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Donbas conductivity anomaly in the Karpinsky Swell

I.I. Rokityansky, A.V. Tereshyn, 2022

S.I. Subbotin Institute of Geophysics of the National Academy
of Science of Ukraine, Kyiv, Ukraine
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Donbas Foldbelt (DF) and Karpinsky Swell (KS) are contiguous parts of a system of elongated sedimentary basins forming lineament from Poland through Pripyat Trough in Belarus, the Dnieper-Donets Basin (DDB) and DF in Ukraine, KS in Russia, across the Caspian Sea, through Mangyshlak in Turanian plate in Asia. In DF, the Mesozoic-Cenozoic sediments were raised, and subsequent erosion exposed the Carboniferous coal-bearing strata. In contrast to DF, the Paleozoic rocks in KS are covered by 1—3 km thick sediments of Mesozoic-Cenozoic age; productive structures of the earlier age cannot be confidently studied in KS by geological methods. So, geophysical methods are the promising approach for the KS deep structure studies.

This work is devoted to electromagnetic (EM) studies of the electrical conductivity of rocks by the methods of magnetic variation profiling (MVP) and magnetotelluric sounding (MTS). Previously [Rokityansky, Tereshyn, 2022], we described the results of the EM research on DF in detail. MVP reveals the intense Donbas electrical Conductivity Anomaly (DCA) running along the main anticline of the folded Donbas. DCA parameters: maximum possible depth of the anomalous currents center h=18±2 km. Frequency response maximum T_0≈3600 s yields the total longitudinal conductance G=(8±2)·10^8 S·m. 70 MTS at periods 0.1—3000 s yield two conductive stripes, with the upper edge varying from 0.3 to 5 km. The stripes are parallel to the DCA axis and are considered as part of DCA. A very large value of G suggests that the anomalous body extends to some considerable depth. The DCA axis spatially coincides with an intense (up to 90 mW/m^2) deep heat flow anomaly. Thus, the nature of the DCA lower part can be a partial melting. Theoretical estimates show that intense anomalous fields of geomagnetic variations arise over highly elongated conductors. Therefore, there is reason to expect that the anomaly continues eastward. We found two MTS profiles crossing the Karpinsky swell, and under both profiles strong conductivity anomalies are clearly seen. We re-interpreted original data and presented parameters of all 3 anomalies in an identical style. The main conclusion: the anomaly parameters on the three profiles are approximately the same, and one can assume with a high probability the existence of a single anomaly of electrical conductivity in the Donbas and Karpinsky Swell with a common length of more than 500 km and longitudinal conductance G≈8×10^8 S×m.

Key words: geomagnetic variations, magnetotelluric sounding, magnetic variation profiling, electric conductivity anomaly, Karpinsky swell.

Introduction. The object of this study is the electrical conductivity structure of the Donbas Foldbelt (DF) and Karpinsky Swell (KS) located at the junction of the Precambrian East European Craton and Scythian Plate. DF and KS are contiguous parts of the elongated sedimentary basins chain: Pripyat Trough, Dnieper-Donets Basin (DDB) — in the West-North-West, Peri-Caspian Basin and Mangyshlak at Turanian Plate — in the East-South-East. DDB and DF were formed by the middle-late Devonian rifting accompanied by intensive magmatism. During the Carboniferous, the basin subsidence and sedimentation continued in the Donbas, where 15 km thick strata of Carboniferous coal-bearing deposits were accumulated. The total thickness of sediments reaches more than 20 km. The next important event in the Donbas's geological history was folding, which occurred in a compressional regime during the late Triassic — early Jurassic and late Cretaceous — early Tertiary. Inversion raised the upper part of the folded Donbas, and erosion exposed the Carboniferous coal-bearing strata. Many outcrops, hundreds of mines and boreholes give us great material for studying the region's geological history and structure of upper strata.

In contrast to Donbas, the Paleozoic rocks in KS are covered by 1—3 km thick sediments of Mesozoic-Cenozoic age that can be seen in Fig. 1, *a*. So, folds and other compressional structures of the earlier age cannot be con-

