Program for one-dimensional interpretation of data obtained by magnetotelluric soundings (MT, AMT, RMT).

ZONDMT1D

User manual

Contents

Program functionality

«ZONDMT1D» a computer program for 1D interpretation of profile data obtained by magneto telluric soundings via MT, AMT, and RMT modifications. Friendly interface and ample opportunities for data presentation allows solving assigned geological problem with maximum efficiency.

«ZONDMT1D» is an easy-to-use instrument for automatic and interactive profile data interpretation and can be used on IBM-PC compatible PC with Windows system.

Electrical resistivity (ER) (units are the ohm*meter (Om*m)) is a measure of how strongly rocks oppose the flow of electric current and is the most universal electromagnetic property. In rocks and ores it varies within wide limits: from 10^{-3} to 10^{15} Om*m. For the most widespread sedimentary, volcanic, and metamorphic rocks ER depends on mineral composition, physical-mechanical and water properties, salt concentration in groundwater, in a less degree on their chemical composition, and on other factors (temperature, depth of occurrence, metamorphism degree, etc.) [Hmelevskoj, 1997].

Electrical resistivity of minerals depends on their crystal bonds. Dielectric minerals (quartz, micas, feldspars, etc.) which mostly have covalent forces are characterized by very high resistivity (10^{12} - 10^{15} Om*m). Semiconductor minerals (carbonates, sulfates, haloids, etc.) which mostly have ionic bonds are characterized by high resistivity (10^{4} - 10^{8} Om*m). Clay minerals (hydromicas, montmorillonite, kaolin, etc.) have ion-covalent bonds and are characterized by quite low resistivity.

Ore minerals (native and some oxides) have electronic conduction and carry current very well. First two groups of minerals create "rigid" matrix solid material. Clay minerals create "plastic" matrix solid material that is able to adsorb bound water whereas rocks with "rigid" minerals can adsorb only solutions and free water (water that can be extracted from rock).

Electrical resistivity of free groundwater changes from Om*m unit fractions in case of high total salt content to 1000 Om*m in case of low one. Chemical composition of dissolved salts does not really matter that is why electrical exploration allows assessing only total salt content. Electrical resistivity of bound water that is adsorbed by solid particles of rocks is very low and does not change greatly (from 1 to 100 Om*m). Its constant mineralization (3-1 g/l) explains this fact. Average mineralization of ocean water is 36 g/l.

Pore water (bound and free) has very low electric resistivity in comparison to matrix of the majority rocks, that is why electric resistivity of rocks is almost independent of their mineral composition but depends on porosity, fracturing, and water saturation. Increase of their values causes decrease of electric resistivity because ion content in groundwater grows. This is the reason why electro conductivity of the majority of rocks is ionic (electrolytic).

Rise of temperature in 40^0 causes resistivity decrease in half. It can be explained by ion mobility increase. Resistivity of rocks increases unevenly at freezing as free water becomes almost dielectric and electro conductivity is determined only by bound water that freezes at very low temperatures (below -50^0 C). Increase of resistivity in different rocks while freezing varies: several times in clays, up to 10 times in hard rocks, up to 100 times in clay and sandy loams, and up to 1000 times and more in sands and coarse rocks.

Despite the fact that resistivity depends on numerous factors and varies within wide limits in different rocks, main laws of ER are well determined. Volcanic and metamorphic rocks are characterized by high resistivity (from 500 to 10000 Om*m). Among sedimentary rocks high resistivity (100 – 1000 Om*m) can be found in rock salts, gypsums, limestones, sandstones, and some other rocks. As a rule, in detrital sedimentary rocks the more grain size is the higher resistivity rock has, that is ER depends on clayiness on the first place. In passing from clays to clay and sandy loams and sands resistivity changes from unit fractions and first Om*m to tens and hundreds of Om*m [Hmelevskoj, 1997].

System requirements

«ZONDMT1D» can be installed on PC with OS Windows 98 and higher. Recommended system parameters are processor P IV-2 GHz, memory 512 Mb, screen resolution 1024 X 768, color mode – True color (screen resolution change is not recommended while working with data).

As far as the program actively uses the registry, it is recommended to launch it as administrator (right click on program shortcut – run as administrator), when using systems higher than Windows XP.

Program installation and deinstallation

«ZONDMT1D» program is supplied on CD or by internet. Current manual is included in the delivery set. Latest updates of the program can be downloaded from website: www.zond-geo.com/english.

To install the program copy it from CD to necessary directory (for example, Zond). To install updates rewrite previous version of the program with the new one.

Secure key SenseLock driver must be installed before starting the program. To do that open SenseLock folder (the driver can be downloaded from CD or website) and run InstWiz3.exe file. After installation of the driver insert key. If everything is all right, a message announcing that the key is detected will appear in the lower system panel.

To uninstall the program delete work directory of the program.

Adopted definitions

Ro_a – apparent resistivity.

Phi - impedance phase, degrees. Positive number.

Period is inverse value of measurement frequency, seconds.

Pseudodepth – approximate depth of investigation connected with skin-layer thickness.

All geometric values are specified in kilometers.

Creation and opening of data file

To start up «ZONDMT1D» it is necessary to create data file of certain format which contains information on measurement times (seconds) and apparent resistivity and phase values. One profile data usually corresponds to one file.

Apparent resistivity or phase versus period curve is considered as data element in «ZONDMT1D» program. That's why data should be represented as a set of sounding curves.

Field data file	Open Zond data file.

Project data file	Open Zond project file.
Model data file	Open model data file.
EDI data file	Open EDI data file.
J data file	Open J data file.
StrataGem data file	Open StrataGem (*.*) data file.

Text data files of «ZONDMT1D» format have «*.mdf» and «*.mdp» extensions. See **data file format** for details.

For correct running of the program data file must not contain:

- curves with less than 3 periods;
- incorrect symbols of records separator (TAB and SPACE use only);
- absurd data values.

Desirably, total record number should be no more than 5000 in one file. It influences operation speed. Previous interpretation model loads together with field data while opening «*.mdp» file.

Program also supports the most popular data formats: EDI, StrataGem (*.*) and J files.

To open these files, select the appropriate option in the pop-up menu. When the item Field data file is selected, program also allows working with USF (Universal soundings format) and *.mt formats.

In case initial file does not contain station coordinates, **Station locations** window (fig. 1) appears at file opening. User can specify point coordinates manually, copy data from Excel or load text file with coordinates via button in this window.
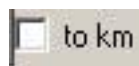
Toolbar buttons allow performing the following coordinate transformations:

 - convert the geographical coordinates in rectangular

 - convert geographic coordinates to UTM system

 - specify the units. By default, the coordinates and height are given in meters, when choosing the option - in kilometers.

Fig. 1 Stations locations window. Definition of sounding station coordinates

Sounding points table contains the following columns: Name - the name of the source file, X, Y, Z - coordinates and elevation of the point, v - t include or exclude point.

Setup of profile line(s) for areal survey data.

