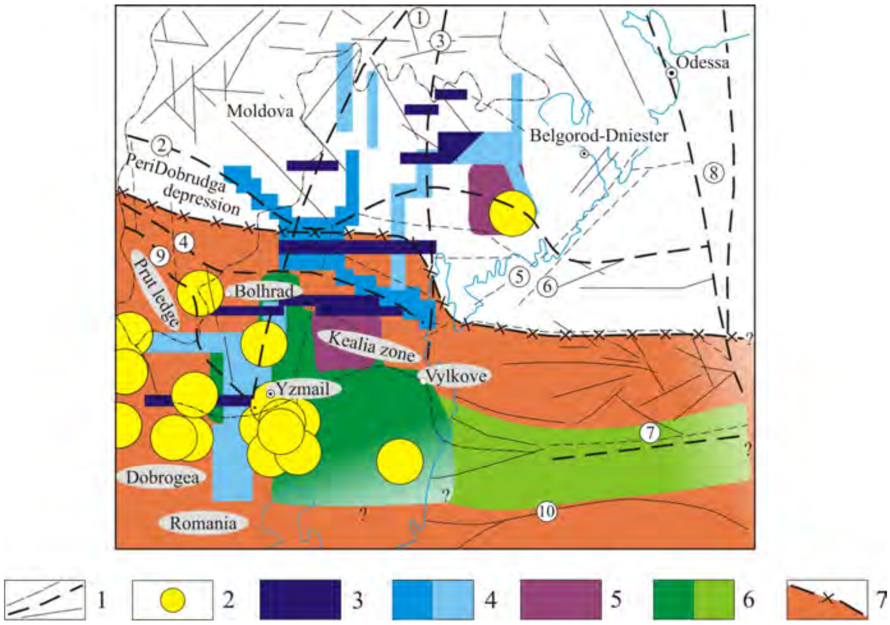


Fig. 2. Scheme of study methods MTS and MVP according to [Rokityansky et al, 1979, Ingerov et al, 1988, Burakhovich et al, 1995, Burakhovich et al, 2011]**.** Comparison of observed and calculated curves MTS and induction parameters for the period geomagnetic variations 400 s for the three-dimensional model presented in Fig. 3

The part of Bolgrad fracture which lies between Frunze and Saratsk fractures can be attributed to the same zones. In addition, the conductive zone (over 100 km long and 10 km wide), which changes its direction from sub-latitudinal to sub-longitudinal, is related to the junction region of Cahul-Izmailov margin suture separating Prut ledge and PeriDobrudga depression from Frunze fault. At the very top of the geoelectric cross-section at a depth of 1 km a series sub-latitudinal conductors (width from 5 to 10 km, length from 20 to 65 km) is identified. Most elongated conductors are concentrated in the axial part of PeriDobrudga depression.

In the Earth's crust and at the top of upper mantle (from 10 to 60 km) the main conductive structure with a complex configuration is geographically related to the block that is confined between Frunze and Cahul-Izmailov (west), Saratsk (east) and Bolgrad (north) fractures on the southern slope of PeriDobrudga depression. The southern boundary is not identified. It can be assumed that it consists of two interconnected parts: top part – vertical, with small spatial dimensions, of nearly isometric shape with a diameter of up to 20 km at a depth of 10 to 40 km, and lower part – a layer with spatial dimensions from 15 to 65 km in sub-latitudinal direction and more than 90 km in sub-longitudinal direction at a depth of 40 to 60 km.



1 – deep fault zones of different rank (numbers in circles): 1 – Frunze, 2 – Chadyrlunhskyy 3 – Saratsky, 4 – Bolgradsky 5 – Alibeyskyy, 6 – Black Sea, 7 – Sulina, 8 – Odessa 9 – Kahulsko-Izmayilivska; 2 – epicenters of earthquakes according to [Kutas et al, 2005]; geoelectrical parameters of conductivity anomalies: 3 – the depth of the roof and the base (h) from the surface to 1 km, ρ=2 Ohm·m; 4 – h=1-10 km, ρ =2 Ohm·m (a) and 10 Ohm·m (b); 5 – h=10-40 km, ρ=10 Ohm·m; 6 – h=40-60 km, ρ=10 Ohm·m (a), h=20-100 km, ρ=25 Ohm·m (b); 7 – h=110-160 km, ρ=70 Ohm·m

Fig. 3. The spatial location of the anomalies of high conductivity of three-dimensional geoelectric model PeriDobrudga depression and Dobrudga

Yet another almost isometric region (15 x 25 km) of high conductivity at a depth of 10 to 40 km can be identified in the north and is related to flexure of Chadyrlung fault.

The northern boundary of the conducting layer in the upper mantle at a depth of 110 to 160 km stretches in sub-latitudinal direction and is geographically located between Chadyrlung and Bolgrad faults. Along Saratsk fault the boundary shifts by 30 km to the south, where it probably extends further in sub-latitudinal direction in the Black Sea basin.