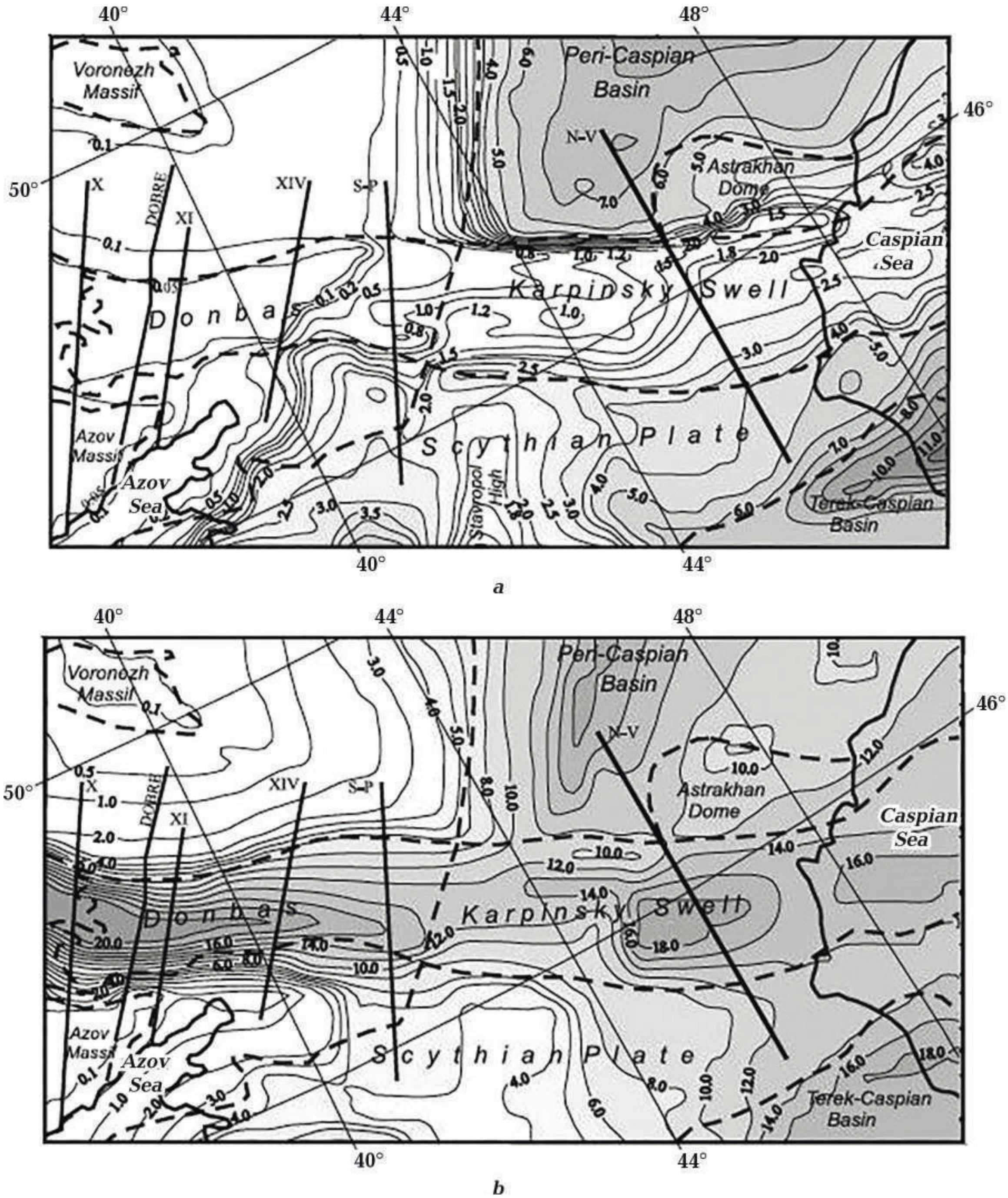

Fig. 1. Depth (km) to the top (*a*) and the bottom (*b*) of the folded/compacted Paleozoic sediments in the Donbas Foldbelt — Karpinsky Swell and adjacent tectonic structures. Solid right lines indicate DSS profiles; dashed ones outline tectonic units [Yegorova et al., 2004].

fidently studied in KS by geological data. Thus the study and comparison of geophysical fields in both regions is the promising approach for the KS deep structure research.

MTS-MVP profile Morozovsk-Tsimlyansk-Kamyshev on the Karpinsky Swell. The materials analyzed in this section are taken from [Berzin et al., 2003] and the poster of the corresponding report at the V Fedynsky readings kindly provided to us by the authors. Analyzing the results of this study, we wanted to reprocess the observations to obtain an anomalous field in horizontal magnetic components and to re-interpret it. We contacted two co-authors of the article and they informed us that the original records were lost.

The materials are presented in three original [Berzin et al., poster, 2003] figures (Fig. 2—4)

Induction vector calculation at the period T_0 for the Morozovsk—Kamyshev profile. The frequency characteristics of the anomalous magnetic field can be represented [Rokityansky, 1975, 1982] as the product of the normal impedance (decreasing function of the period) by the non-decreasing function of period V ($0 \le V \le 1$, $V=1$ corresponds DC). V describes the degree of filling of the conductor by the anomalous currents. The product of such functions has a maximum at some period T_0. The position of T_0 is closely related to the total longitudinal conductance G (S×m) of the elongated anomalous body and can be used to estimate G.

On the period T_0, the anomalous fields and induction vector become real $C=C_u$, and the imaginary vector C_v passes through zero changing its sign: usually at $T<T_0$ C_u and C_v are parallel, while at $T>T_0$, they are anti-parallel for 2D anomalies [Rokityansky 1975, 1982]. This sign rule is valid when choosing an $e^{-\omega t}$ time dependence for a harmonically varying field. For the $e^{+i\omega t}$ choice, the rule will be the opposite.

Consider induction vectors in the northern part of the Morozovsk—Kamyshev profile in zones I—II. On the map (see Fig. 2), C_v is anti-parallel to C_u; in frequency response curves of Fig. 3, C_v and C_u have the same sign