Once all data files are loaded, it is possible to set profile line(s) in the **Line setting** window (Fig. 2). It shows areal positions of sounding stations.
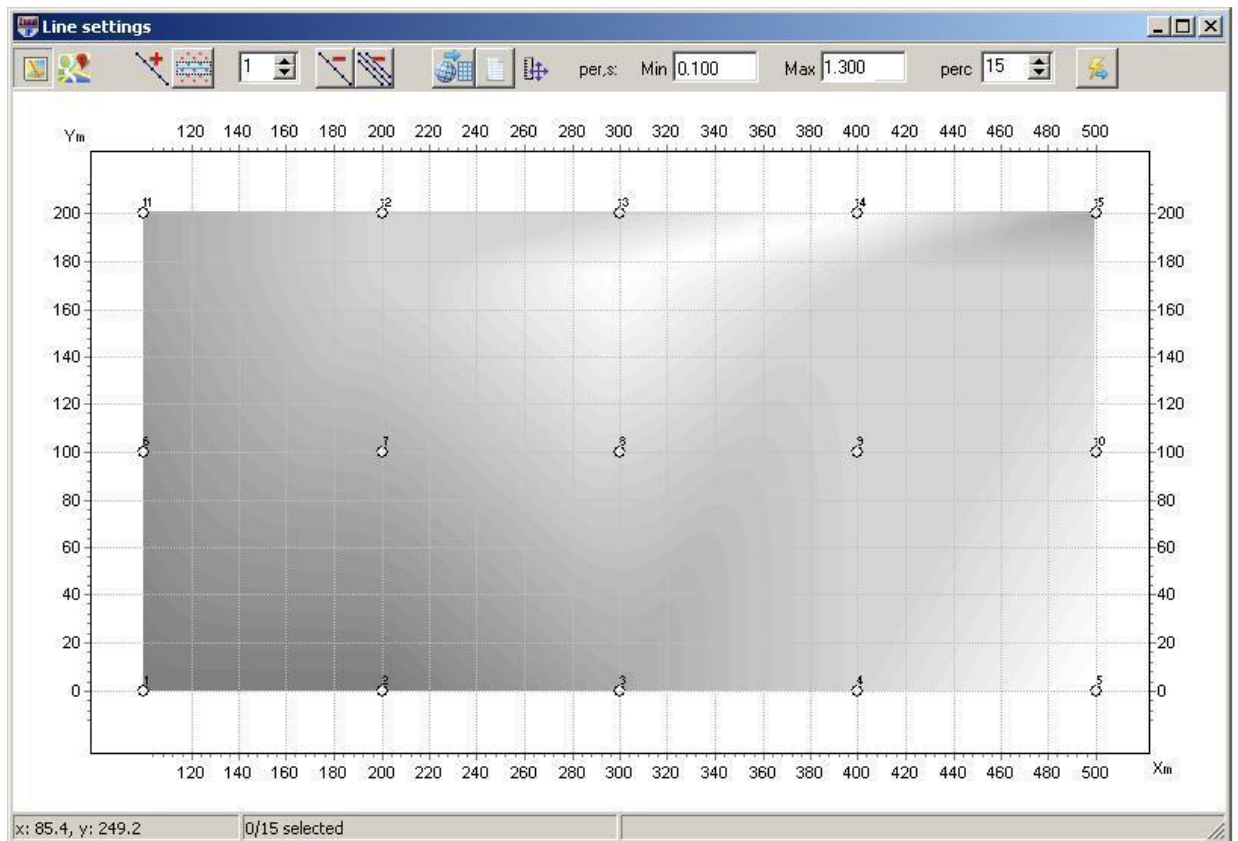
Fig. 2 **Line settings** dialog window for setting profile line\lines, working with areal data. Topo isolines are drawn.

Window main toolbar contains the following functions:

	Function
	Load raster file of map.
	Load Google map.
	Add profile line. Left click to set profile points, right click to specify the last point.
	Include sounding stations (located within rectangular area around selected line) in profile automatically.
	Set active profile number
	Delete current profile.
	Delete all profiles.
	Recalculate geographical coordinates to rectangular. When EDI files are loaded they are recalculated automatically. If file is known to contain geographical coordinates (latitude and longitude) beforehand then prior to interpretation they must be recalculated to rectangular coordinates using this button.
	Open and edit table of coordinates.
	Select image scale: equiaxial or maximum window filling.
Frq: Min-Max	Set minimum and maximum sounding frequency respectively. Out-of-range measurements are not loaded to the program.

Perc	Set size of sounding station automatic selection domain for profile.
	Start data inversion for selected profile set.

A few profile lines can be specified in the program simultaneously. When profile and all points around it are set, all included in profile points are displayed in blue. Left click to include/exclude profile point. If profile line does not cross points then position of sounding station projection is displayed in green. Press button to start data interpretation when profile is set. Main window of the program appears then.

Usually, data contain information about TM and TE modes. After loading, supplementary buttons appear in the toolbar. They allow choosing type of data polarization:

Tm	Use TM mode data.
Te	Use TE mode data.
S	Use effective curves (averaged TM and TE).

Data file format

Program presents universal data format which consists of information on coordinates and relative elevations of sounding stations.

«ZONDMT1D» *data files* format (*.mdf extension).

First line – contains sequence of measurement periods (in seconds) in increasing order of magnitude.

Information on each sounding station follows. It is divided into described below blocks.

Sounding station description block

First line – indicates beginning of sounding station description block (must contain «{» symbol).

Second line – sounding station name.

Third line – supplementary sounding parameters.

First record – sounding station coordinate along profile. Second record – relief elevation (positive number; minimum height is taken equal to 0, others are calculated as elevations above it (in meters)).

Forth and fifth lines contain field data.

Each line must start with code-key which shows the program what type of data follows this key.

Code-keys which control data type have the following values:

«Ro_a» – apparent resistivity.

«Phi» – impedance phase (positive number).

If «_w» is added to the key then certain measurement weights are specified in current line.

Number and order of records in lines must strictly correspond to acquisition geometry described in the second and third lines of the file. If measurements at some periods are missing, their values are replaced by «*» symbol.

Sixth line – indicates end of sounding station description block (must contain «}» symbol).

Stations must be recorded in the same order as on profile (in increasing order of coordinate).

In case of controlled-source sounding (fig. 3) key word **controlled source** must be entered in the first line of the file. After the key coordinates of potential line beginning and end must be entered: Ax Ay Bx By.

For example:

controlled source AB= -10000 -1000 -10000 1000

In addition position of current line and antenna must be specified after coordinates in station description block. For example:

EMN= 0 -0.5 0 0.5 Hc= 0 0 Hdir= 1 0

where EMN – four records – beginning and end of potential line Mx My Nx Ny, Hc – X and Y coordinates of magnetic antenna and Hdir – antenna direction cosines.

