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INDUCTION STUDIES IN STABLE SHIELD AND PLATFORM AREAS

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Precambrian shields and platforms occupy on the globe more than a half of the surface of the dry land. The largest part of magnetotelluric and magnetovariational research has been carried out up to now on these areas. The greatest number of the results refers to the three cratons: North-American, Russian and Sibirian. The conductivity of ancient shields varies strongly in horizontal direction due to the existence of a great number of fractures and strong foldness of ancient basement.

Graphitized and sulphidized rocks with high conductivity ($0.1 - 1\Omega^{-1}m^{-1}$) correspond to the regions of great fracture zones of the crystalline basement.

The conductive regions have a strong effect on the spatial distribution of the electric field, and produce strong screen effect on the upper mantle down to considerable depths.

These aspects as well as errors in the interpretation of curves in the complicate geoelectrical conditions, lead to considerable differences between the results of ancient shields.

At present we have almost no results on which a study of the "normal" distribution conductivity vs. depth in Precambrian shields could be based.

The presence of a thin sedimentary cover diminishes somewhat the influence of horizontal inhomogeneities of the ancient basement, but at the same time there are distortions of another type, connected with the inhomogeneity of the sedimentary cover. The information about the conductivity vs. depth is, however, in this regions more reliable than in the shields. A conductive layer at depths of 15—100 km and some local regions of high conductivity at depths of 5—20 km can be at least traced rather reliable. To obtain a "generalized" curve better reflecting the shallowest part of the profile, it is necessary to use more reliable sounding data on the shields.

Precambrian shields and platform occupy more than a half of the dry part of the globe and from the cores of the continents — the so called cratons (see Fig. 1). Shields and platform are geological objects of different kind. The shields are uplift areas and the platforms areas with settling basement. According to geothermic, seismic and other geophysical data this is no substantial difference. Therefore there is no reason to distinguish them from the point of view of electric conductivity at the present level of knowledge. Up to now a great part of the magnetotelluric and magnetovariation research has been carried out on stable shields and platforms. But the data are irregularly distributed. We have no data about the Brasilian, Chinese and Antarctic Cratons.

The main part of the available material refers to three cratons situated to the north of the Alpine latitudinal zone of folding: to the North-American, East-European (Russian) and Sibirian Cratons. As a rule the magnetovariational methods have the purpose to reveal areas of anomalous electric conductivity, while magnetotelluric soundings are carried out to study the normal deep distribution of the conductivity. These methods ought to make a pair. They have developed, however, independently and only in a limited number of cases they have been purposefully used in the same geological area.

Fig. 1

Magnetovariational studies have been reviewed completely enough by Gough [1] and Lilley [2]. Therefore, it is possible to pay more attention in this paper to magnetotelluric results.

1. In the area of the Russian craton, different institutions have made a great number of magnetotelluric soundings. The measurements were processed with account of the tensor character of the impedance, only in a few cases sounding curves were computed from apparent impedances or from complete field vectors. An analysis of the influence of horizontal inhomogeneities enabled to choose sounding curves most truly reflecting the distribution of the conductivity in the whole depth range. These curves were interpreted as horizontally homogeneous ones.

Magnetotelluric data at the Russian platform attract attention by a great variety of geoelectric profiles. Even after a reduction due to possible distortions by horizontal inhomogeneities, it can be said that the crystalline basement of a stable platform has very inhomogeneous geoelectric properties.

Fig. 2a shows magnetotelluric sounding curves for the eastern part of the Baltic shield (Zhemaletdinov et al. [3]). The curves are computed from complete vectors or the maximum value of the impedance. A great horizontal inhomogeneity of the sounding area displays itself in a considerable divergence