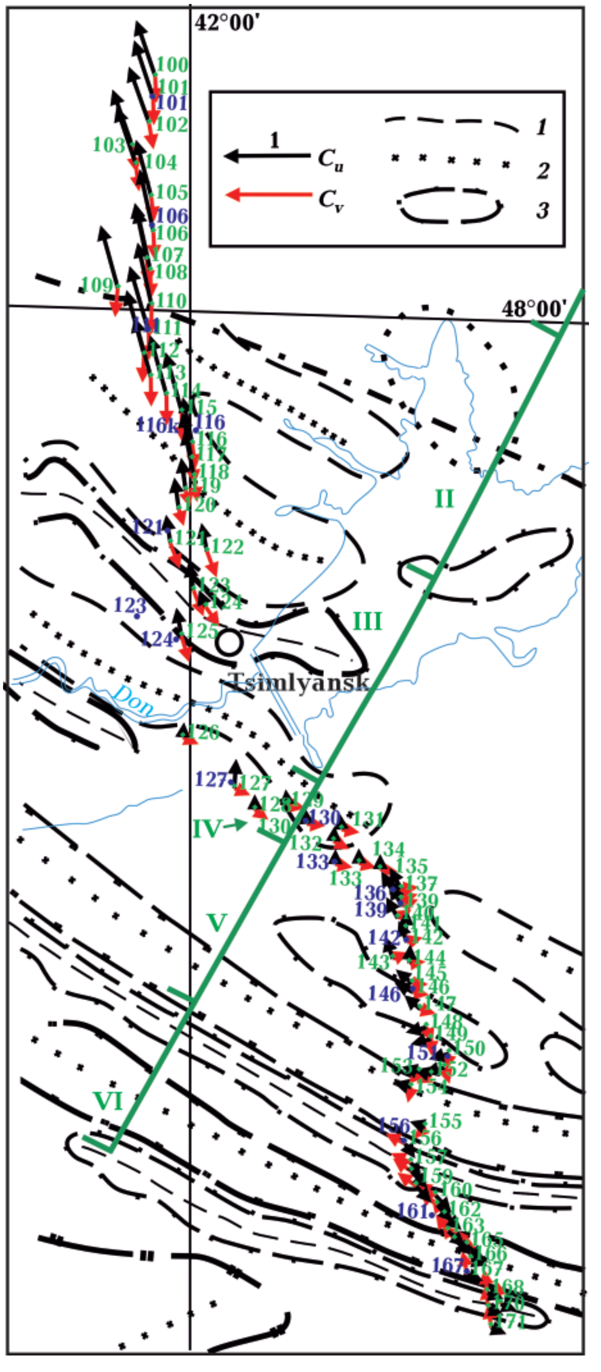

Fig. 2. MTS-MVP profile Morozovsk—Tsimlyansk—Kamyshev on a structural-tectonic scheme with the induction vectors C at a period of 1000 s: *1* — axes of positive structures (anticlines), *2* — axes of negative structures, *3* — swell-like zones in Paleozoic and Mesozoic deposits [Berzin et al., poster, 2003]. The green straight line with dashes on the boundaries of the six zones shown in Fig. 3 and 4 by Roman numerals is a profile that should be used for 2D interpretation.

at the same period T=1000 s. A little strange! Perhaps the authors changed the direction of the C_v in Fig. 2 to avoid the overlay of the real and imaginary vectors. In any case, we can extrapolate C_u and C_v to longer periods because the Hilbert transform uniquely interconnects the real and imaginary parts. Consider the *y*-components of the induction vectors in zones I—II (see Fig. 3). For short periods, the real and imaginary parts have the same sign, and both increase in absolute value with an increasing period — deviate downwards in Fig. 3. At a period of about 500 s, the imaginary component (light blue line) reaches a minimum and begins a movement to zero to change the sign on the period T_0. The recording ends at a period of ≈1500 s. Extrapolating to longer periods, we obtain a sign change of C_v on the period T_0=3600±500 s. The real part C_u (the blue line) moving to its extremum on T_0 will reach the level 1.05±0.1. The resulting uncertainties give an estimate of the error from the process of curve extrapolation. The *x*-component of the induction vector (red and

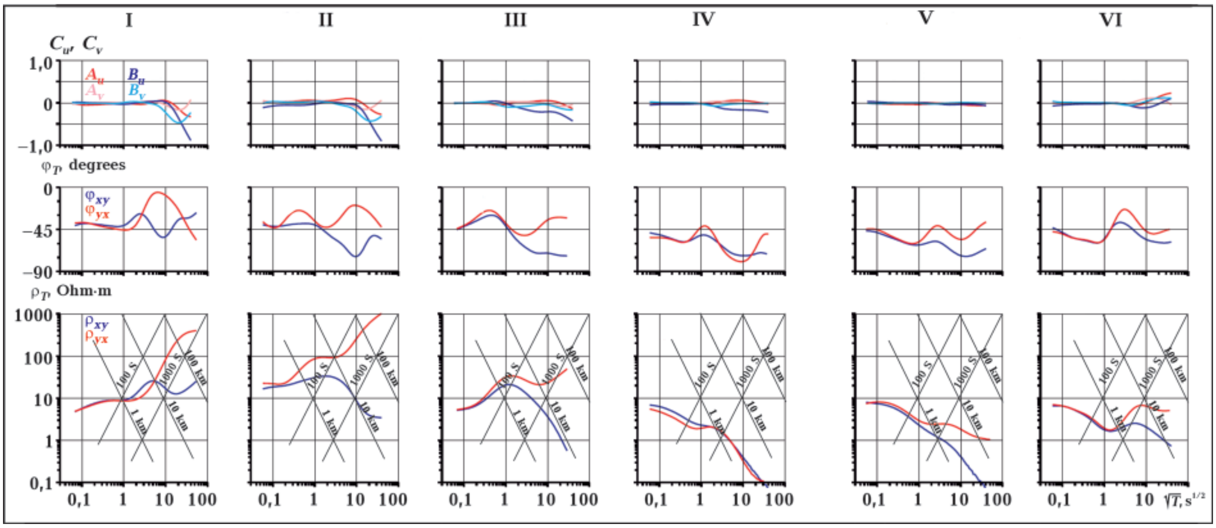

Fig. 3. Typical MVP-MTS curves in 6 zones separated from data obtained on the quasi-meridional (41°E) profile Morozovsk—Kamyshev 190 km long with 71 observation sites. The order of the columns is from North to South. Blue and light-blue curves present longitudinal polarization, and red and pink ones — transverse one $C=A\mathbf{e}_x+B\mathbf{e}_y$ [Bersin et al., 2003, poster].