{

station1

0.0 1.0

EMN= 0 -0.5 0 0.5 Hc= 0 0 Hdir= 1 0

ro_a 37.016 36.857 44.230 48.167 52.694 61.749 72.687 76.278 79.726 83.422

phi 49.985 43.093 37.668 36.851 36.516 36.915 38.421 39.039 39.749 41.216

}
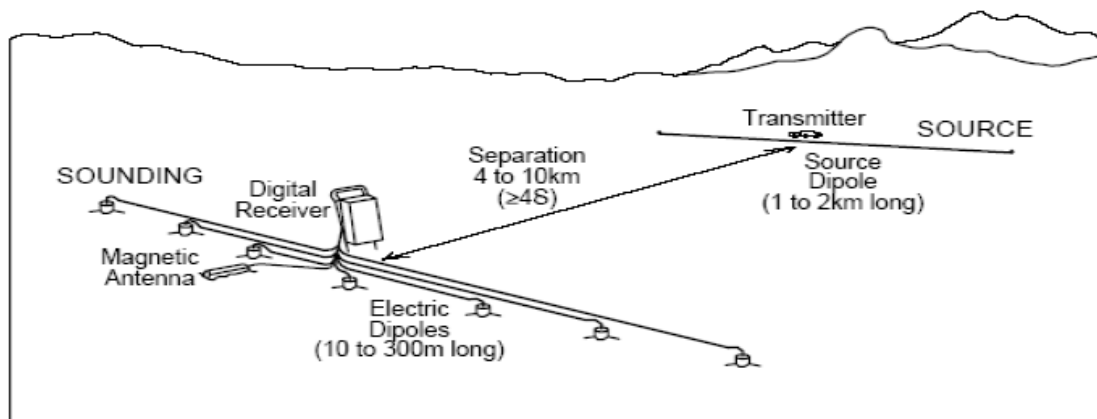
Fig. 3 Scheme of controlled-source sounding

Data file can be created using Zdconvert program supplied with inversion program. Operation procedures of this program are described in **Appendix 1.**

Dialog of field data input (MT Notepad)

This dialog is aimed at new data input and can be found in the main menu of the program **File/MT Notepad**. Figure 4 shows **MT Notepad** dialog window.
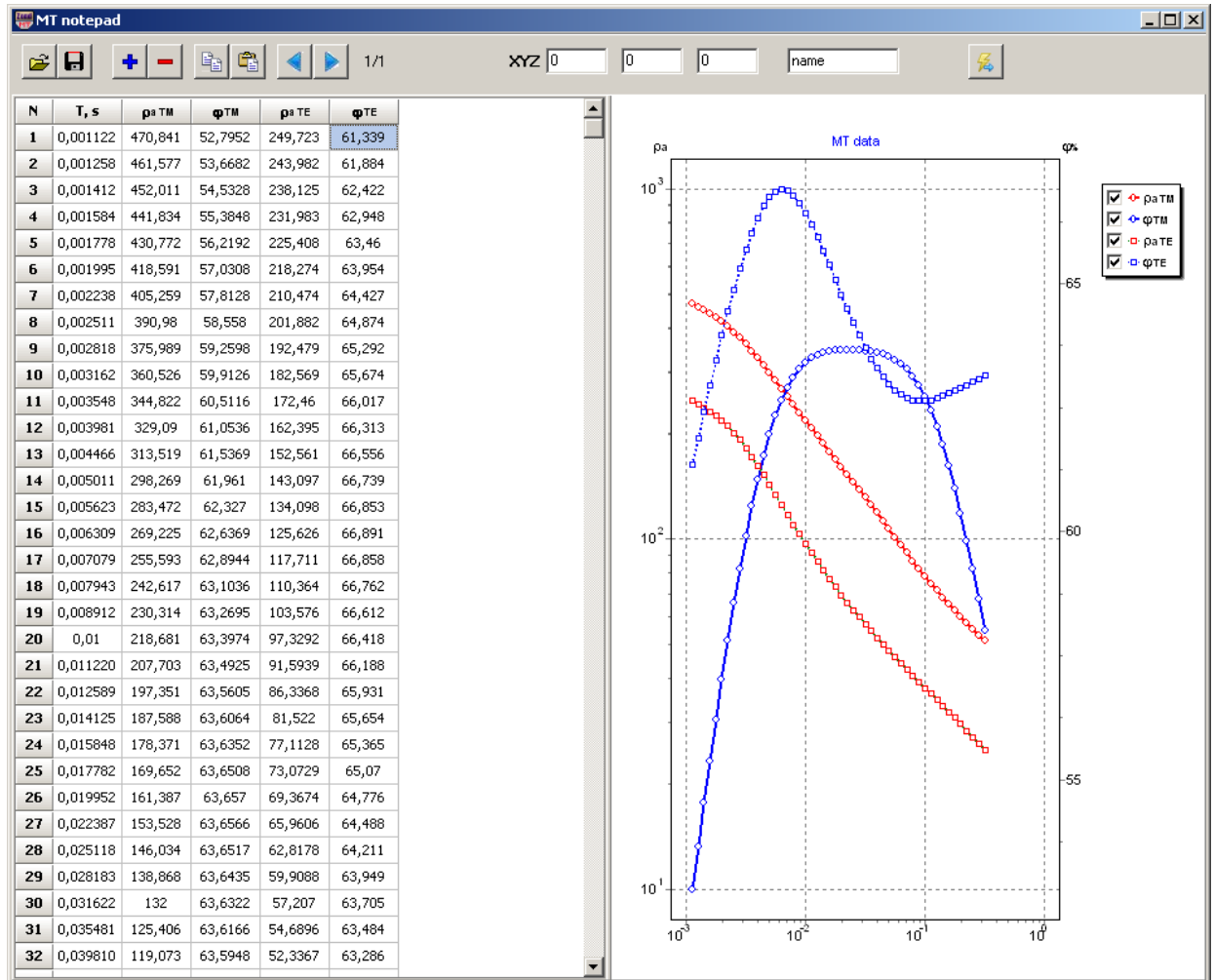
Fig. 4 **MT Notepad** dialog window

Main menu of the window contains the following buttons:

(open icon)	Open *.txt data file format for a single sounding or multiple soundings database.
(save icon)	Save as *.txt data file format for a single sounding or multiple soundings database.
(plus icon)	Add sounding point.
(minus icon)	Delete sounding point.
(copy icon)	Copy.
(paste icon)	Paste.
(arrow icons)	Proceed to the neighboring point.

	Proceed to inversion.

Data can be copied directly to the table from the MS Excel.

Use XYZ field to specify coordinates of sounding station and its name (field «name» in fig. 3).

There is a table in the left part of the window which contains the following columns: T,s − period in seconds. Then follow columns, which contain values of apparent resistivity (ρ_aTM and ρ_aTE) and impedance phases (φTM and φTE) for appropriate frequencies.

Use to create next sounding points. Press the bottom to start inversion, once all parameters are set.

Interpretation results saving

Profile interpretation result is hold in «ZONDMT1D» *project files* (extension *.mdp). This file contains name of file with field data, selected parameters and parameters variation limits for each sounding station. Use button in the tool bar or corresponding menu option (**File/Save fil**e) to save interpretation result. If autosave option is on interpretation result is saved automatically in specified period of time.

There are a few options to save data:

Project data file	Save measured values and current subsurface model.
Field data file	Save measured values.
XYZ model file	Save subsurface model as table file.
Section file	Save current model in Section format. This file type can be used as background.

Data export

«ZONDMT1D» program allows exporting data to MS Excel, AutoCAD formats and also creating files for later use in other Zond programs. This function can be found in **File/Export to**.

