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New approaches to electrical soundings of horizontally inhomogeneous media

A. A. Bobachev, M. N. Marchenko, I. N. Modin, E. V. Pervago,
A. V. Urusova, and V. A. Shevnin

Lomonosov Moscow University

Abstract. To study horizontally stratified media the vertical electric sounding method may be used. In this case a model of a medium contains three components: a horizontally stratified background, near-surface inhomogeneities, and deep inhomogeneities. Near-surface inhomogeneities are considered as a geological interferences. The new developed technology of continuous electric soundings (CES) includes the technique of field observations, which is fit to use multichannel complexes with computers, and methods of treatment, visualization, and interpretation. The method of suppressing geological interferences, which increases the accuracy of construction of subhorizontal boundaries and deep objects, is an original part of this work. The CES method is suitable to solve archaeology, engineering geology, and ecology problems in regions with a high level of geological interferences (in towns, on mine dumps, near the route of pipelines, cables, and in regions with a broken upper layer).

Introduction

The model of horizontally stratified section, which is usually used in the VES method, is a classical model for explorations. For this case, the observation technique is justified theoretically and tried out practically, and it provides an increase of spacing as geometrical progression in accordance with the depth principle of the VES. To reduce the influence of errors and noises the symmetrical four-electrode setup by Schlumberger is used as a rule. Usually, few MN lines of various lengths are used, which results in segmental VES curves. The VES points are arranged along profiles or on an area. Every curve is interpreted within the scope of a horizontally stratified model of a medium (HSM), and then a total section is plotted where determined boundaries are correlated with points of the VES. Such a technique follows the idea of "electrical drilling," when in isolated points the variations of resistivity versus a depth are investigated, and then a correlation of geoelectric horizons is carried out on a geoelectric section.

When experimental and theoretical VES curves are matched, they often reveal incomplete agreement. It may be caused by both occasional errors of measurements and geological inhomogeneities of medium, which are beyond the scope of the HSM model. By a locally normal VES curve we mean such a curve that corresponds to the real section in the sounding point if all the layer boundaries crossed by a well in a given point are considered as horizontal.

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We will call the differences between the VES and locally normal curves distortions. Analysis of distortions has been initiated by magnetotelluric methods [*Berdichevsky et al.*, 1989; *Dmitriev and Berdichevsky*, 1975] and have had a strong influence on analogous explorations for VES [*Khmelevskiy and Shevnin*, 1994; *Yakovlev*, 1989]. In foreign literature the problems of distortions of VES data are not practically considered.

Different types of distortions are revealed differently on (1) an isolated continuous VES curve (with a single MN line); (2) segmental VES curve (with a few MN lines); (3) a set of VES curves (profile); and a (4) couple of the VES curves measured at one point by the two-side, three-electrode setup (AMN and MNB) [*Khmelevskiy and Shevnin*, 1994].

Analysis of experimental VES data measured at various regions shows that one or another indication of the curve distortions, even for the quietest geoelectric conditions, is revealed on more than 70% of the VES curves. However, the VES method was used for many years without analyzing the distortions caused by inhomogeneities of a medium. In our opinion, analysis of distortions (their detection and suppression) need to be a necessary element of interpretation. In other words, the VES technique should be modified to minimize the damage of distortions.

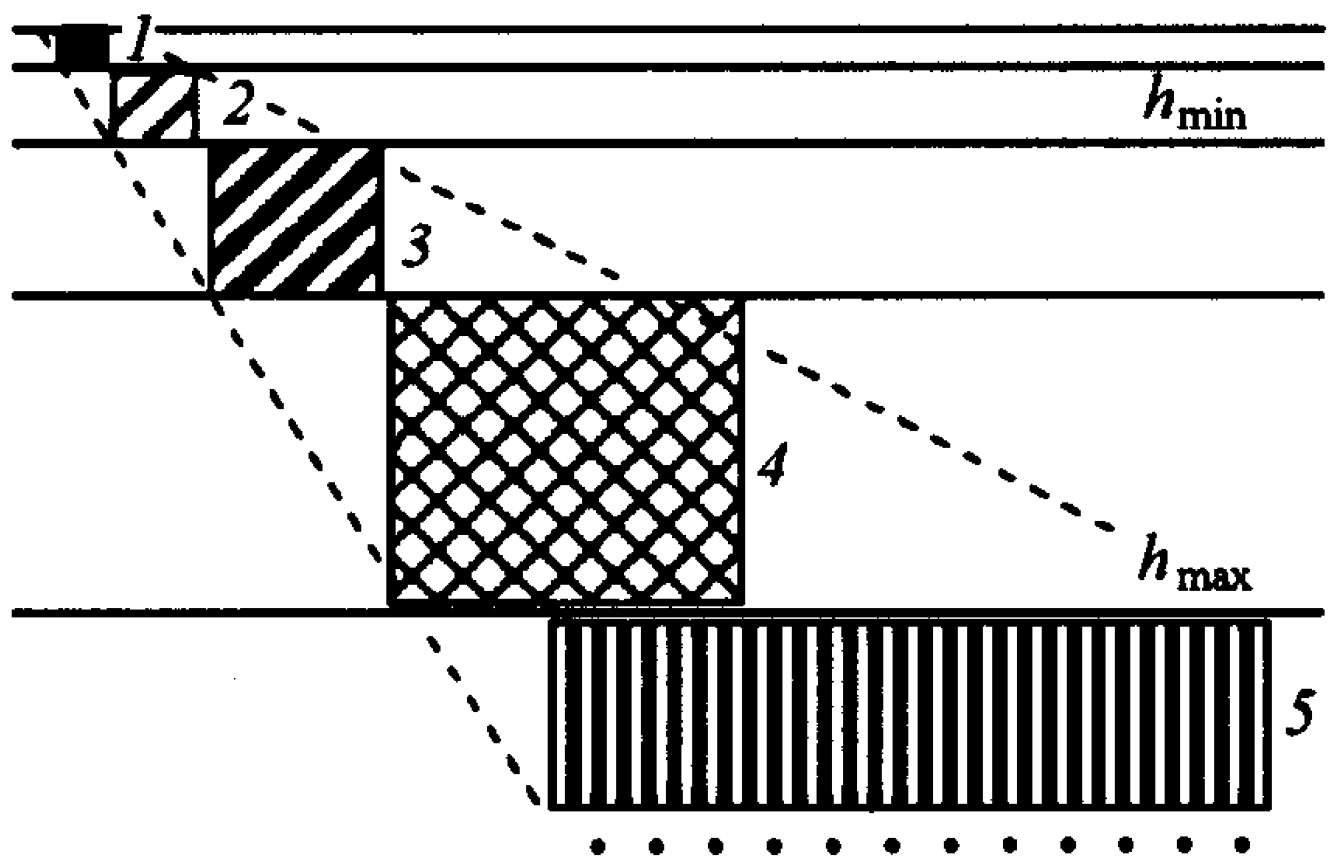

Figure 1. Base model for the CES.

Since 1990 in Moscow State University studies to develop a technique of continuous electrical soundings (CES) for the study of two-dimensional media were carried out. There is much in common with the techniques of electrical imaging by *Barker* [1992] or resistivity tomography by *Shima* [1989]. However, a characteristic of our approach is the extraction of distortion analysis as a separate stage, which defines in many respects a success of interpretation as a whole.

We should consider a combination of a horizontally stratified component, deep inhomogeneities (DI), and near-surface inhomogeneities (NSI) (Figure 1). Deep inhomogeneities (3 and 4), as a rule, are the goal of study. Sizes of deep inhomogeneities define a step of sounding, and a deposition depth defines a required maximum depth.

Near-surface inhomogeneities (1 and 2) are not usually of interest and they are considered as pure geological noise, but their effect may be stronger than the effect of deep inhomogeneities, because they are located closer to the points of excitation and measurement of the field. If there are many near-surface inhomogeneities, their action is similar to the effects of glass covered with a net of numerous cracks or a sea surface covered with a wave ripple. Evidently, those near-surface interferences hinder the detection of deeper objects.

Sizes of near-surface inhomogeneities are usually small. It is practically impossible to obtain information about its detail structure, and as we cannot ignore their existence, it is desirable to reject these interferences before the interpretation.

We have many examples, when a wrong geological interpretation is given for distortions caused by a NSI. The influence of NSI is particularly great in towns, regions with an artificial upper layer (for example, on waste dumps near routes of pipelines and cables). The correction of distortions needs rather closely spaced observations. In this way, we have came to a concept of continuous electric soundings.

The technique of CES is as follows.

1. Sounding points are arranged along a profile with constant spacing.
2. For every point two-side, three-electrode soundings should be held, allowing deep inhomogeneous objects to be brought out from all sides.
3. Power electrodes display along a profile line with arithmetical step on the spacing axis so a step in spacing and the step of a VES on profile would be equal and power electrodes of different soundings would get into the same ground points. For that it is convenient to carry out measurements using the system of electrodes arranged in advance at all the necessary profile stations and to hook up the necessary electrodes by switching.
4. For the interval of depths from h_{min} to h_{max} being studied, the step in profile may be chosen equal to h_{min} or 1/10–1/20 of h_{max}.

In other countries for analogous work, a two-electrode AM setup or a dipole axial setup are more often used. (In American geophysical literature the DAS setup is often called an expander.) In these setups the point of recording is usually related to the middle of spacing. So far as the power and receiving elements of the setup are single electrodes or dipoles, then their functions by virtue of the principle of reversibility are the same, and two-side observations are not required. In the two-side, three-electrode setup that we use the point of recording relates to its stationary element (*MN* dipole). Power and receiving elements of the three-electrode setup are unequivalent, and two-side observations are very useful.

Abroad, similar profile observations are usually performed using the multichannel apparatus (multielectrode scythe controlled by the field microprocessor). Similar apparatus are manufactured by OYO Corporation in Japan, ABEM in Sweden, Scintrex in Canada, Campus in England, *DMT* in Germany, and many others.