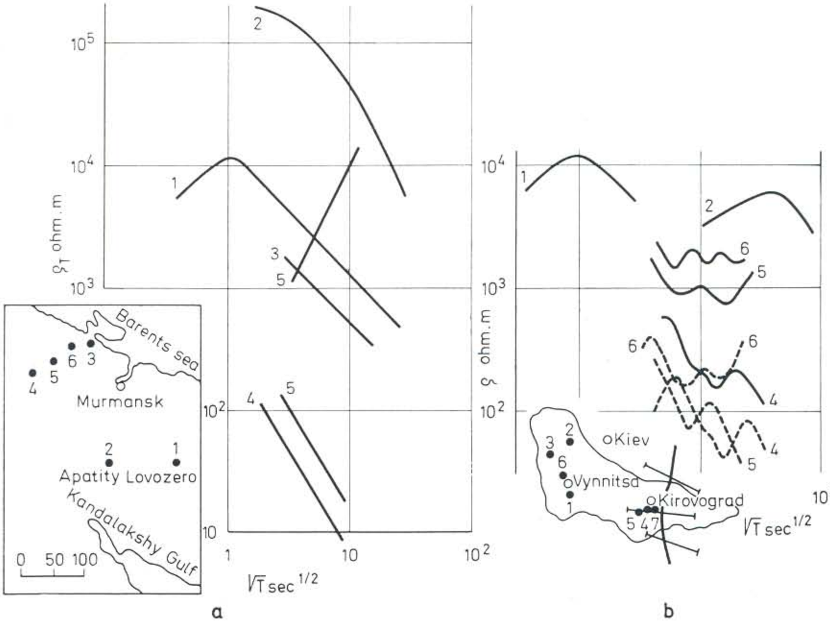

Fig. 2

of curves in the directions of the inhomogeneity axes and in a strong displacement of "maximum" curves from point to point. Nearly all curves have decreasing asymptotes in the period intervals 0.1—10^4 sec, indicating the presence of a conducting layer. According to the formal interpretation of these curves, the depth of the conducting layer changes from some to several hundred kilometres. The shield area of the Kola peninsula and Karelia may be approximated by a medium with an average specific resistivity of about 10^4 ohmm, containing extensive bed-like conductors, such as mighty vertical bodies of graphitized shales, rocks with sulphidic and graphitic mineralization, generally occurring in areas of stable basement fractures [3—6]. The resistivity of conducting rocks fluctuates within the limits from 0.1 ohmm to some tens ohmm. The conducting zones reach often depths of 10 —15 km. These conducting bodies strongly affect the spatial distribution of the electric field acting as a conductive layer at some fictitious depth. The effective longitudinal conductance of these zones reaches often 1000 ohm^{-1}, therefore they screen the distribution of crustal and mantle conductivity down to considerable depths. This makes clear that in such areas deep magnetotelluric studies are impossible. It is necessary to study at first the distribution of the electric field in order to separate regions where soundings give the least distorted information about the deep geoelectric profile. The range of these phenomena on other shields is not well studied. But as it has been shown by ZHEMALETDINOV et al. [3], similar fractures of the stable basement occur in Voronezh massif and also on the Ukrainian shield [7] where sounding curves differ in neighbouring points often considerably, too (Fig. 2b). The inhomogeneity of the Ukrainian shield and of the Voronezh massif has also been noticed in magnetovariational data [8—10]. In both cases the magnetovariational anomalies are connected with deep fracture zones — those of Kirovograd and Voronezh.