The following options to export data are available:

Excel report	Create a file containing information about every measurement point, information about frequency distribution of measured and calculated

	values of apparent resistivity and impedance phase, measurement point coordinates, etc.
Excel map	Create a file containing stations name, their coordinates and resistivity values (calculated) and background position of all layers on each observation point (useful when creating area maps of parameter distribution).
CAD section	Export models in AutoCad file format *.dxf.
Pseudo BH data	Create a file set corresponding sounding points, in borehole data format
MOD1D file	Save model file with extension *.mod1d for later use in other Zond programs

Select **Export/Pseudo BH data** to create a data set in the log data and lithology format. These data are useful as, for example, reference during interpretation of other methods in Zond programs, or for data interpretation on adjacent profiles. In this case, the data are loaded as lithological columns with the color scale corresponding to values of the resistivity (Fig. 5).
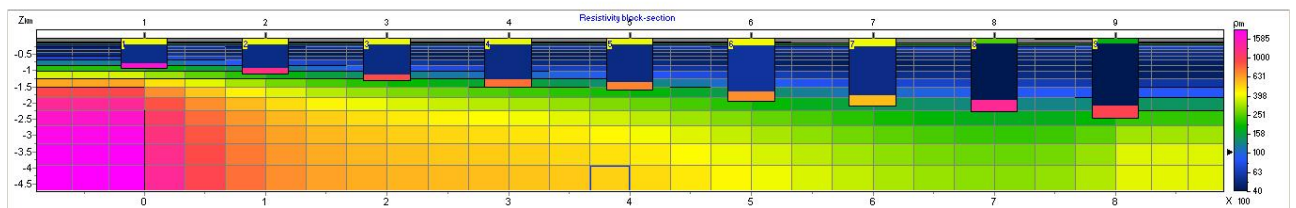
Fig. 5 Example of using option Export/Pseudo BH data.

To compare results of different methods it is also possible to use the export function MOD1D file. When using the file in another Zond program or for other profile in areal surveying saved in such way model will be loaded as a new model (Fig. 6).
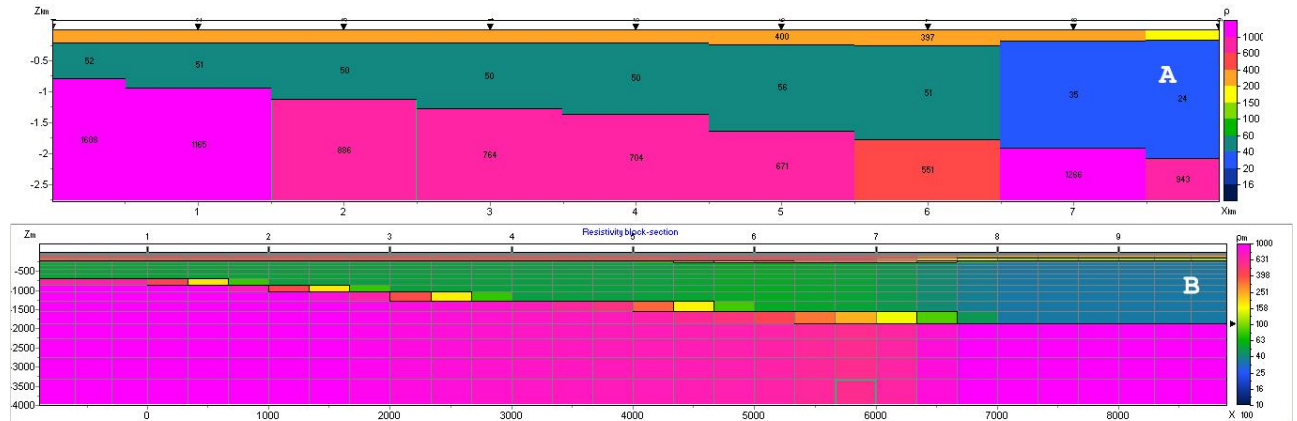
Fig. 6 Example of using options Export/MOD1D file. A - the original model, B - the result of importing *.MOD1D file in the ZondMT2D program.

Program workflow
Main Window

After successful loading of files functional buttons to work with data are activated in the main window toolbar (fig. 7) and short information on first sounding station appears in the right section of status panel. While moving the cursor in created windows, coordinates which correspond to axes in every window are displayed in the left section of status panel. Use the first system button ▼ of the window, marked in plan as "**objects setup**", to open context menu which allows running setup dialog for each object in the window. Methods of editing are described in detail in the following chapters (**Model editor**, **Section**, **Parameters table**, **Pseudosection**, **Profile plot**, **Graph of theoretical and observed curves**).

Second ◄ and third ► buttons serve to proceed from one sounding station to another.
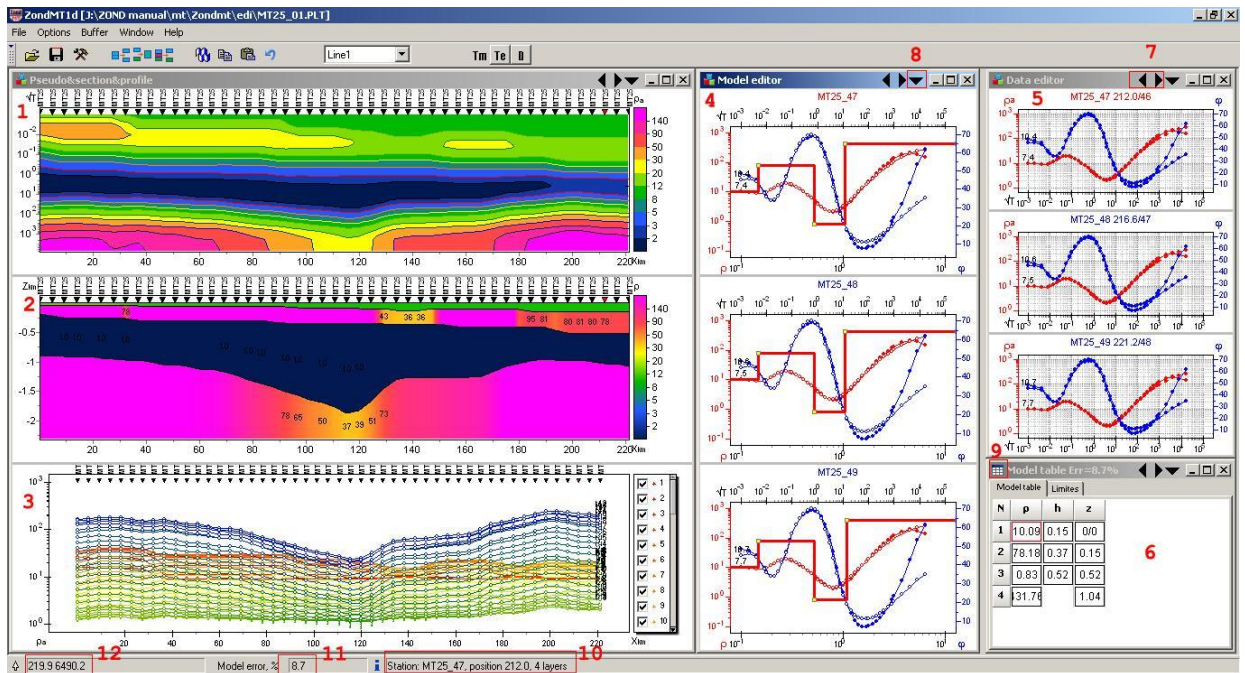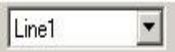
Fig. 7 Program main window. The following windows is marked by numbers: 1 - pseudo sections 2 - Section 3 – profile plot 4 - model editor, 5 - graph of theoretical and experimental curves 6 – parameters table; 7 – buttons for moving from one point to another, 8 - objects settings button 9 – button of additional options 10 - information about sounding point, 11 - an inversion error, 12 - the cursor position.