Under a traditional increase in spacing by geomet-

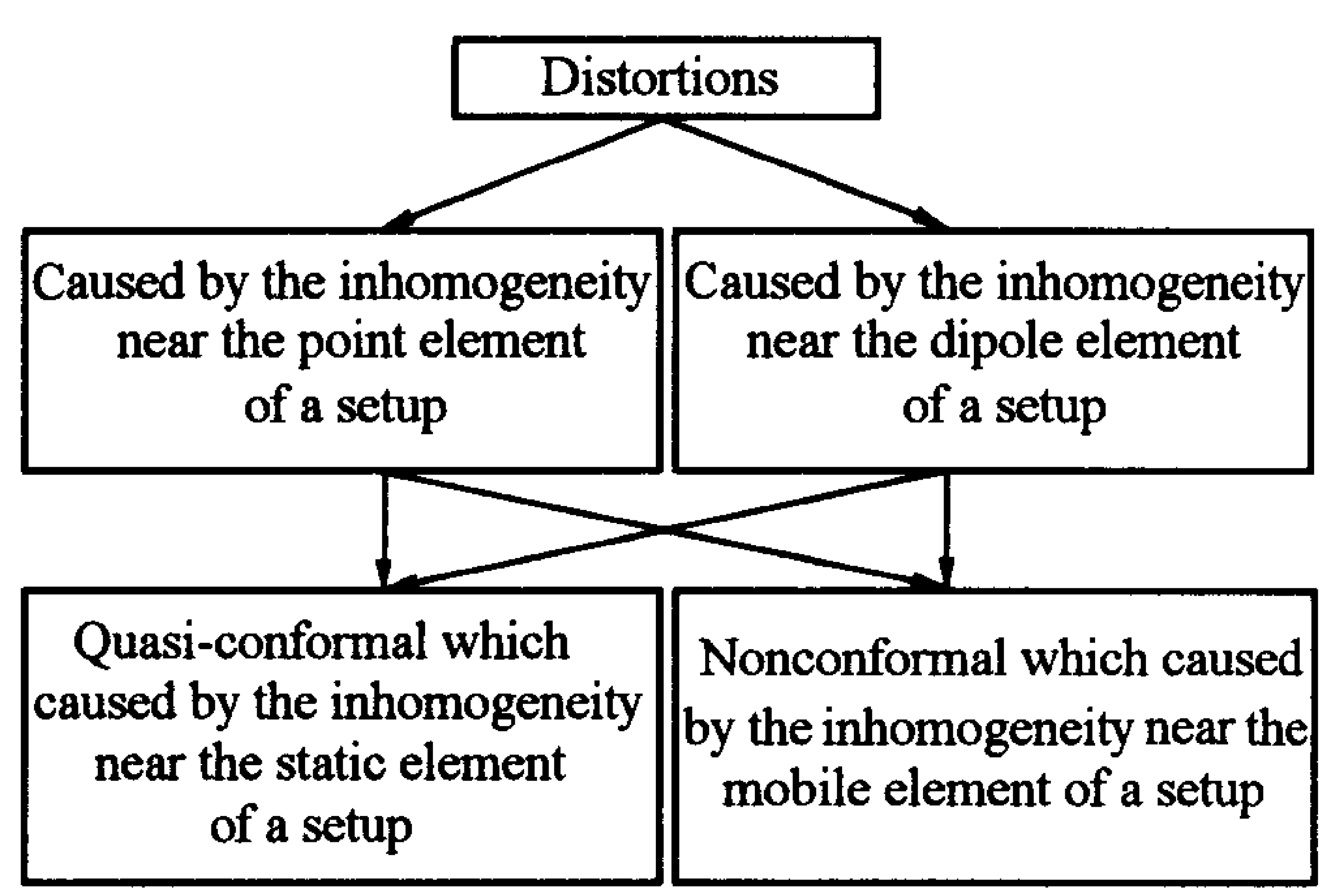

Figure 2. Classification of distortions caused by NSI.

ric progression of the distortions caused by NSI near the moving power electrodes display in the VES curves and pseudosection of apparent resisitivity (from now on we will call it the ρ_a field) as an occasional geological interference. If we perform soundings with spacings increased with arithmetical step equal to a distance between sounding points, then, power electrodes from different VES would fall in the same points, and the exhibition of inhomogeneity in the ρ_a field would be uniform. In the last case it is considerably easier to detect, to classify, and later to eliminate this interference. So, for near-surface inhomogeneities to be more precisely displayed, it is necessary to use an arithmetical step to increase spacings.

In our opinion, the optimal conditions for the use of the CES are the following: the minimum number of VES on a profile is 30, the step on a profile is from 0.5 to 20 m, the depth interval is from 0.2 to 100 m, and the sizes of region under study are from 20 m to 3 km. This allows the problems of archaeology, engineering geology, hydrology, and ecology to be solved.

The change to a multichannel measurement system in the CES method is similar with the change in seismic prospecting by MRW. It is possible to detect wave arrivals using one seismic path and estimating their nature and velocity one may evaluate the boundary depth. However, multichannel reception allows us to resolve phase synchronism axes, to detect a wave nature (direct, reflected, refracted, and so on), to construct hodographs and to estimate velocities, to reveal and to suppress harmonics, and to spatially filter records. The advantages of multichannel recording in MRW are so evident that one-channel measurements (on land) are not practically used and what is more, there is a tendency to increase the number of channels and to pass from a profile measurement system to a surface one. In other countries, the experience of the application of a multichannel system of electric prospecting have shown that they not only provided a substantial increase in information but also increased the productivity of works per unit of profile length in comparison with traditional VES methods.

To use effectively the VES method it is necessary to imagine clearly the nature and morphology of distortions caused by two- and three-dimensional inhomogeneities. For this purpose a great number of models were investigated which contained both near-surface and deep inhomogeneities. Simulations were made with programs of modeling the electric field in inhomogeneous media (IE2DL, FDM2D, IE3D1, IE3D2, and others) which were developed in the Department of Geophysics of the geological faculty of the Moscow State University. On this basis a classification of distortions was made, and ways of detecting them were suggested [*Khmelevskiy and Shevnin*, 1988, 1994; *Modin et al.*, 1994; *Yakovlev*, 1989].

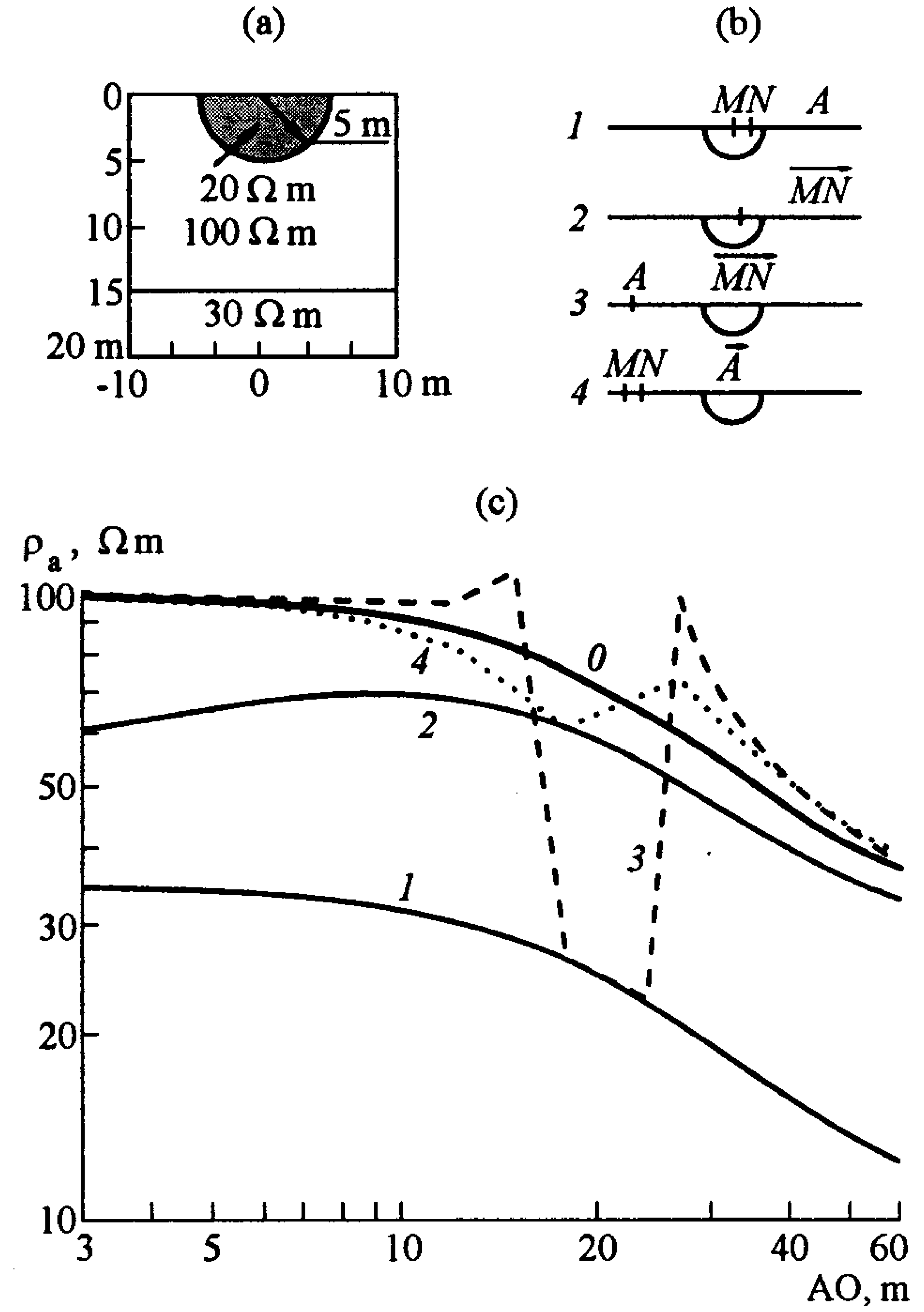

Figure 3. Distortions of the VES curves by near-surface inhomogeneities: (a) model, (b) variations of meeting with a NSI (mobile elements of a setup are marked by an arrow), and (c) curves of the *AMN* soundings.

It was established that the distorting influence of near-surface inhomogeneities depends first on the setup element type (dipole or single) which falls in an inhomogeneity (Figure 2). Besides, distortions depend on choosing the recording point (to which an element of setup is it related: stationary or mobile). The distortions by the inhomogeneities located near a stationary element of a setup and the inhomogeneities crossed by mobile elements of a setup are displayed differently.

Distortions may be revealed on the pseudosection ρ_a obtained by the CES method, as well as on an individual sounding curve.

Figure 3 shows how a half spherical NSI displays on electric sounding curves for a three-electrode *AMN* setup with the recording point related to the stationary element of a setup. The curve 0 corresponds to a background two-layer section without NSI. The curves 1, 2, 3, and 4 correspond to various variants of relative position (Figure 3b) of *AMN* setup elements and a NSI.