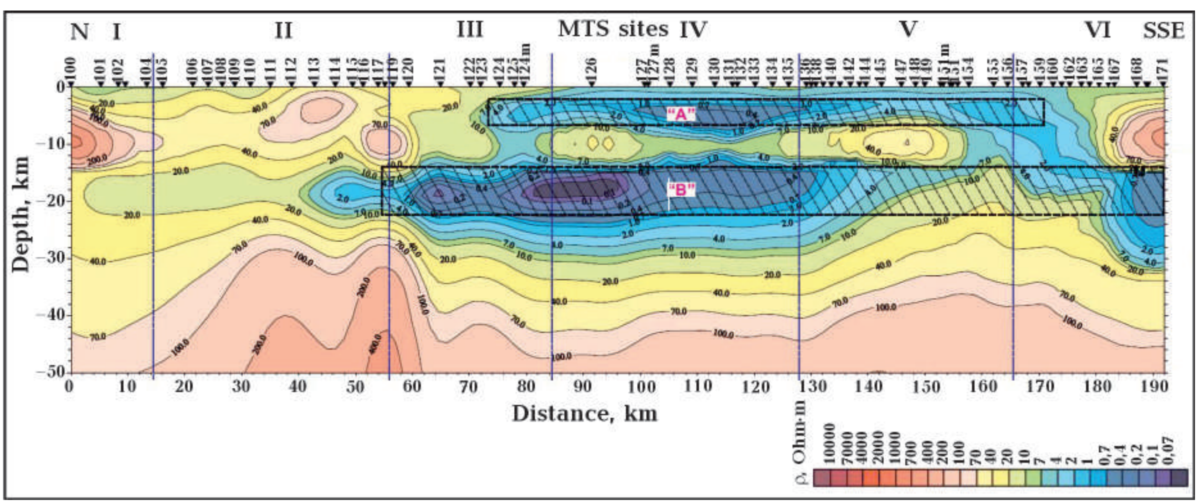

Fig. 4. Geoelectric cross-section along the Morozovsk—Kamyshev profile, synthesized from two 2D inversions: 1) using only the transverse MTS curves — upper ≈10 km; 2) using the tipper — below ≈10 km [Berzin et al., poster, 2003]. Conductor *A* is approximately isometric on the map; conductor *B* is two-dimensional with a strike in ESE direction (azimuth 117±8°).

pink in Fig. 3) behaves like the *y*-component but is three times less in amplitude. So, the resulting real induction vector on T_0 attains value 1.1±0.1 and deviates ≈25 degrees from the *y*-axis.

The orientation of the *x* and *y* axes is not clearly determined in [Berzin et al., 2003]. However, according to the figure in the article, the *x* axis coincides with the axis of the 2D conductor, which creates the anomaly of geomagnetic variations. We will assume that the *x* axis is directed to the ESE along the strike of the KS structures, and the *y* axis is directed to the SSW.

The real induction vectors calculated for the period T_0 are presented for a reduced number of sites in Fig. 5, together with induction vectors in the Ukrainian territory.

The induction vectors in the northern part of the profile are directed to NNW, although from the conductor of the ESE strike drawn in Fig. 5, they should be directed to the NNE. Apparently, the observed direction of the vectors is caused by superimposed anomalous fields of the Western direction from the sedimentary strata of the Peri-Caspian Basin with a conductance of more than 3000 S located to the East (see Fig. 1, *a*).

Geoelectrical cross-section along the Morozovsk—Kamyshev profile. At first, we consider the location of the profile, which is shown on the maps in Figs. 2 and 5. The northern part of the profile from Morozovsk to Tsimlyansk (sites 101—125) goes almost along the meridian 42°E, its azimuth *Az*≈180°. South of Tsimlyansk town, the profile (sites 126—137) runs to the SE (*Az*≈135°) nearly parallel to the strike of folded structures, further at *Az*≈160° (sites 138—151) and the last group of sites 156—171 at *Az*≈150° is at an angle of ≈35° to the stretching of structures. The average azimuth of structures in the profile area is 117°. Therefore, if we correctly understand Fig. 2 in [Berzin et al., 2003], the *x* axis has an azimuth along the KS structures 117±8°, and the y axis 207±8°. These numbers we