Main Window Toolbar

The toolbar is meant for quick run of the most frequently used functions. It contains the following functional buttons (from left to right):

	Open data file.
	Save interpretation result or calculated curves.
	Run parameters setup dialog.
	Merge two layers with summary thickness.
	Add layer. User-selected layer is divided into two layers with equal thicknesses (in logarithmic scale).
	Delete selected layer.

	When clicking the **right** mouse button: display a pop-up menu in which it is necessary to choose for which items inversion will be performed: *current* - for current point, *to end* - from the current point to the profile end, *to start* - from the current point to the profile beginning.
	When clicking the **left** mouse button: to run inversion for the selected profile area or the current point
	Copy model at current stake to buffer.
	Paste model from buffer and use it at current station (left click) or at all following stations (right click).
Line1 ▾	Select profile (when working with areal data).
Tm	Use TM mode data
Te	Use TE mode data
S	Use effective curves (average between TM and TE)

Main menu functions

The following table lists items found in the Menu with their corresponding functions:

File	Open data	Open «*.mdf» or «*.mdp» data file.
File	Save data	Save interpretation result or theoretical curves.
File	Project information	Add information about current project (Company name, work place, the project name, equipment, operator, additional information, etc.).
File	Edit data	Open currently used data file in Notepad.
File	Units in file	Specify measurement units in the data file (meters or kilometers)
File	Export to	Export field data or calculated data (more).
File	Load MOD1D/2D	Load MOD1D or MOD2D format model from other Zond program or other profile
File	Print preview	Run print dialog of model and data (more).
File	Program setup	Run parameters setup dialog (more).
File	Registration file	Create registration file.

File	Registration	Enter registration password.
File	Recent	Open one of recently used projects.
File	Exit	Exit program.
File	MT Notepad	Open dialog of field data input (more)
Options	Set lines/coordinates	Set profile line (when working with areal data).
Options	Plane data	Display isoline map of selected parameter (more). Recommended for areal data.
Options	3D section	Run dialog of 3D model visualization. It works with areal data (more)
Options	BiLog equal scale	Set the same logarithmic scale for the axes in the displaying windows of sounding curves
Options	Load borehole data	Load lithology file.
Options	Create/Edit borehole data	Create/edit lithology file (more)
Options	Remove borehole data	Delete lithology file.
Options	Set boundaries	Set geological boundaries (more)
Options	Smooth model	Smooth model (more)
Options	Controlled source settings	Controlled source settings (when working with CSRMT and CSAMT methods) (more)
Options	VES data/ Load VES data	Load VES data (more)
Options	VES data/ Remove VES data	Remove VES data
Options	VES data/ Joint inversion	Joint inversion with VES data
Options	VES data/ Display VES Plot	Display window with VES curves
Options	Denoise data	Denoise data (more)
Options	2D smoothing	Denoise data using 2D filtering (more)
Options	Origin data	Back to the original data
Options	Multiply phase (-1)	Multiply impedance phase value at current site by (-1).
Options	Multiply phase (-1)	Multiply impedance phase value at all sites by (-1).

	All	
Options	Phase +90	Add 90 degrees to impedance phase value at current site.
Options	Phase +90 All	Add 90 degrees to impedance phase value at all sites.
Options	Phase -90	Subtract 90 degrees from impedance phase value at current site.
Options	Phase -90 All	Subtract 90 degrees from impedance phase value at all sites.
Buffer	Model 1,2…5	Save from 1 to 5 calculated models to the buffer for further comparisons
Buffer	Open	Open saved model in a single window (more)
Window	Tile vertical	Order windows vertically.
Window	Tile horizontal	Order windows horizontally.
Window	MT "Standard"	Load "Standard" style.
Window	MT "Interpretation"	Load "Interpretation" style.
Window	MT "Vision"	Load "Vision" style.
Window	Default	Order windows on default for current style.
Help	About	About program.
Help	Context	Display manual.
Help	Check for updates	Check for updates.
Help	Error! Clear setting	Reload the program when an error occurs

"Hot" keys

[Space]	Run data inversion process for current station.
[S]	Add layer. User-selected layer is divided into two layers with equal (in logarithmic scale) thicknesses.
[M]	Merge two layers with summary thickness.
[D]	Delete selected layer.
->	Proceed to next station.
<-	Return to previous station.
[Escape]	Stop inversion process.

Style sheet

Use tab **Widow** in program main window to select style. Library has four options of objects configuration.

If **Standard** style (see fig. 4) is used then user simultaneously operates with four windows: first one contains pseudo section, section and profiling plots (displayed parameter can be chosen), spaced by floating slider; the second one contains graphs (from one to three) of model setup; the third window contains graphs (from one to three) of theoretical and observed curves, the forth one contains parameters table.

Graph of theoretical and observed curves and profile plot window are absent in **Interpretation** style.

Graph of theoretical and observed curves is absent in **Vision** style.

Program setup window

The window serves to adjust autosaving options, specify starting model, set default values and inversion parameters. Use ⚒ button in the toolbar or corresponding menu item (**File/Program setup**) to run it.

Tab Options
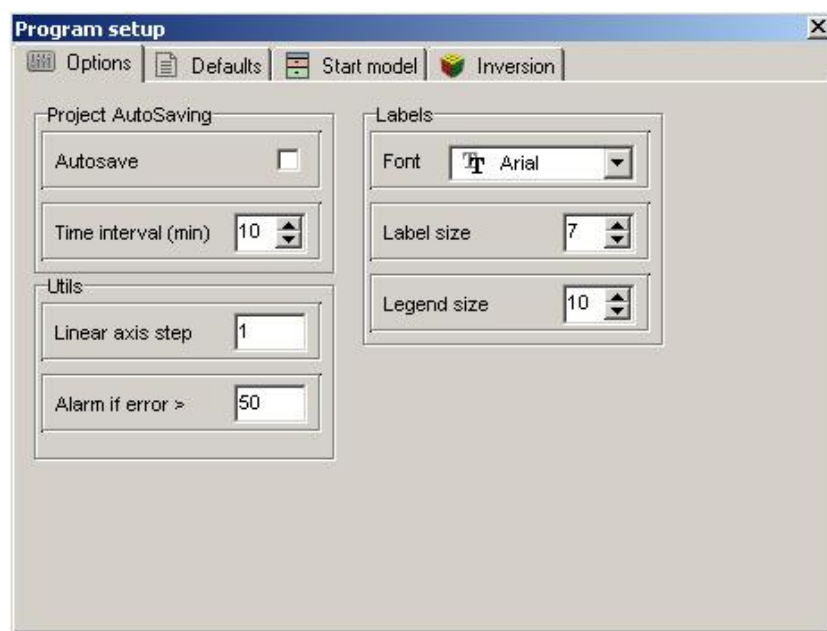
Fig. 8 Window **Program Setup**, tab **Options**

Field Project AutoSaving sets autosaving mode for open project.