Island Zmeinyy, and also Zmiinoostrivne and Vilkivske of raising on depths a 20-100 km in a cut show up as an electro conductive structure, which is expressed a sub-latitudinal conductor that occupies intermediate position between faults of Pechenga-Kamena on a south and Kiliyskim on the north.

In this way the territory of North Dobrudga and PeriDobrudga depression, as well as the whole south-western margin of the EEP, is rich in anomalous objects of high electrical conductivity in the Earth's crust, and the distribution of electrical conductivity in the upper mantle reflects the location of the junction between the ancient EEP and young Scythian plate.

Manifestation of seismicity in the territory of Northern Dobrudga and PeriDobrudga depression

According to many seismologists [Kutas et al, 2005, Drumea et al, 1964, Pustovitenko et al, 2006, Nikonov and Nikonova, 1990] the territory of North Dobrudga and PeriDobrudga depression is seismically poorly studied. Throughout historic times several earthquakes with a magnitude of M=3.5-7.0 with intensity of >5 points in the epicenter [Nikonov and Nikonova, 1990] are known. According to various sources, the intensity of the shocks reaches 6 [Pustovitenko et al, 2006] and 7-8 points [Drumea et al, 1964]. Earthquake foci are located at depths ranging from 0 to 35 km or more. According to [Kutas et al, 2005] the most earthquake-prone areas are (see Fig. 3) intersection of the boundary suture that follows PeriDobrudga depression from the north (Chadyrlungsk) and south (Cahul, Ismail) with a regional mantle sub-longitudinal faults – Frunze and Saratsk. In addition, a seismically active zone is Chadyrlungsk boundary suture (Artsyz part), fragmented by breaking of fractures of a lower rank – Alibeysk and the Black Sea.

Earthquakes epicenters in North Dobrudga (Tulcea, Izmail, Reni, Kealia) are concentrated on the border of a shallow (1-10 km) high conductivity anomaly (ρ=10 Ohm·m) which coincides geographically with the location of Frunze fault and its intersection with Cahul-Izmail suture. Foci of these seismic events are located above the full-scale anomaly of high conductivity at a depth of 40 to 60 km, ρ=10 Ohm·m.

Epicenters of earthquakes on the northern slope of PeriDobrudga depression also coincide with the location of the anomaly of high electrical conductivity of complex configuration at the depth range between 1 and 40 km, ρ=2-10 Ohm·m (see Fig. 3).

Thus, earthquakes occur on both sides of the boundary of anomalous distribution in the upper mantle of the junction of the ancient EEP and young Scythian plate. However, the majority of them are observed in the region of concentration of conductivity anomalies at different depths from 1 to 40 km.

PeriDobrudga depression belong to the border zone of the mantle under the EEP, distinguished by the changes of zero isoline of velocity discrepancies with the depth within the limits of the upper mantle and its transition zone according to the data of 3-D P – velocity model [Tsvetkova and Bugaenko, 2012, Bugaenko et al, 2008]. Mantle boundary zone corresponds to a system of inclined layers. Special features of mantle velocity structure under PeriDobrudga and North-Crimean depressions and its surroundings made possible to partition mantle prerequisites of seismicity of the area under consideration related to manifestation of mantle plume in the lower and medium mantle. The spatial location of the electrical conductivity anomalies corresponds to the manifestation of sub-vertical mantle columns in the range of 28-30^0 E x 45-46^0 N.

Originality

Three-dimensional deep geoelectric model built on experimental results of modern MTS and MVP data reflects inhomogeneous distribution of electric conductivity in the depth on the territory of Peri-Dobrudga depression and North Dobrudga.

Practical significance

The results will make it possible to estimate more reliably the peculiarities of seismic hazard for the Dobrudga region of Ukraine and concrete seismically active zones and structures.

Conclusions

Anomalies of high electric conductivity from the surface of the Earth crust to the upper mantle are identified. Stretched for hundreds of kilometers conductors are associated with deep conductive fractures of different ranks and with their intersections: Frunze, Saratsky, Bolgrad, Cahul-Izmail, Chadyrlungsk fractures and others. A highly conductive layer is identified on the southern side of Peridobrudga depression and lies at the depth corresponding to the lower crust and the top part of upper mantle. North side of Peridobrudga depression is characterized by the distribution of electrical conductivity in the upper mantle which is the same as that of EEP, while presence of conductive structure at the depths of 110 to 160 km differs the southern slope from the northern slope.

Without a doubt, there is a relationship between seismicity and geoelectric parameters that reflect the current state of the Earth's interior. The origin of high electric conductivity anomalies may be the result of geodynamic processes on the boundaries of regions characterized by various manifestations of these processes.