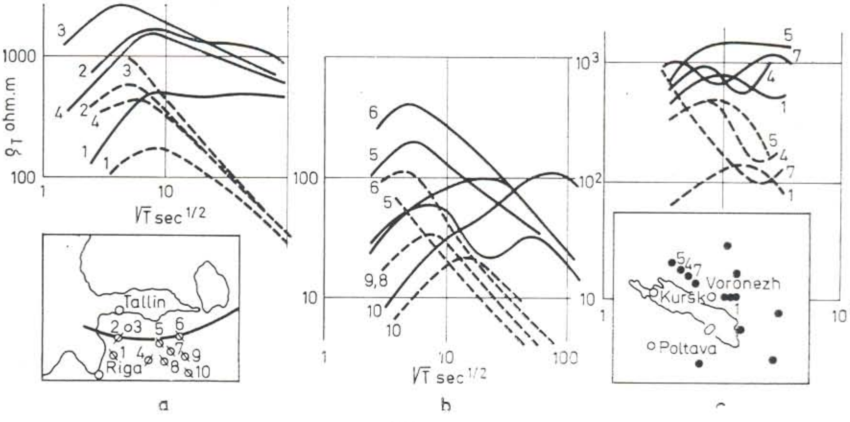

Fig. 3

Data from zones with a thin sedimentary cover, from the slopes of shields and in regions of elevated basement (Byelorussian elevation, Voronezh massif) show that the presence of a thin sedimentary cover diminishes somewhat the influence of the horizontal inhomogeneity of the stable basement. But there is another type of distortion, connected with the inhomogeneity of the sedimentary cover, e.g. with pinching out. Fig. 3 shows sounding curves corresponding to maximum and minimum impedances in two neighbouring regions on the south-eastern slope of the Baltic shield. The direction of the isodepth lines of the basement and the maximum axis of the impedance diagram are at these stations nearly orthogonal, therefore, the information of the "maximum" curves about great depth is reduced, as in this case low-frequency asymptotes are displaced because of the "S-effect" [11]. This is especially clear farther to the west (Fig. 3a), where the sedimentary cover quickly pinches out. The asymptotes of the "maximum" curves correspond to a depth of the conducting level at 600—1000 km. According to the "minimum" curves, the depth of the conduncting layer would be 40—70 km. There is an additional intermediate conducting level in the neigbouring eastern region, the depth of which is on the basis of the descending branches of the "minimum" curves about 20 km. It is interesting to note that in this region there is also a lot of deep fractures, striking nearly parallel with the basement isodepth lines. The thickest, the Krests fracture lies near stations 9, 10 (Fig. 3b). The layer in a depth of 40—70 km discovered to the west from these stations does not appear on the "minimum" curves here, it is most probably screened by this much nearer conducting layer. The second conducting level appears most clearly on the "maximum" curves at station 9, where two low-frequency asymptotes are present: the first hints at a depth of 25, and the second at 60 km. An intermediate conducting level in small depths was also discovered at the northern slopes of the Baltic depression and in the region of the Latvian saddle. The depth of this level is variable, its longitudinal conductance is not more than 500—600 ohm^{-1} [12]. Dipole soundings [13] in the Finnish Gulf confirm a conducting level in small depths on the Baltic shield and its slopes. A similar geoelectric situation is found in the central part of the Voronezh massif [14—15].

A local NW-striking conducting layer can be observed not far from the deep Voronezh fracture. The "minimum" curves which are in this region nearly in the strike indicate the first conducting layer at about 17—20 km, and the second at 70 km. At stations far from this fracture, there is only one conducting layer, its depth is about 40—70 km; that means that on the Voronezh massif one finds nearly the same intermediate levels as on the slopes of the Baltic shield.

In the area of the Byelorussian massif where the depth of the basement does not exceed 400 m, 8 soundings were made. Only "maximum" curves are presented in [16], these are here near to the direction of dip, and therefore they can be distorted by the "S-effect". Low-frequency asymptotes of these curves correspond to a conducting layer in depths more than 600 km. As "minimum" curves are not known, the possibility of the existence of an intermediate layer at 40—70 km cannot be excluded as this can influence "maximum" curves only slightly.

Soundings from deeper parts of the Russian platform enable to conclude only about the conductivity of mantle material, owing to the great longitudinal conductivity of the sedimentary cover. Thus, a series of soundings on the Middle-Russian depression indicates only a decrease of the mantle resistivity to 10—50 ohmm in depth of 200—350 km [17—18]. The distortion of the curves due to inhomogeneities in the sedimentary cover and in the basement is in these regions not so strong, and therefore sounding curves of rather far situated stations have similar descending asymptotes (Fig. 4). In areas with mighty sedimentary cover one can also see, however, sometimes intermediate conducting bodies. Thus, at stations 8, 9 (Fig. 4a) located nearly in the centre of the Middle-Russian depression, a local conductive level was discovered at the depth of 8—20 km with a longitudinal conductivity of 4000 ohm^{-1} [17] Using soundings over different thick sedimentary covers, it is possible to form