Option *Autosave* enables autosaving for open project in certain time intervals.

Field *Time interval* sets time interval (in minutes) for autosaving (file is saved with the same name but with "Temp" added).

Field Labels sets parameters of used fonts.

Field *Font* sets font style for marks on axes, curves, etc.

Field *Label size* sets font size for marks on axes, curves, etc.

Field *Legend size* sets font size used to display parameters names.

Field Utils sets additional parameters.

Field *Linear axis step* sets necessary step for axes. This option is used for axes scaling.

Field *Alarm if error* > runs confirmation dialog of profile inversion if station value of RMS error exceeds specified in the field value.

Tab Default values

This tab serves to set different parameters used while working with model. Rows correspond to types of layer parameters (properties and thickness), columns correspond to options (fig. 9).

First row *Value* – default values (used for starting model definition).

><	Value	Minimum	Maximum	Fixed	Invert
ρ	100	0.010	10000	☐	☑
h	0.01	0.0010	100	☐	☑
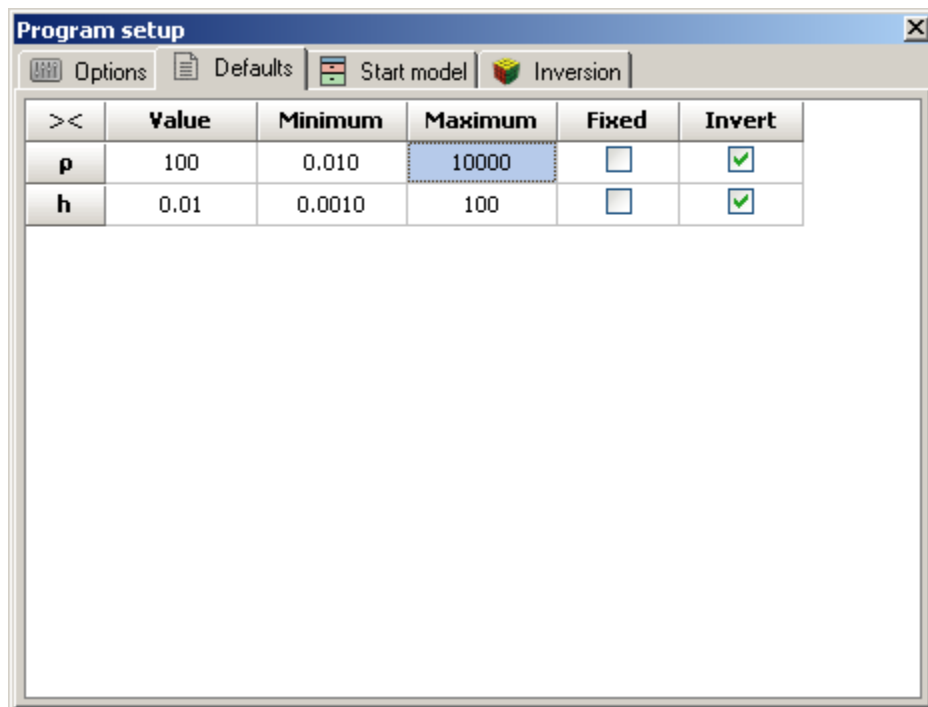
Fig. 9 Window **Program Setup**, tab **Defaults**

Second column *Minimum* – smallest extreme of default parameters (used for parameters fixing).

Third column *Maximum* – superior limit of default parameters (used for parameters fixing).

Forth column *Fixed* – defines if parameter of specified type should be fixed after file reading or not. This option is not available in case of loading project file.

Fifth column *Invert* – defines if parameter is corrected during inversion or not.

Tab Start model
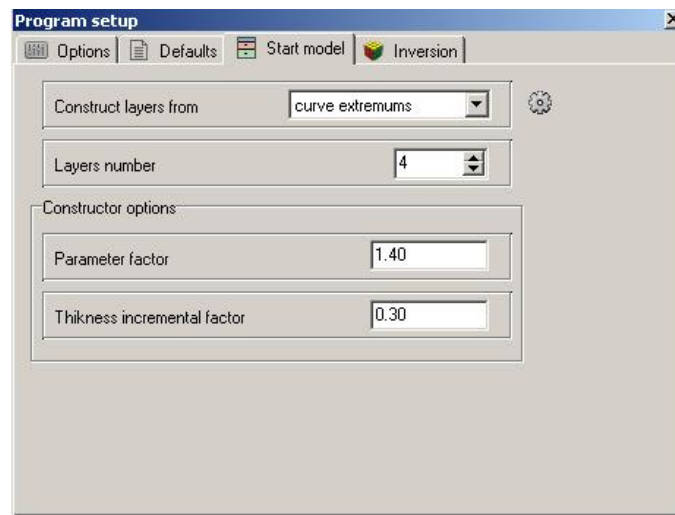
Fig. 10 Window **Program Setup**, tab **Start model**

Current tab is used as starting model constructor during field data reading.

Field **Construct layers from** – sets algorithm which determines positions of layer boundaries.

Value *Curve extremums* – boundary positions are determined by field curves (from extremum analysis). Maximum number of layers is specified in *Layers number* field.

Value *incremental factor* – default values are used to specify thickness of layers. Thickness of each layer is equal to thickness of the previous one multiplied by *Thickness incremental factor*. Number of layers is specified in *Layers number* field.

Field Constructor options – contains options used to specify starting model parameters.

Field *Parameter factor* sets coefficient which model parameters maximums are multiplied by and minimums are divided by (ranges from 1 to 4). This coefficient increases starting model contrast which is very important if curves do not have asymptotes.

Field *Thickness incremental factor* – sets coefficient which layer thicknesses are multiplied by (ranges from 0.2 to 1) or coefficient of thickness increase for each following layer in *incremental factor* mode (ranges from 1 to 2).

23

When starting model parameters are set use ⚙ button to apply them to current project without closing parameters setup window.