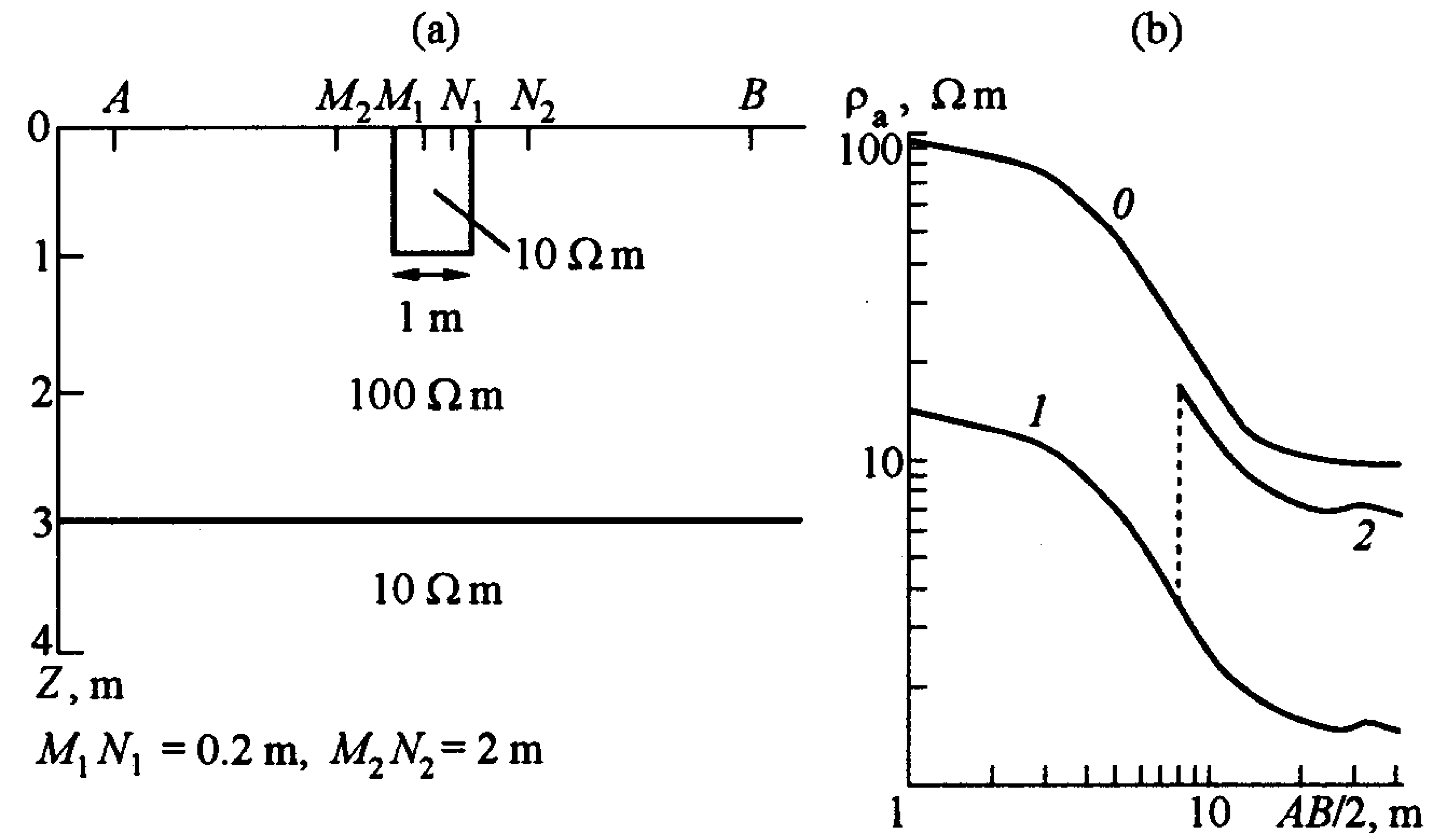

Figure 4. Display of the P effect on the segmental VES curve.

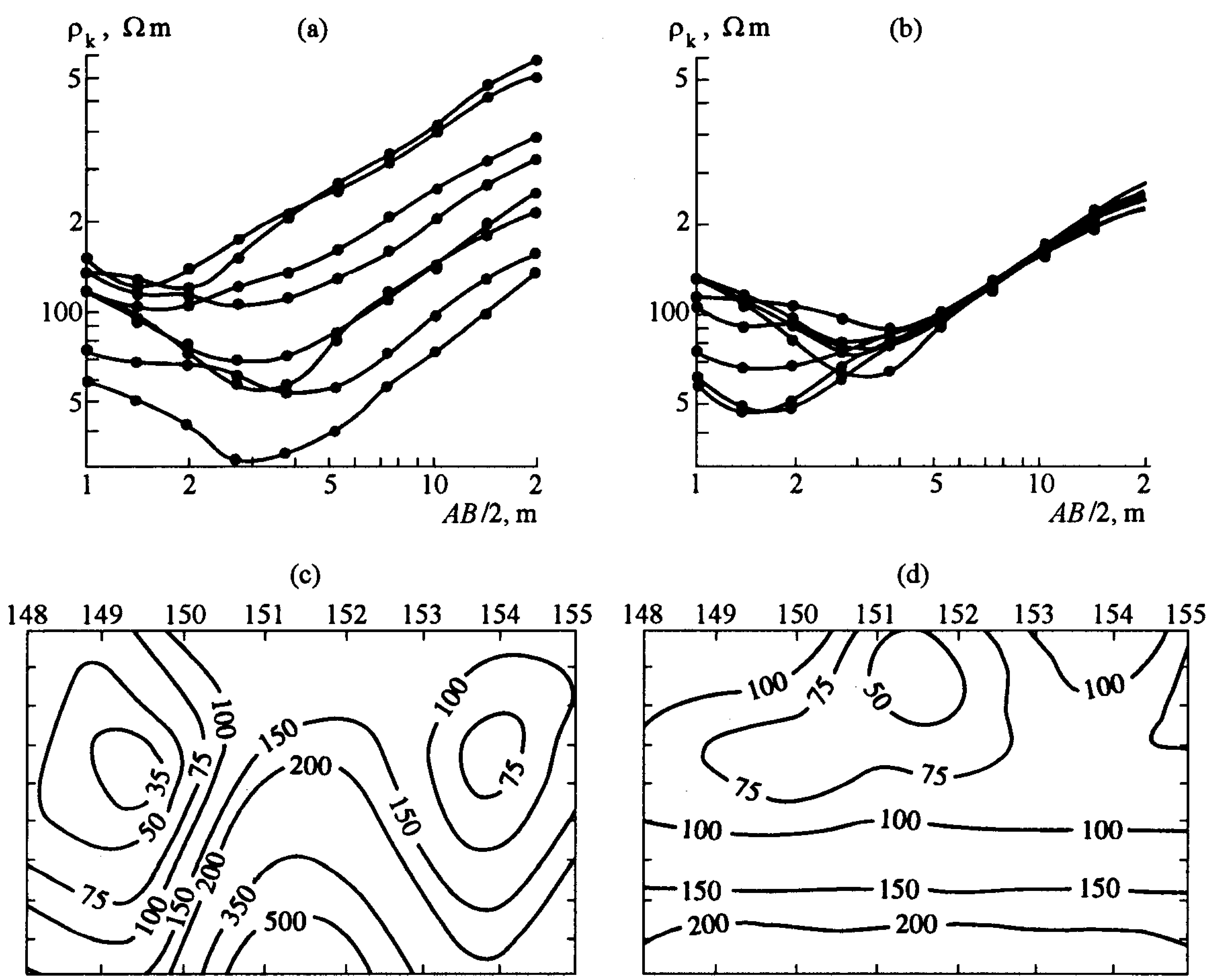

Figure 5. Distortions of experimental VES, P effect (d. Krasnoe, Kulikovo pole): (a, b) VES curves. (c, d) ρ_a sections. Isolines are numbered in Ω m. For Figures 5b and 5d results have been normalized.

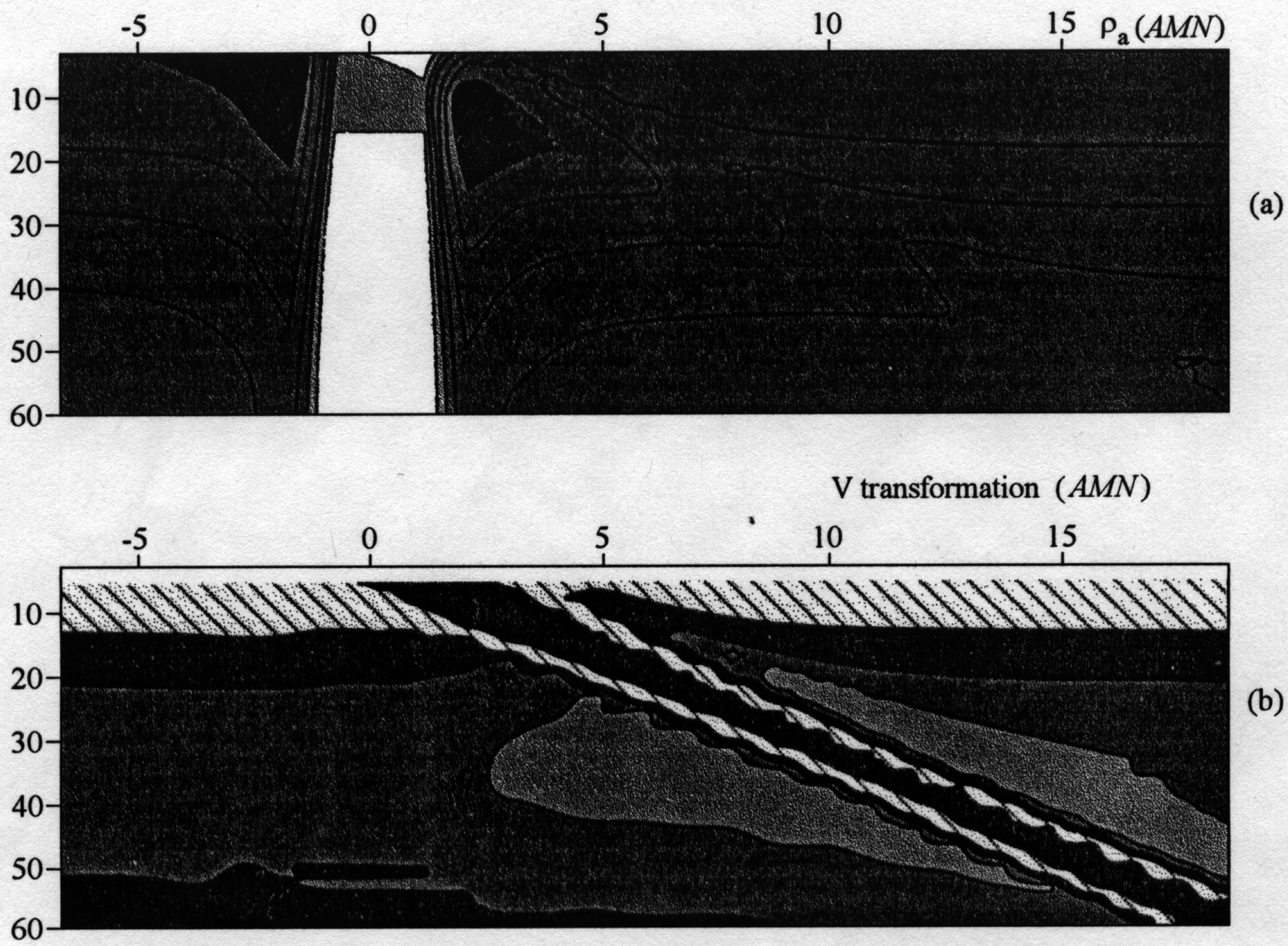

Figure 6. Display of distortions caused by NSI on the (a) ρ_a section and (b) V transformation.