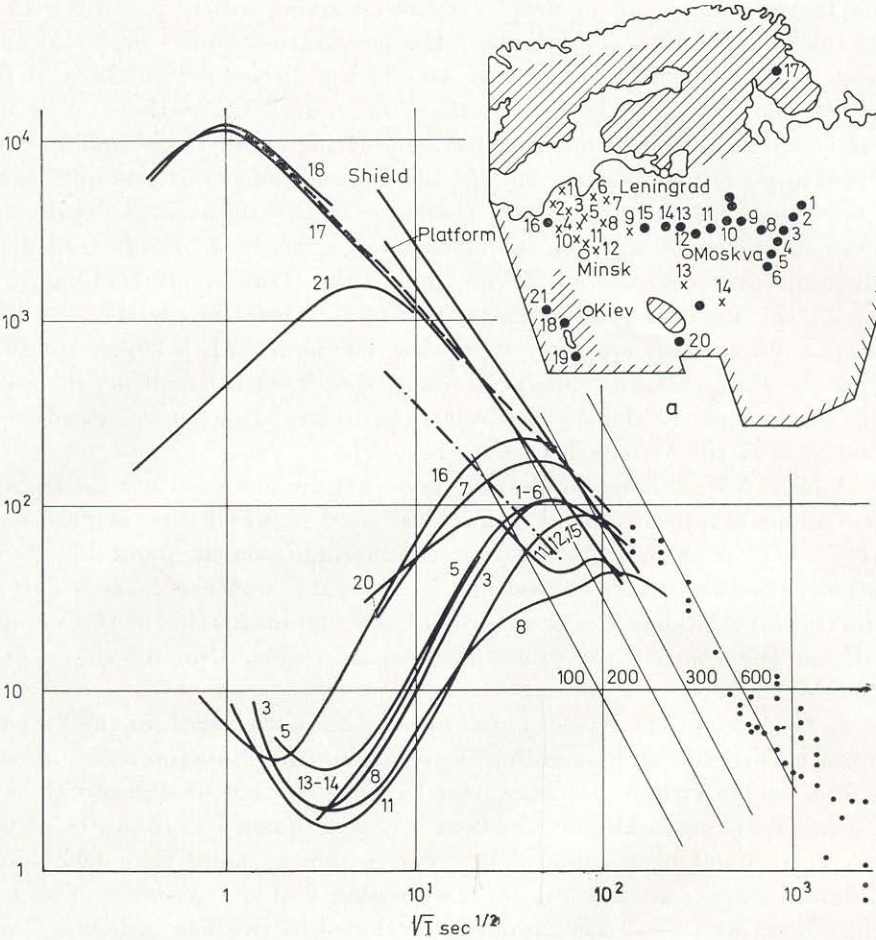

Fig. 4a, b

an opinion about the deep distribution of conductivity of the whole Russian platform. An attempt to realize this idea was made by Vladimirov and Dmitriev [19]. They have chosen sounding curves possibly least distorted by the "S-effect". The envelope of these curves in the range of long periods can be taken as a sounding curve for a stable platform without sedimentary cover (dotted line in Fig. 4b). ϱ_T values from global magnetovariational data [10] confirm rather well the generalized curve in the range of long periods and ϱ_T curves, computed from geothermal data for stable shields and platforms [20] (continuous lines on Fig. 4b), are only slightly dis-placed upwards from it in the range of short periods. It is, however, not yet possible to interpret this curve, as the generalized curve needs a more precise definition. The initial branch of the curve is mostly uncertain, as it was constructed from only two-three soundings on shields in regions with small sedimentary cover where the influence of the horizontal inhomogeneity in the environment of the sounding station was not sufficiently known.

The generalized curve cannot be characteristic of the geoelectric structure of the whole platform, since there are extended regions with intermediate conducting layers at 40—70 km. On the southern slope of the Baltic shield and of the Voronezh massif the "generalized" curve will be of a quite different type (dash-dot line in Fig. 4b). This curve runs considerably lower than the curve corresponding to geothermic data with the supposition that the crust and the mantle consist of high-resistance rocks, like granite, basalt, olivine etc. The cause of such a great decrease of the resistivity at these depths is not clear.