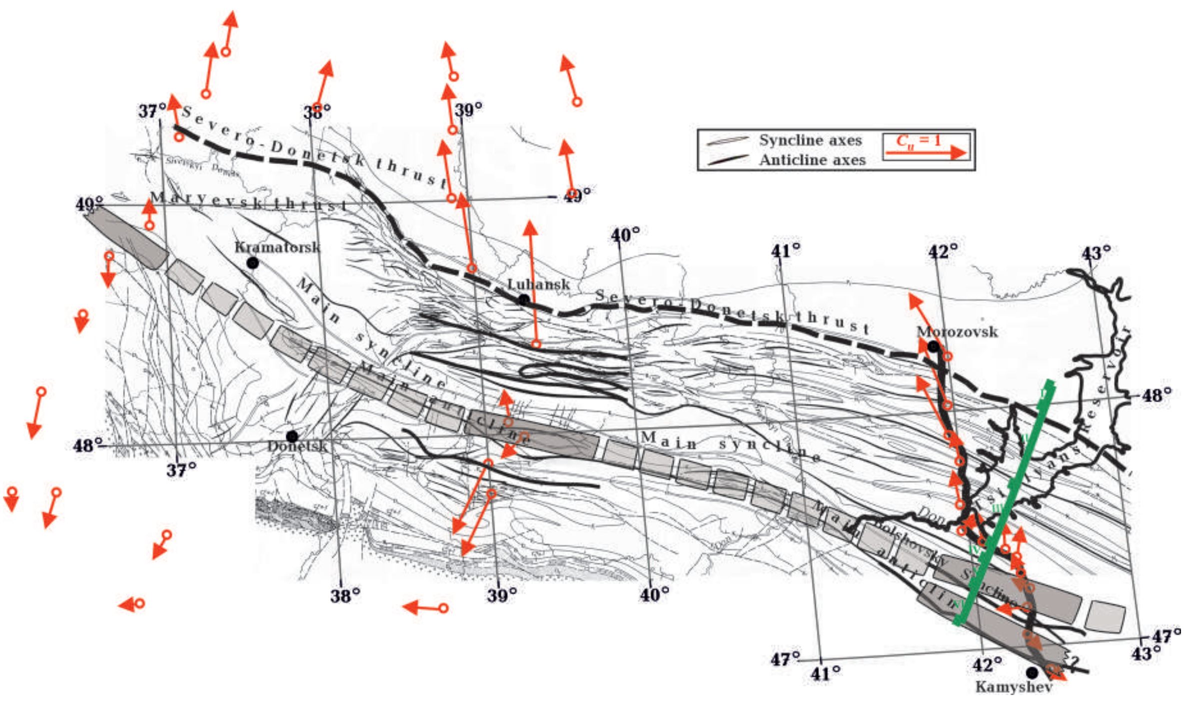

Fig. 5. MVP sites with real induction vectors for the period's interval 1800—3600 s on the tectonic scheme of the Paleozoic structures [Popov, 1963]. Dark gray strips in the areas of three observation profiles are reliably established anomalies of electrical conductivity. The wide light gray dotted lines between the continuous grey strips are the proposed connection of these three local anomalies into one regional anomaly. The straight green line with rectangular protrusions on the boundaries of the six zones shown in Fig. 3 and 4 by Roman numerals is a profile that should be used for 2D interpretation of the profile Morozovsk—Kamyshev data.

determined from the strike of the tectonic structures in Fig. 2 and 5. In the area of the Morozovsk—Kamyshev profile, the tectonic objects are presented not identically, and its strike does not coincide everywhere in the two figures. However, the average strike of the structures and its uncertainty were estimated, and it was assumed that the strike «*x*» of the electrical conductivity anomaly coincides with the strike of the structures. Then the «*y*» axis will be normal to the strike of the anomaly, and the profile for observations and interpretation should be placed along it. We drew such a profile in Fig. 2 and 5 with dashes on the boundaries of the six zones marked in Fig. 2—5 by Roman numerals. The *y*-profile is parallel to the DSS profile Surovikino—Peschanokopskaya (S-P in Fig. 1) but lies 15 km East of it.

*Construction of a simplified geoelectric cross-section***.** In [Berzin et al., poster, 2003] two sources of information about the desired cross-section are given: «Geoelectric cross-section resulting from 2D inversion of the transverse MTS curves» (Why transverse? Why not longitudinal or both, or effective one? — it was not explained) which was used only for the upper 10 km of the cross-section, and «Geoelectric cross-section resulting from 2D inversion of tipper» used for the lower part of cross-section. It should be remembered that a tipper cannot provide the true depth of a conductor; it can provide only the maximal possible depth of the anomalous currents' center obtained from the form of the anomalous field profile graphs [Rokityansky, 1975, 1982]. Using the data on the components of the induction vector at long periods, presented in Fig. 3, we plotted the changes in the induction vector along the *y* axis. We obtained a clear discrepancy with the cross-section in Fig. 4. The induction vector passes through zero changing sign in the middle of zone V, and approximately under this place should be the most conductive part of the electrical conductivity anomaly. In the cross-section of Fig. 4, the most conducting part is located near the border between zones III and IV, about a few tens of kilometers north of the location predicted by the MVP data in Fig. 3.

Let's try to extract information about the geoelectric cross-section from the experimental data MTS presented in Fig. 3, sequentially analyzing the data in each zone.

The first thing we see on the apparent resistivity curves is almost the same initial (at short periods ≈0.01 s) level (5—10 Ohm·m and only in zone II — 20 Ohm·m) in all zones. This means the same low resistivity of rocks in the upper hundreds of meters of the cross-section. The second result is about resistivity at a depth of about 1 km. MTS curves in the period's interval 0.04—4 s yield the following: in zones I—III, the curves go up; in zones IV—VI, they go down, thus showing a resistivity increase in the depth interval 0.5-few km in the first case and a decrease in resistivity in the second one.

In zone I, the longitudinal curve ρ_{xy} has a minimum, indicating the presence of a conductor at a distance of ≈10 km with a conductance of about 2000 S; in zone II, ρ_{xy} gives a

Table 1. Parameters of the initial profile MTS—MVP Morozovsk—Kamyshev and its projection onto a rectilinear profile with Az=207°

Zone	Sites	Number of sites	Width *b* of each zone, km	Projection *b* onto the *y* axis, km
1	100—104	5	14	11
2	105—118	14	42	34
3	119—125	7	28	22
4	126—135	10	44	8
5	136—156	20	38	27
6	157—171	15	26	16
Total	100—171	71	192	118

conductance of more than 10,000 S with the same distance from observation points to the conductor — 10 km; in zone III, the distance decreases to ≈3 km, and conductance *S* reaches several tens of thousands of Siemens. Such high conductance contradicts induction vector data which predict maximal conductance southerly, somewhere in the middle of zone V (Fig. 6, *a*). The transverse curve ρ_{yx} «feels» a conductor at the same distance in zones II and III, but its estimation of the conductance is much less than from ρ_{xy}.

Consider MTS curves in zones IV—VI. Here, near the surface, a well-conducting layer of almost isometric shape is known from boreholes drilling with a depth up to 4800 m. Inside such an isometric conductor, the apparent resistivity can be greatly reduced at long periods, and the MTS curves give distorted results.

What can we place in the cross-section from this data? Moreover, what is the single/one MTS curve for zones containing from 5 to 20 observation points with their own MTS curves? How is it obtained, by simple averaging? To what place this single MTS should be attributed: to the middle of the zone or all points of the zone? These issues are important for cross-section construction. But there are no answers, no sure guess. So, a more detailed analysis of the smoothed (averaged) MTS curves presented in Fig. 3 does not appear useful.