In case 1 the stationary MN dipole is 3 m distant to the right from a center and above a NSI, and the single electrod A migrates to the right. In case 2, single electrod A is 3 m distant to the right of a center and above a NSI, and the MN dipole migrates. In case 3, the stationary single electrod is external to a NSI, and the mobIle dipole MN passes above an inhomogeneity. In case 4, the stationary dipole MN is external to a NSI, and a single electrod passes above it.

In the cases in question we have two types of distortions: (1) quasi-conformal and (2) nonconformal. Quasi-conformal distortions are observed in cases 1 and 2, when the stationary element of a setup is above an NSI. In this case curve ρ_a displays along the resistivity axis almost without changing its form. Nonconformal distortions are observed in cases 3 and 4, when a mobile element of a setup passes above an NSI. In this case, the form of the section of ρ_a curve, which relates to the pass of a setup element above an NSI, changes. Note that the dipole element of a setup reveals effects more strongly in amplitude than a single one (a field changes more sharply on the boundary of an NSI). Note also that cases 2 and 3 correspond to the method of point sounding (PS) (power electrod A is stationary, measuring dipole MN passes along a profile; recording point relates to the electrod A).

Each of the setups (AM, DAS, AMN and MNB, and PS) has both merits and demerits. We only note that the distortions of sounding curves, which are caused by a NSI, exhibit similarly for all these setups.

For the AMN setup we use, with the recording points in the middle of stationary line MN the distortions connected with power and measuring elements are different in amplitude and in form. Therefore to describe them we use the more restricted terms, P and C effects.

We call the P effect distortions caused by a NSI near the receiving dipole MN. In MT sounding [*Berdichevskiy et al.,* 1989] to describe an analogous effect the term "static displacement," "S effect" is used.

The quasi-conformal displacement of ρ_a curves is a sign of the P effect. For a segmental curve the P effect is revealed by an appreciable divergence of segments (1 and 2) in an upright position, with the total form of the curve being remained. If a curve is nonsegmental, the P effect is revealed by comparison of this curve (1) with the adjacent ones (see Figure 4). Elimination of the P effect is called correction or normalization of a curve.

For the segmental curve partial normalization is first performed (all the segments are moved until they would be in contact with each other; usually, they are moved to the segment of greater MN). Comparing the curve

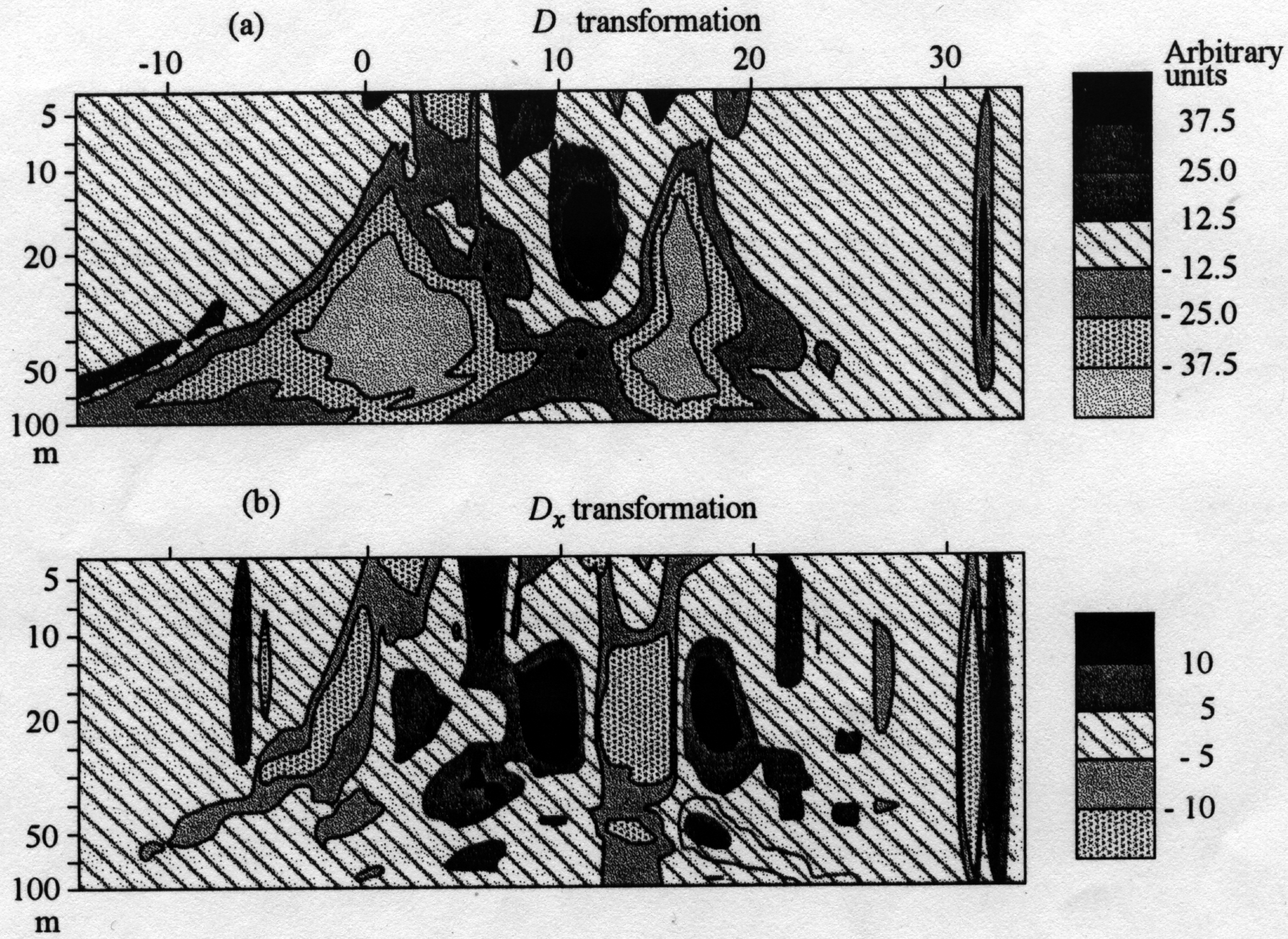

Figure 7. Differentially difference D and D_x transformations in IPI-2D.

in profile one may carry out a more complete normalization if all the curves (Figure 5a) would be shifted to the one mean level in that part of all the curves which is held in profile (Figure 5b). In Figure 5 the experimental VES data that were obtained on an archaeological object near Krasnoe Village are presented on the Kulikovo pole. Maximum half-spacing is 20 m, and a step between soundings is 1 m; therefore different levels of the VES curves cannot be caused by deep

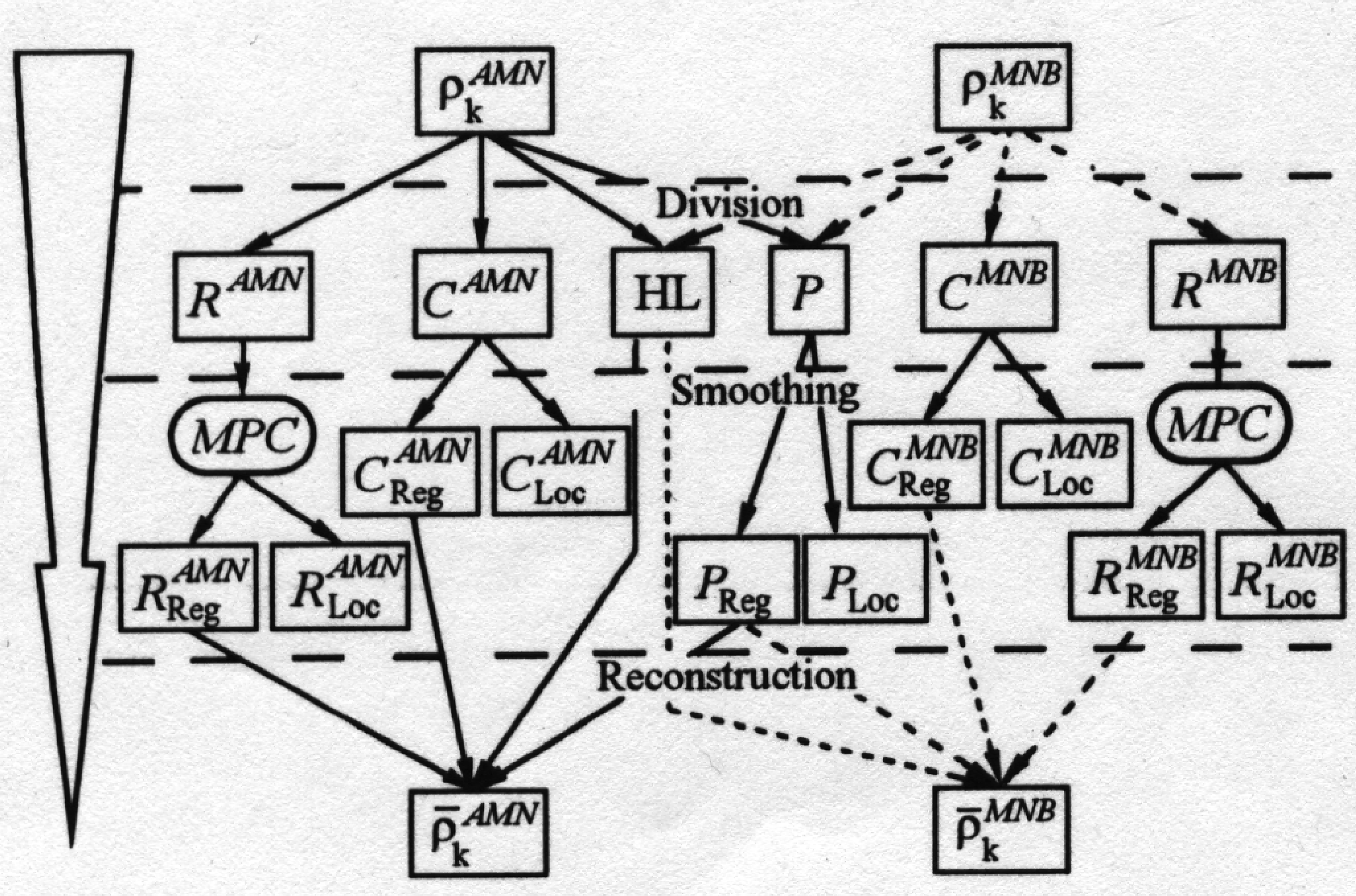

Figure 8. Block scheme of the data treatment by Median program.

objects, although on pseudosection ρ_a (Figure 5c) the isolines resemble a wavelike structure. The curves being normalized,the pseudosection ρ_a looks horizontally stratified (Figure 5d).