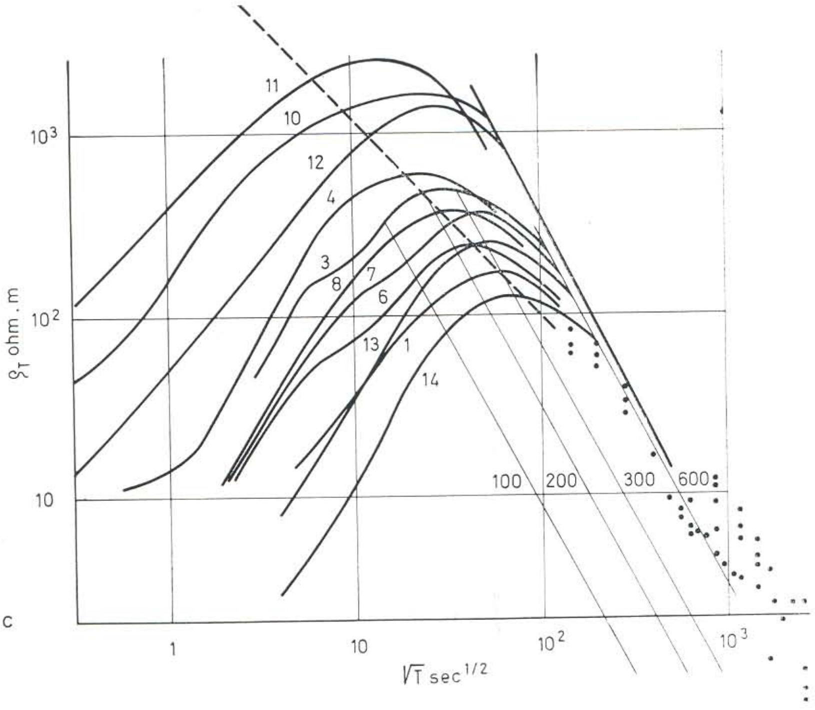

Fig. 4c

There is one more group of curves obtained on a large part of the Russian platform (crosses on Fig. 4a) that does not agree with the generalized curve. The envelope of these curves shown by continuous line in Fig. 4c, runs higher than the "generalized" curve. This difference is probably connected with the influence of the sedimentary cover. This assumption requires, however, a further analysis, because a large part of these curves is in the strike-direction and it was supposed that only insignificant changes of the depth of the basement occur.

2. A great amount of magnetotelluric soundings were carried out in the southern part of the Sibirian platform and in the Tungus syneclise. Interesting results were received in the southeastern part of the Sibirian platform [21].

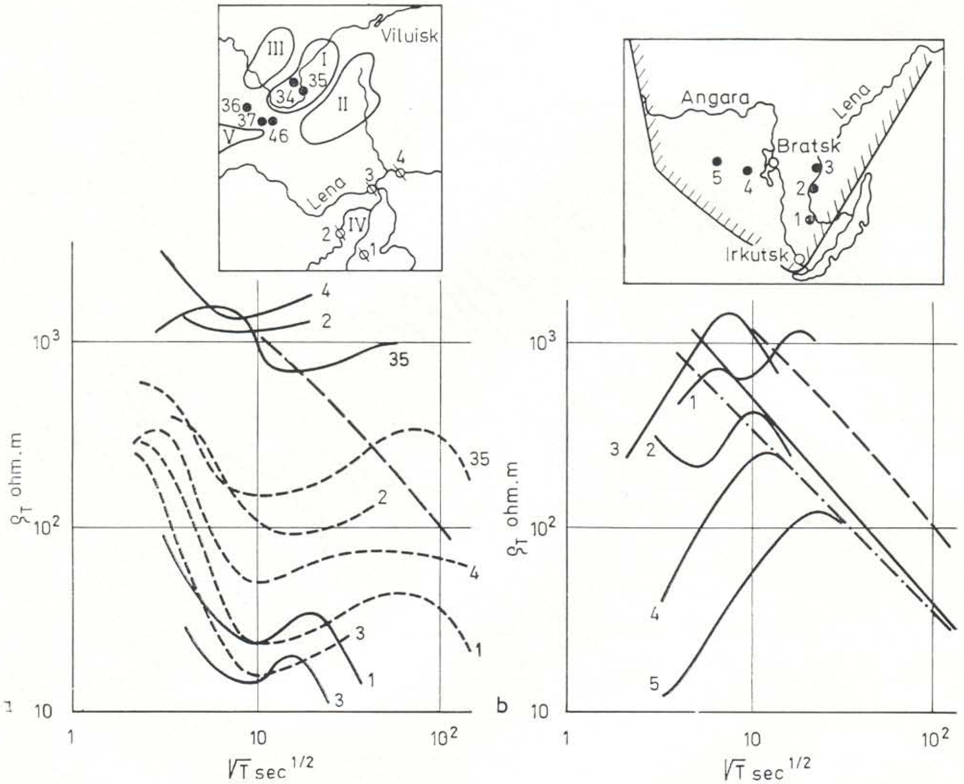

Fig. 5

Soundings were made on the north slope of the Aldan shield, Vilyuisk syneclise and of the Bataubin saddle. According to strike-directed curves (Fig. 5a) which are here the "minimum" ones, an intermediate conducting layer was found at the depth of 15—20 km with a longitudinal conductivity about 600 ohm^{-1}. A second decrease of resistivity was observed at depths of 200—260 km. This second low-frequency asymptote coincides rather well with the "generalized" curve of the Russian platform.