Earthquake sources as well as anomalies of high electric conductivity are mainly correlated with active deep tectonic fractures and juncture zones of geological structures such as different age zones of Precambrian EEP and Cimmerian Scythian plate on the territory of PeriDobrudga depression and North Dobrudga.

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ТРИВИМІРНА ГЕОЕЛЕКТРИЧНА МОДЕЛЬ ЗЕМНОЇ КОРИ ТА ВЕРХНЬОЇ МАНТІЇ ДОБРУЗЬКОГО РЕГІОНУ

Мета. Метою досліджень є створення тривимірної геоелектричної моделі земної кори та верхньої мантії та отримання відповідей на деякі питання глибинної будови і геодинаміки Північної Добруджі та Перед-Добрузького прогину. **Методика.** Методика включає в себе докладний аналіз глибинної будови регіону на основі результатів моделювання 3D експериментальних електромагнітних даних і пошуку взаємозв'язків між аномаліями електропровідності в земній корі і верхній мантії та вогнищами сейсмічних подій. **Результати.** Виявлено аномалії високої електропровідності на глибинах від поверхні до вехньої мантії. Витягнуті на сотні кілометрів аномалії високої електропровідності приурочені до глибинних розломів різного рангу та їх перетинів: Фрунзенського, Саратського, Болградського, Кагульско-Ізмаїльського, Чадирлунгського та інших. Високопровідний шар складної конфігурації виділяється на Південному борті Перед-Добрузького прогину та залягає на глибинах, які відповідають нижній корі та верхам верхньої мантії. Північний борт Перед-Добрузького прогину характеризується розподілом електропровідності у верхній мантії таким же, як у надрах СЄП, в той час як Південний відрізняється від Північного наявністю високопровідної структури на глибинах від 110 до 160 км. Вогнища землетрусу, як і аномалії високої електропровідності, в основному, корелюють з активними глибинними тектонічними розломами та зонами зчленування геологічних структур, такими, якими є різновікові докембрійська СЄП та кіммерійська Скіфська плита на території Добрузького регіону. **Наукова новизна.** Тривимірна геоелектрична модель, побудована за сучасними експериментальними результатами МТЗ та МВП, відображає неоднорідний розподіл електричної провідності в глибині на території Перед-Добрузького прогину та Північної Добруджі. **Практична значущість.** Результати досліджень дадуть можливість більш надійно оцінювати особливості сейсмічної небезпеки для Добрузького регіону України та конкретних сейсмоактивних зон і структур.

Ключові слова: 3D геоелектричні моделі; аномалії електропровідності; сейсмічність; Добруджа.

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ТРЕХМЕРНАЯ ГЕОЭЛЕКТРИЧЕСКАЯ МОДЕЛЬ ЗЕМНОЙ КОРЫ И ВЕРХНЕЙ МАНТИИ ДОБРУДЖСКОГО РЕГИОНА

Цель. Целью исследований является создание трехмерной геоэлектрической модели земной коры и верхней мантии и получение ответов на некоторые вопросы глубинного строения и геодинамики Северной Добруджи и Преддобруджского прогиба. **Методология.** Методология включает в себя подробный анализ глубинного строения региона на основе результатов 3D моделирования электромагнитных экспериментальных данных и поиск взаимосвязи между аномалиями высокой электропроводности в земной коре и верхней мантии и очагами сейсмических событий. **Результаты.** Выделены аномалии высокой электропроводности от поверхности земной коры и до верхней мантии. Вытянутые на сотни километров проводники приурочены к глубинным проводящим разломам различного ранга и их пересечениям: Фрунзенскому, Саратскому, Болградскому, Кагульско-Измаильскому, Чадырлунгскому и другим. Высокопроводящий слой выделяется на Южном борту Преддобруджского прогиба и залегает на глубинах, соответствующих нижней коре и верхам верхней мантии. Северный борт Преддобруджского прогиба характеризуется распределением электропроводности в верхней мантии таким же как и ВЕП, в то время как Южный склон отличается от Северного проводящей структурой на глубинах от 110 до 160 км. Очаги землетрясений, как и аномалии высокой электропроводности, в основном, коррелируют с активными глубинными тектоническими разломами и зонами сочленения геологических структур, какими и являются разновозрастные докембрийская ВЕП и киммерийская Скифская плита на территории Добруджского региона. **Научная новизна.** Трехмерная геоэлектрическая модель, построенная по результатам современных экспериментальных данных МТЗ и МВП, отражает неоднородное распределение электрической проводимости в глубине на территории Преддобруджского прогиба и Северной Добруджи. **Практическая значимость.** Результаты исследований дадут возможность более надежно оценить особенности сейсмической опасности для Карпатского региона Украины и конкретных сейсмоактивных зон и структур.

Ключевые слова: 3D геоэлектрическая модель; аномалии электропроводности; сейсмичность; Добруджа.

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