We call a C effect the distortions of the VES curves which are caused by a single power electrode moving above an NSI. Using standard VES methods and a pseudosection of apparent resistivities, the C effect is hardly recognized. The exhibition of the C effect on an AMN curve above a half spherical NSI is shown in Figure 3 (curve 4), and the exhibition on the pseudosection ρ_a is shown in Figure 6a. The strong vertical anomaly, which may be seen in Figure 6a, is the P effect, and the C effect may be detected by bending the isolines, i.e., on the ρ_a section a zone inclined by 45° (on the right and down) appears. For the C effect to exhibit better, the section ρ_a should be differentiated along the vertical (with respect to spacing). Such a transformation of the section ρ_a we call a V transformation. Results of V transformation are shown in Figure 6b. One can see that the conformal distortion (in the present case, the P effect) disappears, and nonconformal (C effect) looks more distinct. C effect has a number of features making it still more dangerous than the P effect: (1) the curve form and visible number of layers vary, (2) on pseudosection ρ_a (Figure 6a) it is reveals as an inclined layer, which looks as rectilinear on a arithmeti-

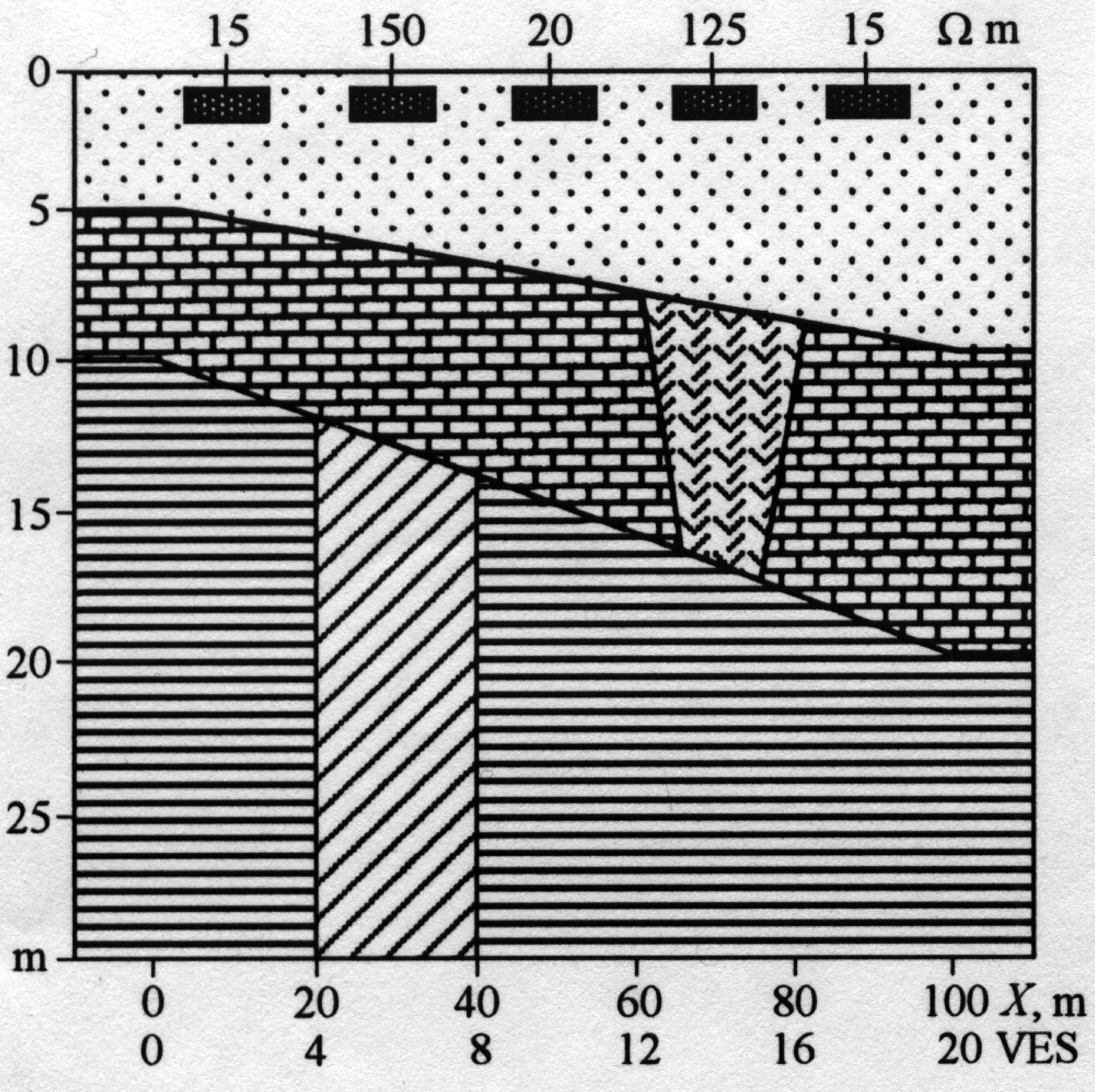

Figure 9. Three-layer model of wedge type.

cal scale of spacing, and bend on a logarithmic scale; (3) with standard methods of sounding by the four-electrode Schlumberger setup and logarithmic step of the increase in spacing the main diagnostic sign of the C effect, regularity, disappears; and (4) on the pseudosection ρ_a the C effect is not very appreciable owing to background variations of a field. To detect clearly the C effect requires the CES method and procedure of visualization (V transformation).

Visualization of the CES Data

The representation of the VES curves as a dependence $\rho_a = f(r)$ is convenient for analyzing a horizontally stratified medium. As the new basic model of a medium (Figure 1) is more complex, then, for each of its elements (HSI, DI, and NSI) its own optimal way of visualization should be found. For this purpose the IPI-2D program complex was made, which allows presenting the CES data in various forms: (1) as a series of CES curves on a profile, where curves for AMN and MNB setups are in agreement at each sounding point; (2) as the pseudosection ρ_a for AMN and MNB setups; they give general knowledge about stratification of a medium, the extent of its variability with the horizontal, and distortions; (3) as differentially difference transformations of pseudosections ρ_a (In figures for all the transformations the value scales are graduated in arbitrary unit (au).) The following transformations are used: (1) D transformation, which is a relative difference of pseudosections ρ_a constructed for the AMN and MNB setups (Figure 7a); and (2) D_x transformation,

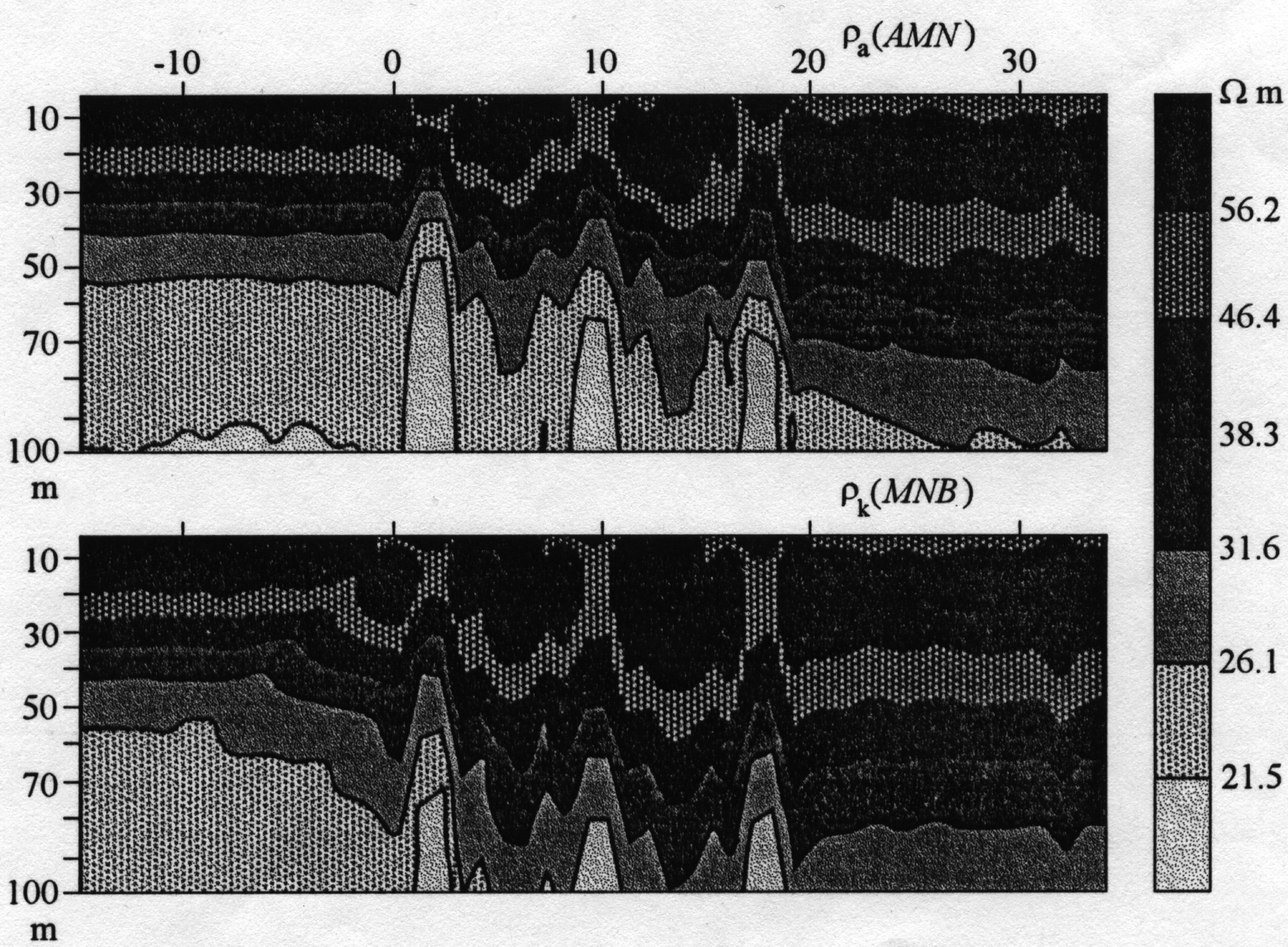

Figure 10. ρ_a sections for AMN and MNB setups.