The soundings in the Tungus syneclise were carried out along the river Lower Tunguska. In the middle and lower part of the Lower Tunguska, a conducting level was found sinking from the west to the east from 70 to 130 km, intermediate levels in depths 15—20 km were not found anywhere [22].

A great number of the soundings was also carried out in the southwestern part of platform in Irkutsk amphitheatre [23]. There is a conducting horizon everywhere at the depth 40—100 km. In the region with a thin sedimentary cover there is a second conducting level at a depth of about 200—350 km. The first low-frequency asymptote of the sounding curves coincides with the second "generalized" curve (dash-dot line) (Fig. 5b).

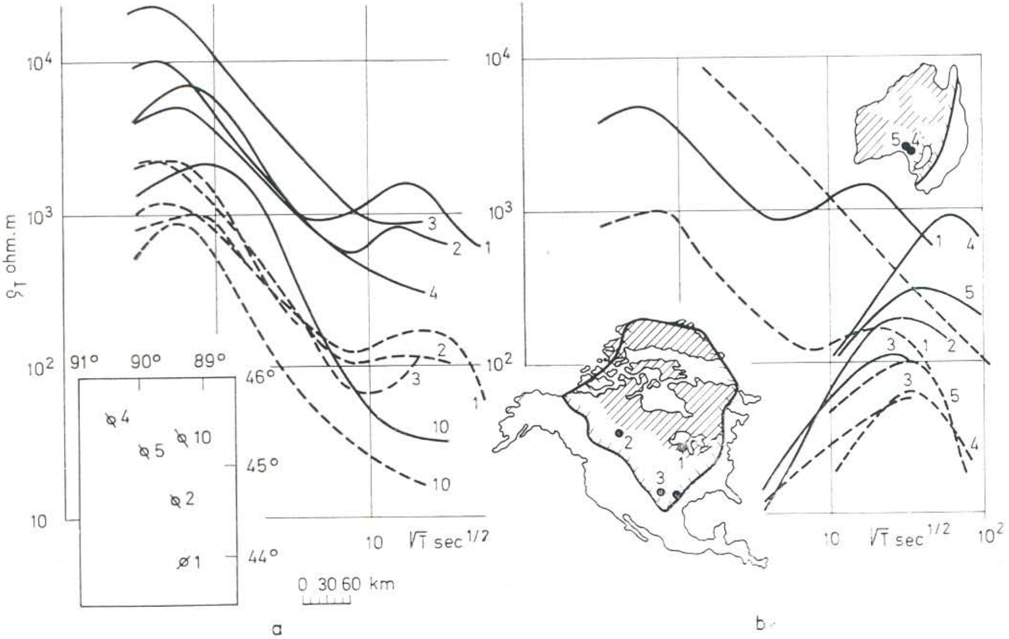

Fig. 6

3. Some soundings are known from the North-American platform. On the southeastern part of the Canadian shield, in the state Wisconsin magnetotelluric soundings were carried out in a great number of points [24] (Fig. 6a) which were carefully analyzed by **Dowling**. He chose curves which reflect most trustworthily the deep situation. According to his interpretation, there is a local conducting layer with a longitudinal conductivity of 600—800 ohm^{-1} at a depth of 8—15 km. A second conducting layer is at a depth of about 170 – 240 km.

Magnetotelluric soundings were carried out in 20 points of Western Texas, just north of Labbock [25]. Here is a conducting layer with a longitudinal conductivity of 300 – 400 ohm^{-1} at a depth of 20 km.

A great number of soundings were made in the northwestern part of the platform (in Alberta, Canada).