Tab Inversion
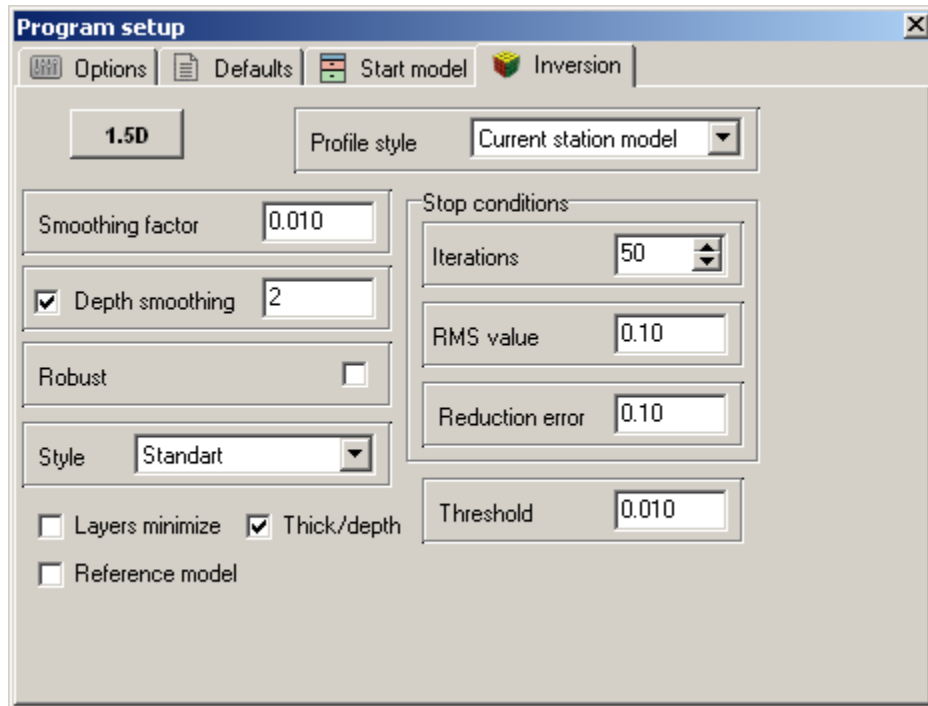
Fig. 11 Window **Program Setup**, tab **Inversion**

Field **Profile style** – sets inversion style of profile inversion.

Value *Current station's model* – current station model is used as starting model for inversion.

Value *Start station's model* – model of inversion start station is considered to be starting model for inversion for all other points.

Value *Previous station's model* – previous station model is used as starting model for inversion.

Field **Smoothing factor** – sets staring value of smoothing parameter. It depends on many factors: condition number of Jacobian matrix, signal to noise ratio of data, and number of model parameters definitions. It is an empiric value. For noisy data or for smooth parameters distribution greater values of smoothing factor are chosen: 0.05 – 10; for precise measurements it ranges from 0.005 to 0.01.

Models created using three different values of smoothing factor (0.01 – blue, 0.1 – red, 1 – black) are shown below (fig. 12).

Fig. 12 Models with different values of **Smoothing factor** (0.01 – blue, 0.1 – red, 1 – black)

Field **Stop conditions** – sets rules which stops inversion.

Field *Iteration's number* – sets maximum number of iterations. Automatic interpretation process stops when it's achieved.

Field *RMS value* – sets minimum RMS error. Automatic interpretation process stops when it's achieved.

Field *Reduction error* – sets discrepancy value. Inversion process stops if this value repeatedly increases (in specified value (%)) for three sequential iterations.

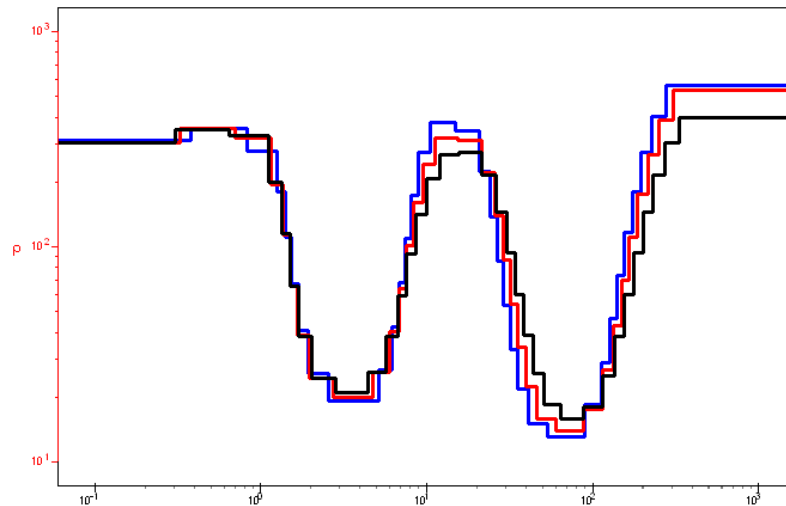Option **Depth smoothing** – sets degree of model depth smoothing (if this option is on). The greater its value is (1 – 10) the more parameters of adjacent layers are averaged with depth. This option is used if *Smooth* field is chosen in procedures of section parameters recovery window **Style**.

Option **Robust** – this option is used if data contain certain significant errors, connected with systematic measurement errors.

Option **Style** – sets type of procedure for section parameters recovery.

Value *Smooth* – inversion by least-square method using smoothing operator and complementary contrast minimization. This algorithm results in the smoothest parameters distribution. This type of inversion is recommended for initial stages of interpretation. But number of model layers must significantly exceed number of layers in real model. It is preferable to have more than 10 layers of fixed thickness.

Value *Standard* – inversion by least-square method using damping factor regularization. It results in model with sharp boundaries. Careless usage of this algorithm leads to results

instability and increase of RMS increase. The best option is to consider this algorithm specifying and use it after inversion by *Smooth* algorithm.

Value *Focused* – inversion by least-square method using smoothing operator and additional contrast focusing. It results in piecewise smooth parameters distribution, that is model consists of layers with equal resistivity. This type of inversion is recommended for initial stages of interpretation. But number of model layers must significantly exceed number of layers in real model. It is preferable to have more than 10 layers of fixed thickness.

Careless usage of this algorithm leads to algorithm discrepancy and model instability.

Figure 13 shows models created using three different inversion algorithms (Standard – black, focused – blue, smooth – red).
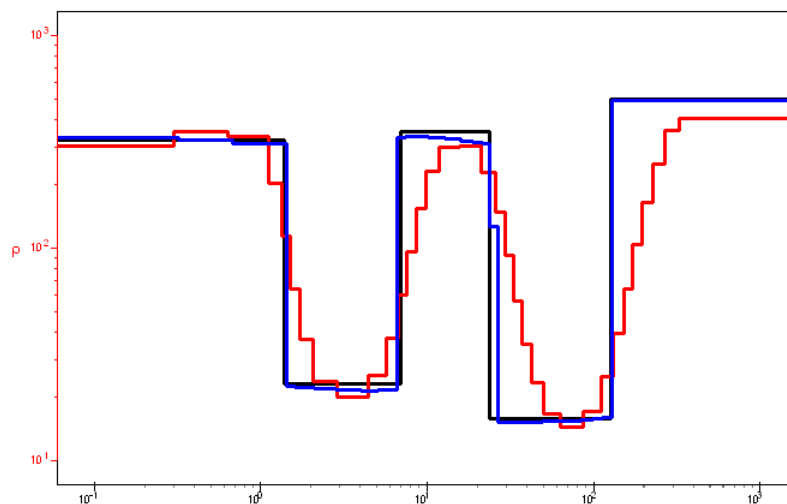
Fig. 13 Models created using different inversion algorithms (Standard – black, focused – blue, smooth – red)

Option **Threshold** – sets maximum contrast value of adjacent layers. When this value is achieved parameters of adjacent layers are not averaged (thus boundary is considered to exist between layers). It is an empiric value (0.001-1). Low values of this parameter lead to algorithm discrepancy (it is recommended to increase it). High values result in smooth distribution.