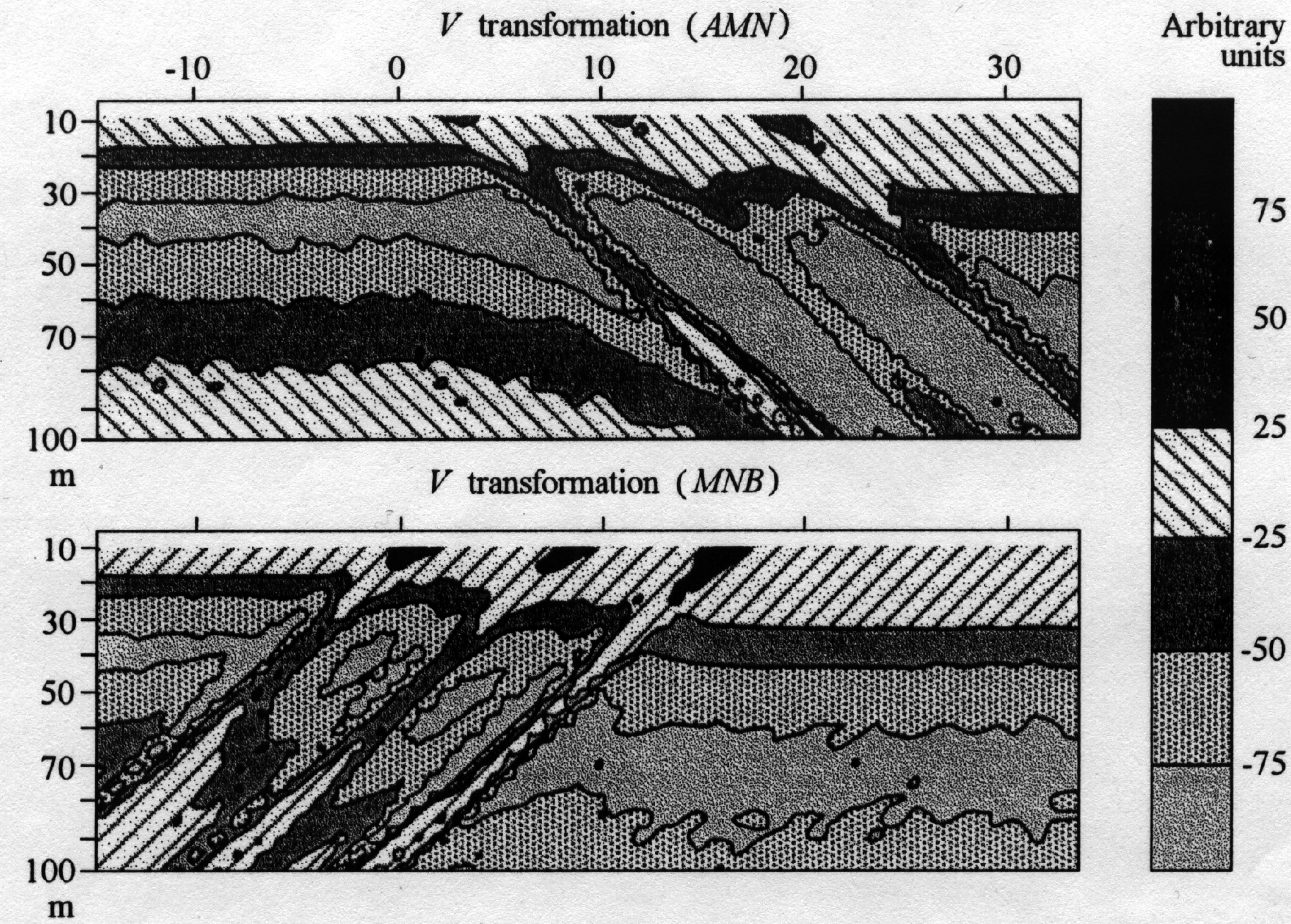

Figure 11. V transformation with the recording point related to the middle of MN.

which is carried out by differentiation of the D transformation in horizontal (in profile) (Figure 7b).

D and D_x transformations allow one to reveal distortions caused by objects located at a great depth. Figure 7a shows that the more strong anomalies may be seen on the 0 and 10–16 PC. After differentiation with respect to x (Figure 7b), the deep object with decreased resistivity is clearly located on the 12–15 PC, which corresponds to a paleovale in Figure 9. The rest of the anomalies have a near-surface origin.

Last, the V transformation is performed by differentiation of the pseudosection ρ_a in vertical (in spacing). This transformation assists one to recognize the C effect. For the image to be more significant, the linear scale in the vertical axis is used. The translation of recording point from the middle of MN to a mobile power electrod is an additional effective procedure, and then the C effect is reflected as vertical anomalies promoting the recognition of it. Examples of the V transformation are presented in Figures 6b, 11, and 12.

In some cases, on the background of the near-surface distortions, the object located at a great depth may be seen using a transformation. In other cases, the near-surface distortions must be removed.

Correction Methods for Distortions Caused by a NSI

Correction of the *P* Effect

To correct the P effect, several procedures may be used: (1) statistical normalization, which is realized in the Median program; and (2) in simple cases it is possible to use hand normalization (reduction of all the curves to one specified level using the one curve section chosen by an investigator, which is common for all the VES curves) (see Figure 5). For the case presented in Figure 5, the step along a profile is much less than a maximum spacing; then, the right parts of the VES curves have to reach the common level of apparent resistivities. The normalization, the results of which are presented in Figures 5b and 5d, was made using the right parts of these curves.

Correction of the *C* Effect

To correct the C effect, statistical normalization algorithms realized in the MPC and Median programs may be used.

The method of principal components (MPC) program

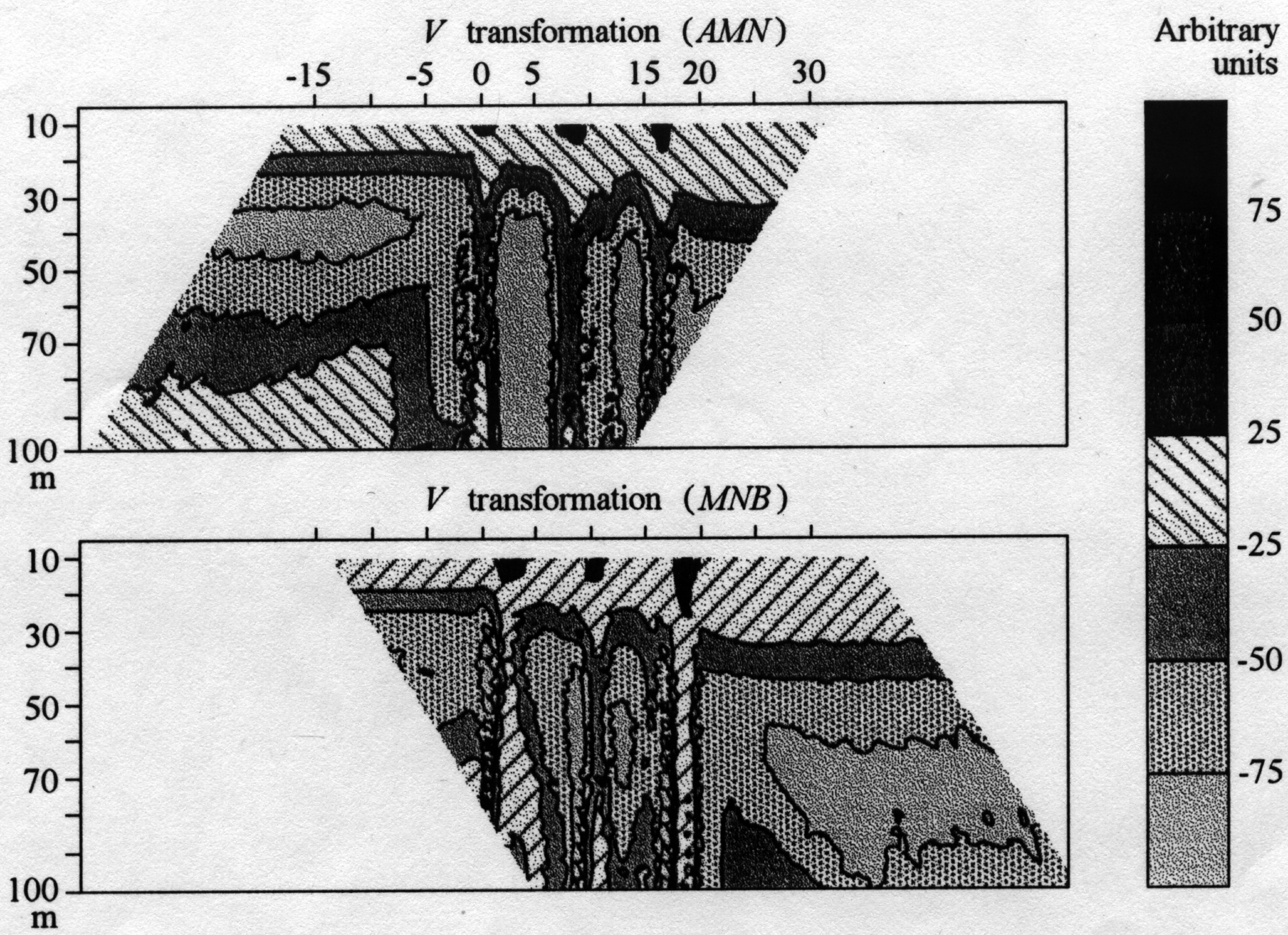

Figure 12. *V* transformation with the recording point related to electrodes *A* and *B*.

employs the algorithm MPC, which is a form of factor analysis well-known in statistics. This approach is often used for treatment of multidimensional statistical geophysical information. The MPC allows expanding the sign fields in linearly independent components in decreasing order of dispersion. In this way, the geophysical anomalies may be revealed on one or several components if in these components the distribution functions