The best analysis of these results was given by Reddy and Rankin [26]. The soundings are situated in the region of an Alpine depression. The large horizontal inhomogeneity of the sedimentary cover and the small range of periods do not allow any significant conclusion about the resistance of the crust and upper mantle.

Comparing soundings from the North-American platform with those from the Russian platform, we do not see any essential differences (Fig. 6b). Some deviations of the curves are caused either by shallow conducting zones (Labbock — 20 km, Wisconsin — 8—15 km), or by distortions due to the horizontal inhomogeneity of the sedimentary cover.

Magnetovariational array studies in the western part of the platform show also local conducting zones in the stable basement of the North-American platform. An elongated conducting region was found at the western boundary of the state Dakota [27]. A comparison with geological data showed that this anomaly is caused by graphitized rocks in small depths. Magnetovariational studies along profiles in western America by Schmucker [28], and also a magnetovariational array study made by the University of Texas (USA) and by the University of Alberta (Canada) cover the western part of the North American platform and give valuable information on the electrical homogeneity of crust and mantle. The small time interval of the magnetovariational observations and also the great distances between the stations impede a solution of the inverse magnetovariational problem. But data about deep conductivity in the western part of the North-American platform coincide with results of magnetotelluric soundings on stable platforms covered by thick sedimentary cover. At a depth of 200 — 350 km, the resistivity of the mantle is 10—50 ohmm [29].

4. Among investigations, carried out on other cratons, it is necessary to mention the work accomplished on the Australian continent. Lilley and Tammemagi [30] supplemented the magnetovariational array study in South Australia [31] by magnetotelluric soundings along a profile, crossing the region with anomalous conductivity. The profile is situated only in its western part on a stable platform. At first, a magnetovariational array discovered a region of change of the sign of the Z-component. With the help of magnetotelluric soundings a quantitative interpretation was carried out. A geoelectric section is given in [30] along the profile of magnetotelluric soundings, showing the existence of a strongly conducting layer in a depth of 5 km. Some discrepancy between experimental and theoretical curves is caused most probably by the neglection of the inhomogeneity of the sedimentary cover, which leads to great differences between "maximum" and "minimum" curves in regions, far from the region with anomalous conductivity. But the average curves coincide with the generalized curve of the Russian platform (Fig. 6b). A successful

combination of magnetotelluric and magnetovariational results is difficult because of greater distances between points (100 km).

An analysis of magnetotelluric and magnetovariational data leads to the following results.

1. The conductivity of ancient shields varies strongly in horizontal direction. Graphitized and sulphidized rocks with high conductivity correspond to fracture zones of the crystalline basement. There are great systems of fractures, which form conductive regions with extents of several tens of kilometers.

Moreover, there are large layers of graphitized schists with conductivities of the order of some tens ohm^{-1} m^{-1}. These layers strongly screen the electrical properties of the mantle down to considerable depths. All these hamper the choice of places for deep sounding. The aspects mentioned above, as well as errors in the interpretation of curves in complicated geoelectrical conditions, lead to the considerable differences between the results on ancient shields. At present, we have almost no results, on which a study of the "normal" distribution of conductivity vs. depth in Precambrian shields could be based.

2. The presence of a thin sedimentary cover diminishes somewhat the influence of horizontal inhomogeneities of the ancient basement, but at the same time there is a distortion of another type connected with the inhomogeneity of the sedimentary cover. The information about the depth conductivity is, however, in this regions greater and more reliable than in the shields. A conductive layer at a depth of 15—100 km and some local regions of high conductivity at depths of 5—20 km can be at least traced rather reliably. In the Russian platform it is now possible to trace the "normal" distribution of conductivity without sedimentary cover with the help of a set of sounding curves, with the "generalized" sounding curve.

To obtain a "generalized" curve better reflecting the shallowest part of the conductivity profile, it is necessary to use more reliable sounding data from the shields.