Consider the cross-section shown in Fig. 4 for the construction of which, apparently, the data of all points were used, but only transverse curves ρ_{yx}, φ_{yx} for the upper 10 km and only tipper for the lower 40 km were used. How two inversions (by ρ_{yx} and tipper presented in [Berzin et al., poster, 2003] in two graphs where the depths are given in the range of 0.1—100 km in logarithmic scale) were combined and connected at a depth of 10 km and how the cross-section of Fig. 4 was obtained, remains unclear. The cross-section of Fig. 4 is overloaded with redundant details not supported by observations. We left isolines 0.2, 1, 5, 20, 100 Ohm·m, projected (see Table 1) each zone length on one straight y axis, perpendicular to the tectonic structures and the strike of the anomaly, changed the profile direction to the opposite, as is accepted for the DSS profiles (in the left S-SW, in the right N-NE), and obtained Fig. 6.

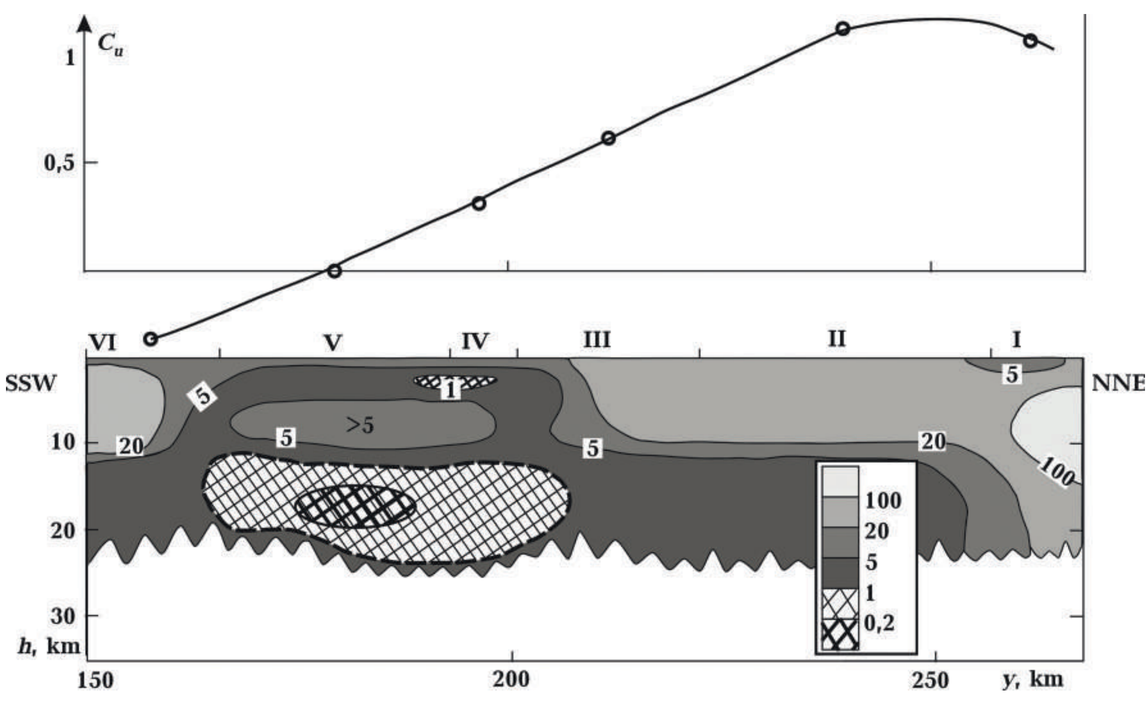

Fig. 6. Real induction vector C_u at period 3600 s along the profile with *Az*=27° and modified simplified inverted geoelectric cross-section along the Morozovsk—Kamyshev profile projected on the straight line with *Az*=27°.

Profile MT-4 near Elista city (45° East longitude). The MT-4 profile begins 30 km southwest of Elista and extends approximately east (*Az*=75°) for 900 km, passing slightly north of Astrakhan and Guryev and ending in northern Kazakhstan. Fig. 8 shows the western part of the profile with marking of kilometers up to 200 km. On the MT-4 profile, only MTS were carried out with an average distance between points 12 km with local concentrations in the western third of the profile up to 2—3 km. A geoelectric cross-section to a depth of 30 km (Fig. 7) is obtained by 1D interpretation in each site.

The cross-section of the most of the profile is approximately uniform and simple: the upper 2—3 km are good conductors with ρ=1÷5 Ohm·m and possibly less than 1 Ohm·m (marking of resistivity scale is given only from 1 to 400 Ohm·m). Below, in the range from 3—6 km to 8—20 km, the resistivity is equal to tens of Ohm·m, and in the lower part of the cross-section ρ is equal to hundreds, possibly thousands of Ohm·m. Such a cross-section is observed at pickets from 160 to 900 km. At the 145 km picket, the cross-section strongly changes: at a depth (probably at a distance) of 12 and 22 km, conductive layers appear with a conductance of ≈500 and ≈2000 S, respectively. At the 140 km picket, the distances decrease by about 1.5 times. On the next 20 km, the MTS were made with the compaction of points up to 3—4 km, and it is clearly seen how smoothly the depth to conducting layers approaches to constant values of 5 and 10 km. The same depths are also observed at pickets from 60 to 110 km. At the pickets from 50 to 0 km, well-conducting layers descend to depths of 10 and 25 km with reduced conductance. Thus, the considered cross-section shows the presence of an electrical conductivity anomaly with the maximum conductivity at pickets approximately from 45 to 130 km, reaching tens of thousands Siemens.