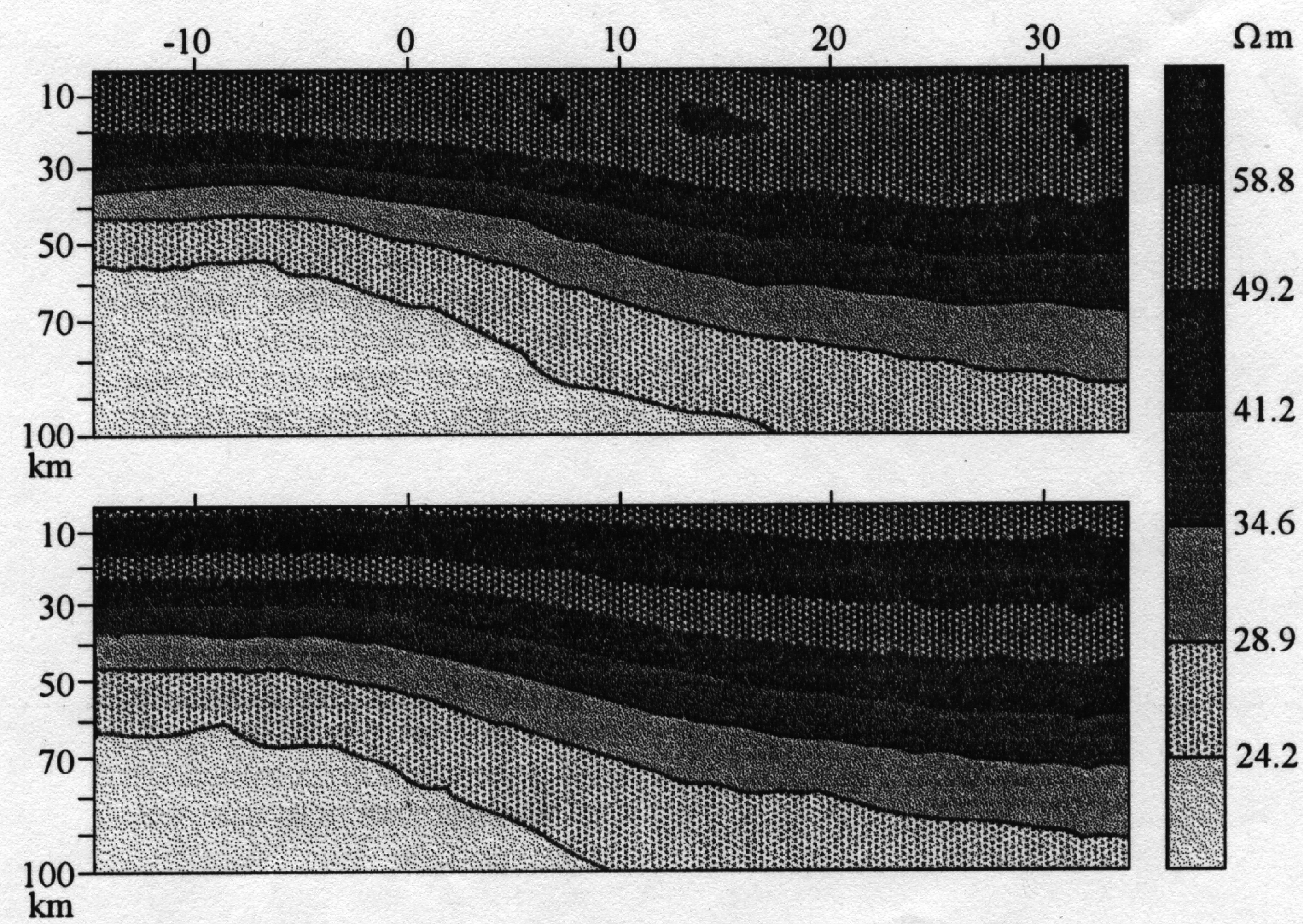

Figure 13. Comparison of ρ_a sections for the model without the deep object.

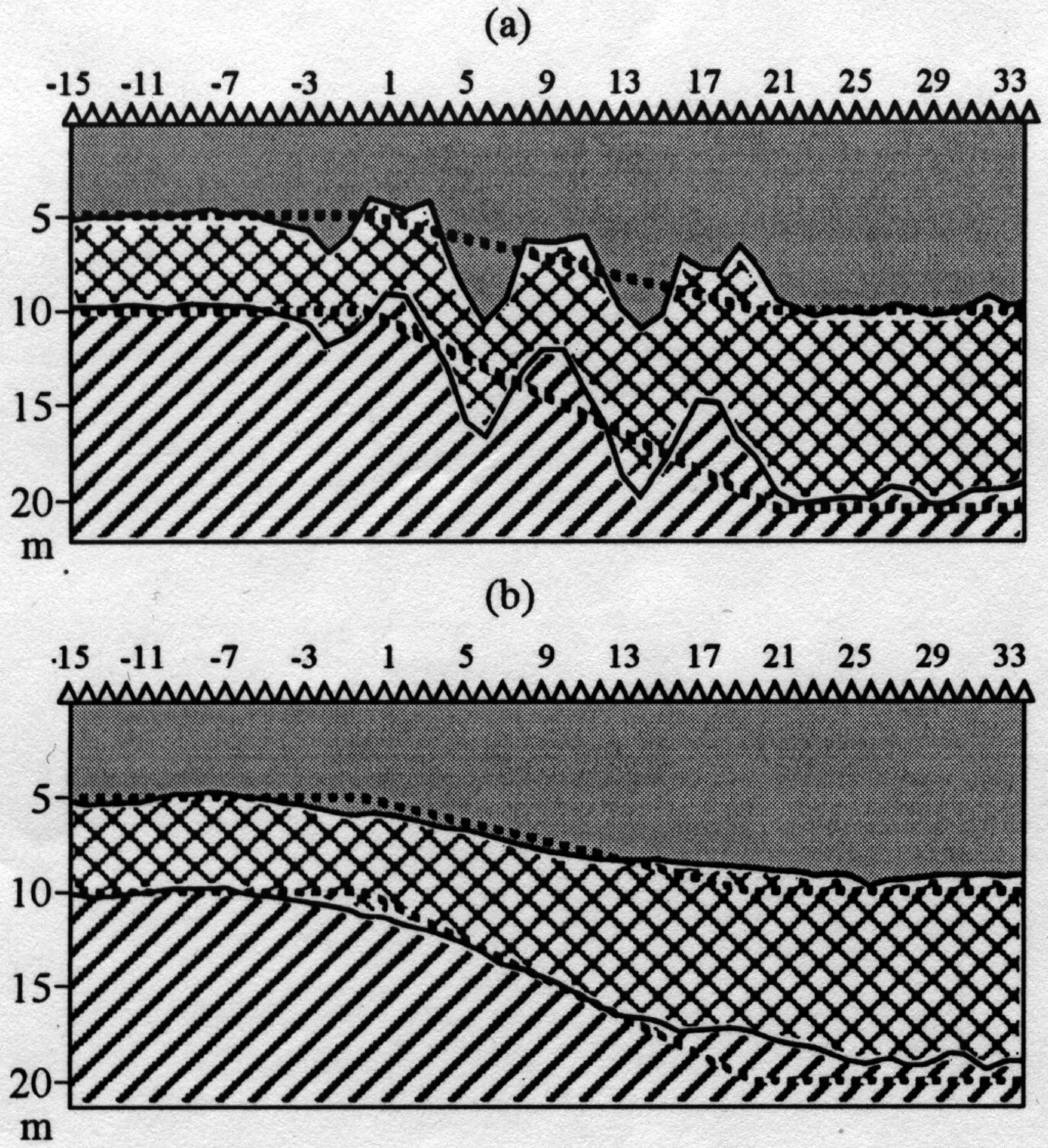

Figure 14. Comparison of results of one-dimensional interpretation of wedge (a) before and (b) after treatment.

of objects may be separated. For the first time, to analyze the apparent resistivity sections obtained above a two-dimensional geoelectrical structure, the principal component method was used by *Venzalek* [1991].

As applied to vertical electric sounding, the idea of the method may be stated as follows. Let the values of apparent resistivity on N spacing and M stations be recorded on a profile of observations. We will treat a set of apparent resistivity values on each spacing as an individual test. Then each station will be seen as a point in the N-dimensional space, and we will have M such points. The boundaries of the region of point distribution in N-dimensional space are approximately described by an N axes ellipsoid. The aim of the MPC is to rotate the coordinate axes so that they will be directed along the principal axes of the N axes ellipsoid. Then, projecting the points on these axes, we will obtain independent noncorrelating parameters, which are called the principal components. Summation of all the principal components gives an original field (pseudosection ρ_a). If the components of the more greater order, which give minor contribution in the total field dispersion, are rejected, then the MPC operates as a method of spatial filtration, with the form of a low-frequency component conserved and high-frequency anomalies effectively suppressed. Experimental studies showed that key information about a geoelectric section is included in the first one-three components. After treatment with MPS the distinctions between the two ρ_a sections for AMN and MNB setups are sufficiently decreased and they may be united in one section corresponding to the $AMNB$ setup.

Operation of the Median program consists of three stages: division of the field into components, smoothing (filtration) them and reconstruction of the field. A block scheme of the program is presented in Figure 8. In the first stage of algorithm operation the pseudosections ρ_a for setups AMN and MNB are divided into a horizontally stratified part, C and P components, and the rest R. For such a division the algorithm of median polish by *Tukey* [1981] is used, which gives a program name. The components C, P, and R contain local high-frequency anomalies (in fact, C and P effects and accidental noise) and regional (low-frequency) anomalies. In filtrating the local components from C, P and the rest R are removed.

To remove more effectively the local components one can also use the MPC algorithm. After such a treatment the regional components together with the horizontally stratified component form again the ρ_a field, but it is now distortionless and free from accidental noises. The correctness of all these operations is subject to additional testing by several types of models. However, so far we do not detect any examples of noncorrect operation of the algorithm.

So, the treatment methods realized in IPI-2D allow one to reveal the distortions by near-surface inhomogeneity and to remove them and effects of inhomogeneity located at a great depth. Stratified section and deep anomalies may be exposed to quantitative interpretation both separately and simultaneously.