3. Magnetotelluric and magnetovariational studies found many anomalous conducting zones in the crust and mantle. Interpretations of the conducting bodies are based on two or three models. It is difficult to disagree with the opinion of Semenov [5] and Gough [1] that the main cause of the rise of conducting zones in the crust is sulphidization and graphitization of rocks, frequently occurring in zones of disturbances of the stable basement. Regarding anomalous conducting zones in depths of 15 km and more, several theories exist. Such are dehydration at the Conrad-boundary [20], partial melting in presence of a small quantity of water at not very high temperatures [32]. These zones can be also connected with the presence of well-conducting minerals, like

magnetite, ilmenite, sulphide, graphite, schungite etc. This point of view is expressed by A. S. **Semenov** [5] and it is worthy of serious attention. Well-conducting minerals can be often met in a scattered state and they sharply increase the conductivity of rocks even in small concentration (3—5%). (According to **Parkhomenko**'s data, the conductivity of rocks containing 3% of graphite, increases from 10^{-4} ohm^{-1} m^{-1} to 10^{-1} ohm^{-1} m^{-1} and it does not decrease at a heating up to 700 °C.)If the high conductivity of intermediate layers is explained so, then it becomes clear, why the dept of this layer so variable is — 5—10 km in some places, 20 — 70 km in others. In order to determine the nature of intermediate conducting layers, it is very desirable to couple magnetotelluric and magnetovariational methods with deep seismic investigations.

4. Very rich information has been received on the character of crustal and mantle conductivity up to now from induction studies. But the greatest part of the results is of a qualitative character. To receive quantitative results, methods ought to be further improved. First of all, it is desirable to carry out joint magnetotelluric and magnetovariational studies. As the greatest part of anomalous conducting bodies are in the upper part of crust, it is necessary to reduce the distance between stations in magnetovariational profiles and arrays. In order to determine the depth of a conducting body, it is necessary to carry out magnetotelluric sounding directly over the epicenter of the conducting body, because the depth of occurrence can be determined exactly enough by the "minimum" curve only in this case, and this is the more correct, the more elongated the conducting body is [33]. If magnetotelluric soundings are carried out to determine the deep distribution of conductivity, then it is necessary to make the sounding in a region, far from the anomalous conducting areas. The determination of the radius of influence of a conducting zone needs an additional investigation. In the interpretation of sounding curves it is necessary to take into account the character of the inhomogeneity of the sedimentary cover, and this is not a very easy problem. The methods of computation of the effect of sedimentary inhomogeneities are most thoroughly treated by **Berdichevskiy** et al. [34]. But the real situation happens to be even much more complicated. It is necessary to develop theoretical and model investigations in this direction. Particular attention must be paid to investigations of three-dimensional sedimentary inhomogeneities. It is necessary to take into account the vertical inhomogeneity of the crust and upper mantle, too. A certain part of mistakes occurs because of this.

As we see, magnetotelluric and magnetovariational methods are far from exhausting their possibilities. Development of technique and methods will permit to improve the quality of obtained results.

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ИНДУКЦИОННЫЕ ИССЛЕДОВАНИЯ НА СТАБИЛЬНЫХ ЩИТАХ И ПЛАТФОРМАХ

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РЕЗЮМЕ

На Земле больше половины поверхности занимают докембрийские щиты и платформы. Наибольшая часть магнитотеллурических и магнитовариационных исследований проведена на таких территориях. Большинство результатов относится к трем кратонам: к Северо-Американскому, Русскому и Сибирскому. Проводимость древних шитов сильно меняется в горизонтальном направлении. Это происходит из-за наличия большого числа разломов и сильной складчатости древнего основания.

Графитизированные и сульфадизированные породы с малым сопротивлением (0,1—1 Ωm) часто приурочены разломным зонам кристаллического основания.

Хорошо проводящие зоны сильно влияют на пространственное распределение электрического поля и экранируют верхнюю мантию до значительных глубин. Ошибки в интерпретации кривых при сложных геоэлектрических условиях, приводят к значительной нестабильности результатов на древних щитах.

В настоящее время почти нет данных для изучения «нормального» глубинного распределения проводимости на докембрийских щитах. Наличие тонкого осадочного покрытия немного уменьшает влияние горизонтальной неоднородности древнего основани но в то же время замечаются искажения из-за неоднородности осадочного покрытия. Информация относительно зависимости проводимости от глубины в этих районах более надежна, чем на территориях щитов. Проводящий слой на глубине 15—100 км и местные с большой проводимостью на глубине 5—20 км могут быть выявлены сравнительно надежно. Для получения «обобщенной» кривой, лучше отражающей верхнюю часть профиля, необходимо иметь более надежные данные зондирования для щитов.