The entire anomalous area (pickets 0—150 km) is located on the Karpinsky swell. Having only the MT-4 profile, the strike of the anomaly would be drawn perpendicularly to the profile. In Fig. 8, the anomaly strike was changed to naturally connect all parts of the Donbas anomaly. Nothing in the MT-4 profile data contradicts such a change. According to Fig. 8, the angle between the assumed direction of the anomaly axis and the profile line was determined to be ≈50°. It means that on the profile for interpretation normal to the strike of the anomaly, all lengths must be multiplied by the cosine of this angle equal to ≈0.64. Therefore, the width of the most conductive part of the anomaly should be re-

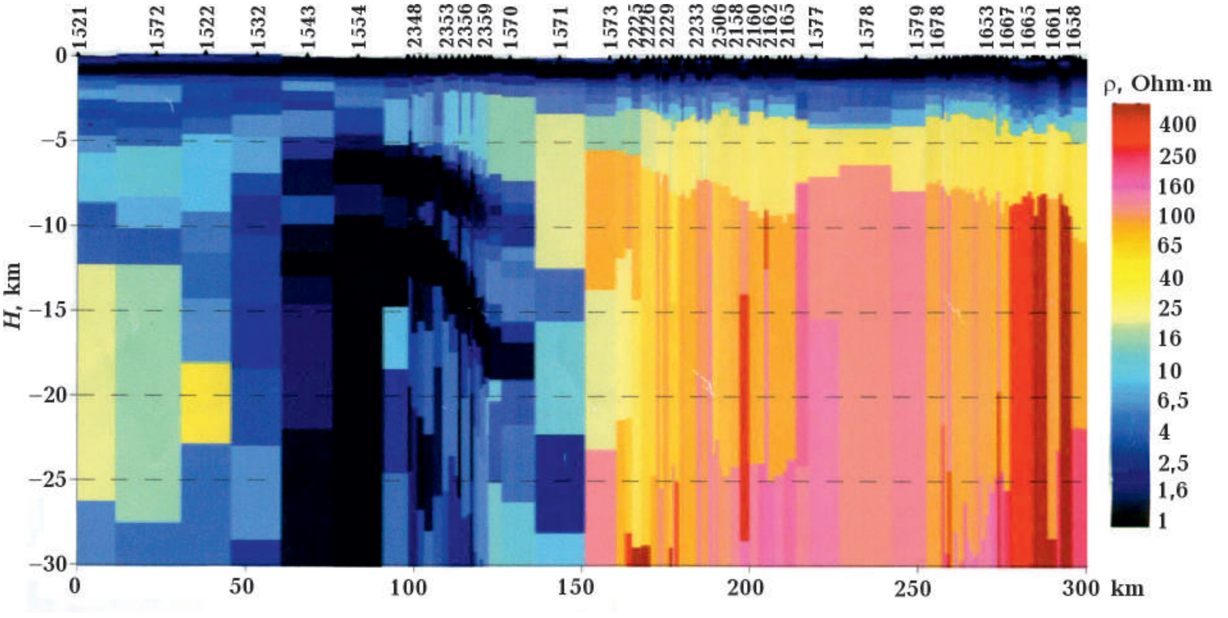

Fig. 7. Geoelectric cross-section along the western part of regional Profile MT-4 [Feldman, 2018].

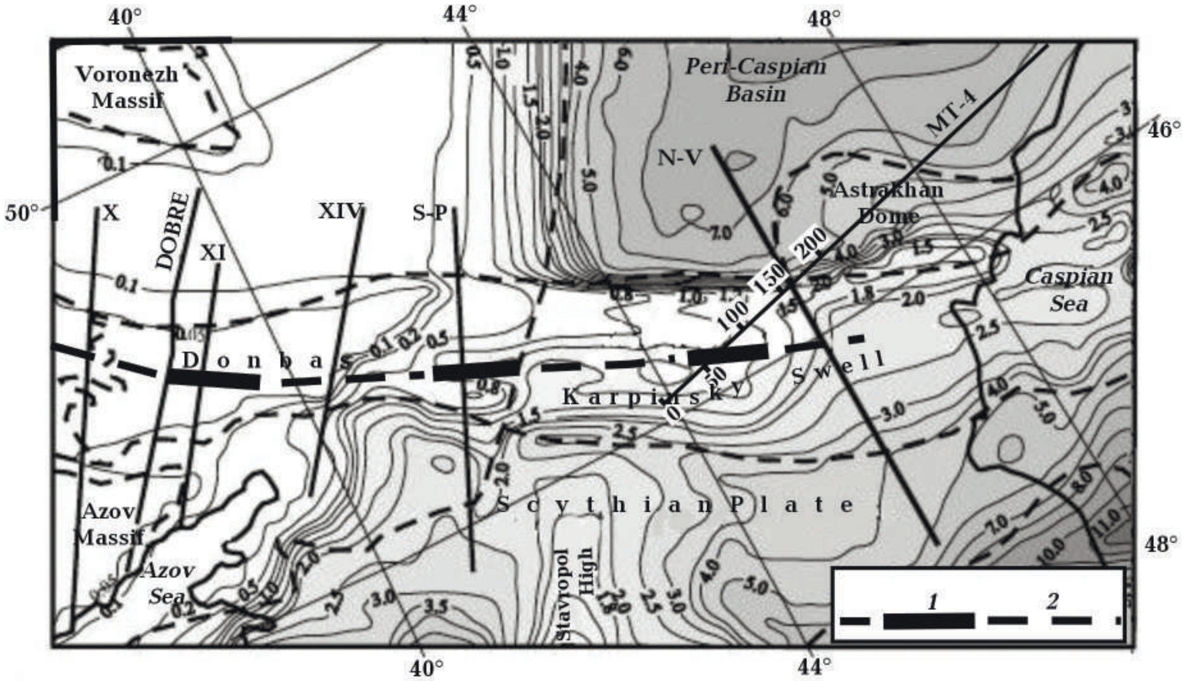

Fig. 8. Donbas electrical conductivity anomaly with continuation to the Karpinsky Swell according to the data of deep electromagnetic studies by the MVP-MTS methods: *1* — areas of the anomaly reliably found by MVP-MTS profile observations, *2* — supposed connection of three local anomalies into one regional anomaly. Other markings are as in Fig. 1, *a*.

duced to 55—60 km, and the width of the entire anomaly to a value greater than or equal to 100 km («greater» because while the profile ended, the anomaly might have continued).