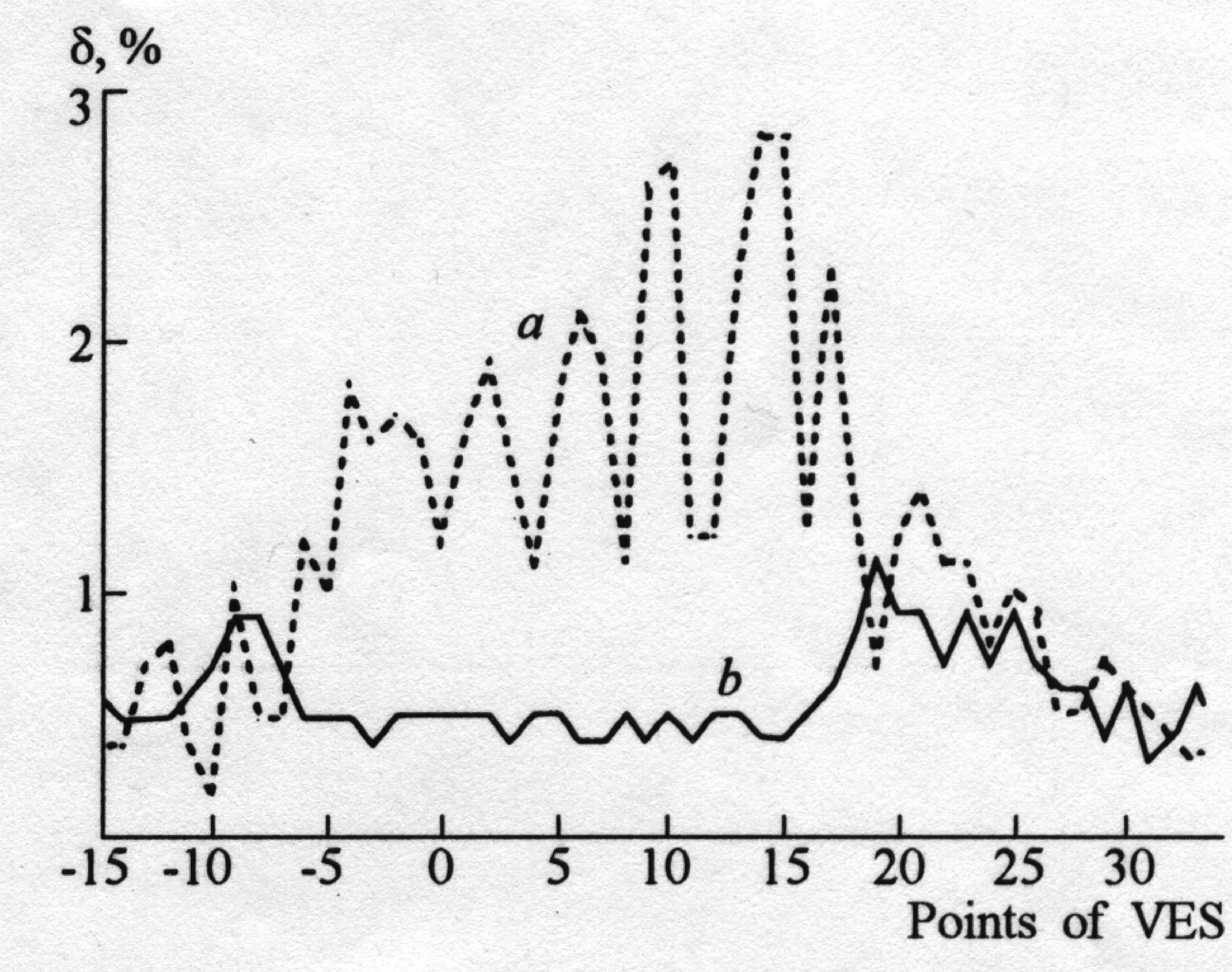

Figure 15. Mean-square error of interpretation of VES (a) before and (b) after the treatment.

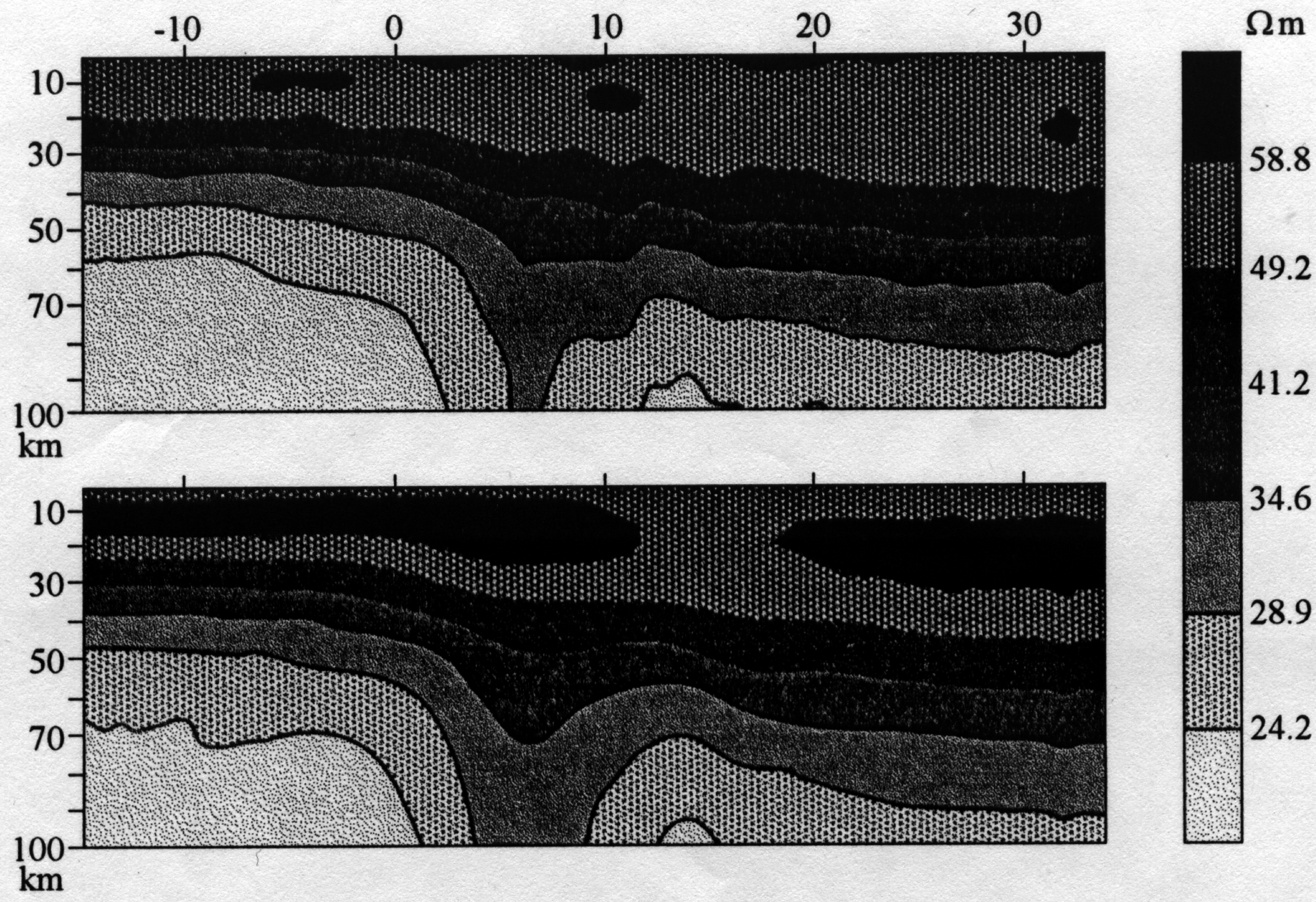

Figure 16. Comparison of ρ_a sections for the model with deep objects.

Model Example

Let us show the possibilities of proposed methods using a three-layer model with wedge-formed change of the two layers. The central part of the model is shown in Figure 9. Beyond its boundary inhomogeneities are absent, and all the boundaries are extended horizontally. There are five inhomogeneities with a 10 m width and a separation of 10 m, imitating two near-surface inhomogeneities, in the first layer. The second layer contains the inhomogeneity of decreased resistivity, which imitates a paleovale, and the third layer is crossed by a zone of decreased resistivity or a zone of fracturing. In the first series of calculations (Figures 10–15) the properties of a paleovale and fracturing zone are adopted as equal to the properties of the stratums contained them, and, in this way, these deep objects are excluded from calculation. The VES step along a profile is 5 m, the VES spacing increases with a 5-m step from 5 to 100 m (Figure 9).

The pseudosections ρ_a for the AMN and MNB setups are shown in Figure 10. The background three-layer section of the K type in the central part is strongly distorted by near-surface inhomogeneity and by the influence of the wedge itself. The P effect of the NSI is well revealed on the pseudosection ρ_a, and the C effect is more evident on the V transformation sections (Figures 11 and 12).

With the recording point being referred to a receiving electrode, the zones of C effect are shown in Figure 11 as stripes inclined by an angle of 45 degrees (on the right and down for AMN and on the left and upward for MNB). With the recording point being referred to power electrodes, the zones of the C effect are vertical (the PC region from 0 to +20)(see Figure 12).

If experimental data are transformed to the $AMNB$ setup

$$\rho_a^{AMNB} = (\rho_a^{AMN} + \rho_a^{MNB})/2$$

and one-dimensional interpretation is performed, then, the form of boundaries will be strongly distorted (Figure 14a) (deep structure is studied as through a broken glass). If the filtration of distortion is performed, then, pseudosection ρ_a (Figure 13a) looks just like the one calculated in the absence of NSI (Figure 13b). After that, the one-dimensional interpretation reproduces the "wedge" structure with the substantially greater accuracy (Figure 14b). The value of mean square error of the interpretation of VES curves (error of closure) may be regarded as an additional estimate of the treatment quality. The curves of such errors before and after treatment for all the points of VES along a profile are presented in Figure 15. We have stated using both theoretical models and experimental data that after treatment the error of interpretation decreases appreciably, and the more appreciably there, where NSI were (PC 0–20).

For a complete model of wedge type including the inhomogeneities located at great depth an analogous treatment was performed to remove the distortions caused by NSI (PC 0–20). After treatment the pseudosection ρ_a (Figure 16a) is not different from the theoretical one calculated for the model without NSI, but with the object located at great depths (Figure 16b), that is, on removing the distortions caused by NSI the influence of deep inhomogeneities is conserved. The form and position of deep objects are revealed using the transformations, and then a model of the section, including the layered structure and inhomogeneous objects, is refined by the process of two-dimensional selection.

For the last 3–4 years nearly 20 sections in the various regions of Russia, Ukraine, and Germany have been studied. Scientists have decided the problem connected with the study of small-amplitude tectonics in Donbass (Donezkaya and Rostovskaya), detection of karst sections along the oil pipeline in Nizhegorodskaya oblast, study of pollution by oil products and by agricultural products at a depth from 0 to 50 m in Moskovskaya and Samarskaya oblasti and in Germany, archaeological research (Manezhnaya ploshad, Moscow), research for underground constructions, study of dumps, and so on. In all these cases the use of CES methods allows one to increase the reliability and accuracy of detecting geological boundaries and local inhomogeneities of various nature.

Conclusions

The CES methods used in this work allow complex geological problems to be solved with greater accuracy than the traditional VES method. It clears the way to investigations in regions with a high level of geological interferences and makes the detail of investigations and accuracy of indication of geological objects available. The algorithm made in the IPI-2D program package is the basis for this technique.

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