Discussion and Conclusion. Donbas conductivity anomaly (DCA) was crossed by three profiles separated from each other by a distance of about 200—240 km. The first profile (Pr-1), de facto areal observations, covering a significant part of eastern Ukraine, was described in work [Rokityansky, Tereshyn, 2022] and references within. It can be assigned to 39° E (see Figs. 5, 8).

The second profile (Pr-2) Morozovsk—Kamyshov is assigned to the meridian 42°E. The observations were made by the expedition of the Ministry of Geology, the interpretation, presentation at a conference and writing of the short article [Bersin et al., 2003] were made in collaboration with university scientists. In Section 2, we made additional interpretation: 1) components of the induction vector were extrapolated to longer periods, the maximum frequency response T_0 of the anomaly was determined, and longitudinal conductance G was estimated; 2) The swinging profile has been straightened out. To refine the cross-section presented in [Berzin et al., 2004], MTS curves were partly re-interpreted.

The third profile (Pr-3) with MTS observations was for the search for mineral resources, hydrocarbon exploration, and geological mapping. The interpretation was made by primitive 1D inversion. It should be noted that there are no sharp near-surface inhomogeneities, which makes it possible to observe smooth changes in the parameters of deep conductors and obtain good results of 1D inversion. As a result, the crustal conductors and some of their parameters are separated here more reliably than in the first two profiles.

Thus, a strong conductivity anomaly is quite reliably seen in the data on all three profiles. Their parameters can be rather different in detail but can be approximately the same in the main. Both options may be valid, given the significant uncertainty of the data and methods of analysis.

Taking into account the theoretical and

model data on the effect of the conductor length on the magnitude of the anomalous field, it is possible to assume with a high probability the existence of a single anomaly of electrical conductivity in the Donbas and Karpinsky Swell.

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Донбаська аномалія електропровідності у валу Карпінського

І.І. Рокитянський, А.В. Терешин, 2022

Інститут геофізики ім. С.І. Субботіна НАН України, Київ, Україна

Донбаський складчастий пояс (ДСП) і вал Карпінського (ВК) є суміжними частинами системи витягнутих осадових басейнів, що утворюють лінеамент від Польщі через Прип'ятський прогин у Білорусі, Дніпровсько-Донецький басейн (ДДБ) і ДСП в Україні, ВК у Росії, через Каспійське море та через Мангишлак у Туранській плиті в Азії.

У ДСП відбулося підняття осадових відкладів мезозойсько-кайнозойського віку і подальша ерозія оголила кам'яновугільні вугленосні товщі. На відміну від порід ДСП палеозойські породи у ВК вкриті відкладами мезозойсько-кайнозойського віку потужністю 1—3 км, і продуктивні структури більш раннього віку не можуть бути впевнено досліджені у ВК геологічними методами. Отже, геофізичні методи є перспективним підходом для дослідження глибинної будови ВК. Стаття присвячена електромагнітним дослідженням електропровідності гірських порід методами магнітоваріаційного профілювання та магнітотелуричного зондування. У попередній статті, що вийшла другом 2022 р., детально описано результати електромагнітних досліджень ДСП. За допомогою даних МВП було виявлено інтенсивну Донбаську аномалію електропровідності, яка проходить уздовж Головної антикліналі Складчастого Донбасу. Параметри ДСП: максимально можлива глибина центру аномальних струмів h=18±2 км. Максимум частотної характеристики T_0≈3600 с дає повну поздовжню провідність G=(8±2)·10^8 См·м. 70 досліджень МТЗ на періодах 0,1—3000 с дають дві провідні смуги, верхній край яких змінюється від 0,3 до 5 км. Смуги паралельні осі ДСП їх розглянуто як частина у цього поясу. Дуже велике значення G дає змогу зробити припущення, що аномальне тіло простягається на значну глибину. Вісь ДСП просторово збігається з інтенсивною (до 90 мВт/$м^2$) глибинною аномалією теплового потоку. Цей факт свідчить про те, що природа нижньої частини ДСП може бути спричинена частковим плавленням. Теоретичні оцінки показують, що над сильно витягнутими провідниками виникають інтенсивні аномальні поля геомагнітних варіацій. Тому є підстави очікувати, що аномалія продовжується у східному напрямку. Ми знайшли два профілі МТЗ, що містять аномалії з приблизно такими ж параметрами, як ДСП; обидві аномалії в межах валу Карпінського. Подано оригінальні матеріали, зроблено доповнення та уточнення в їх інтерпретації та описі. Основний висновок: параметри аномалії на трьох профілях приблизно однакові, і можна з високою ймовірністю припустити існування єдиної аномалії електропровідності Донбасу та валу Карпінського загальною довжиною понад 500 км і поздовжньою електропровідністю G≈8·10^8 См·м.

Ключові слова: геомагнітні варіації, магнітотелуричне зондування, магнітоваріаційне профілювання, аномалія електропровідності, вал Карпінського.