Figure 14 shows models created using two different values of parameter ***Threshold*** (0.01 – black, 0.1 – red).

Fig. 14 Models created using two different values of contrast parameter ***Threshold***

(0.01 – black, 0.1 – red)

Option ***Layers minimize*** sets minimum number of layers. It is used if multilayered section and focusing inversion are combined. This algorithm minimizes number of layers. Multilayered (10-15 layers) model and focusing inversion are chosen (smoothing factor~0.1). During inversion layers with similar parameter are merged and inversion process continues with lower number of layers.
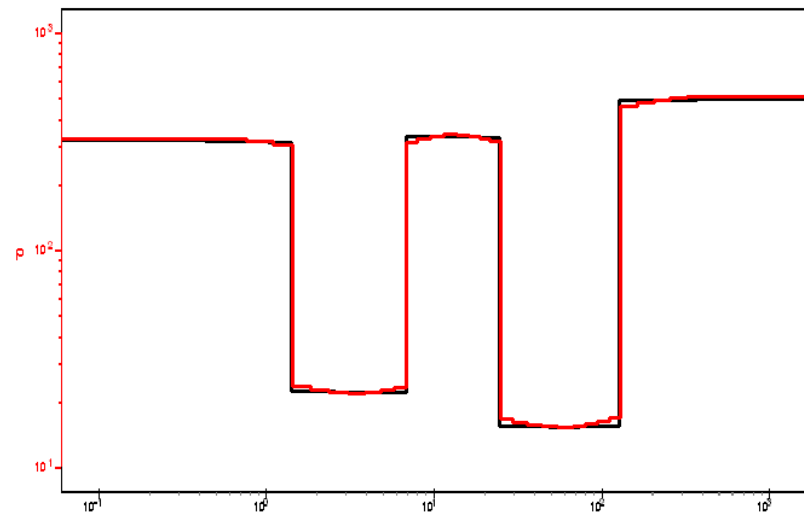
Option ***Thick/depth*** sets thickness (if this option is active) or depth (if not) fitting. Depth fitting is useful if depths of boundaries are known and fixed. It is recommended to assign depth default values for profile inversion with depth fitting.

Option ***Reference model*** takes into account starting model as a reference in the calculation.

Button `1.5D` runs dialog of special profile inversion algorithm.

For this algorithm subsurface model is considered to be horizontally layered or near-horizontally layered (with smooth boundaries) at the bottom. Top part of the section can change greatly from point to point (fig. 15). A few adjacent soundings which have common bottom part and variable top part are used for inverse solution. Fitting is conducted simultaneously for all curves in the window and central point has the greatest weight for discrepancy calculation (fig. 16).

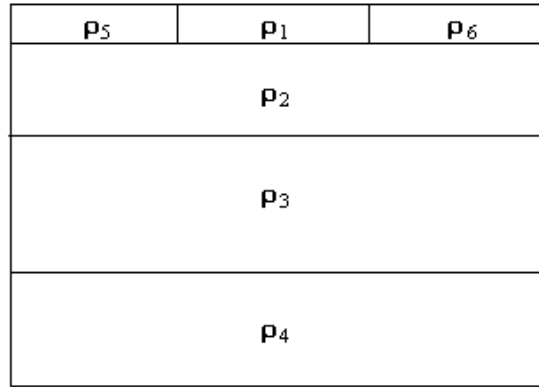| ρ_5	ρ_1	ρ_6
ρ_2		
ρ_3		
ρ_4		

Fig. 15 Sunsurface model for 1.5D inversion
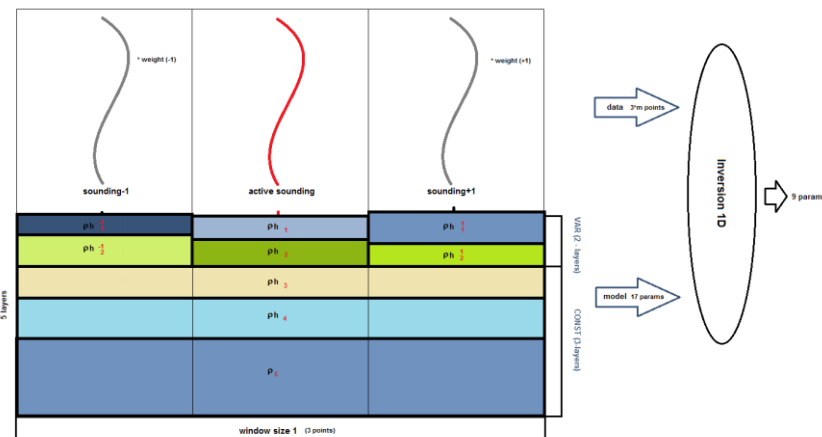
Fig. 16 Scheme of 1.5D inversion

Supplementary parameter - offset to prevent P-effect is assigned to each curve in the window. This parameter is minimized for all curves during fitting and thus it significantly decreases P-effect influence.

Current algorithm differs from standard inversion in additional parameters and construction of smoothing operator. Parameters which model P-effect have less weight compared to the others. Main characteristics of the algorithm are given below.

- Fitting is conducted simultaneously for all curves in the window and central point has the greatest weight for discrepancy calculation.
- P-effect of each curve is selected during inversion process.
- Own model with common bottom part and variable top part corresponds to each curve.
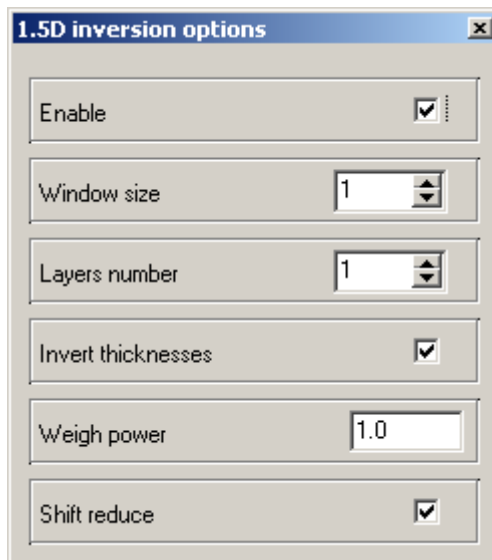
Fig. 17 Parameters window of 1.5D inversion

Option **Enabled** enables current algorithm.

Option **Window size** sets window size for the algorithm. Value 1 means three soundings in the window, 2 - five soundings in the window.

Option **Layers number** sets number of layers which model top (heterogeneous) part of the section.

Option **Inverse thickness** indicates if thicknesses of first layers which model top (heterogeneous) part of the section are fitted or not.

Option **Weight power thickness** sets coefficient of curve weight decrease depending on the distance from the central curve in the window (0 – all curves in the window have the same weight).

Option **Shift reduces** indicates if P-effect is taken into account during inversion or not.

Figure 15 shows results of this algorithm (A) compared to results obtained by standard procedure (B).
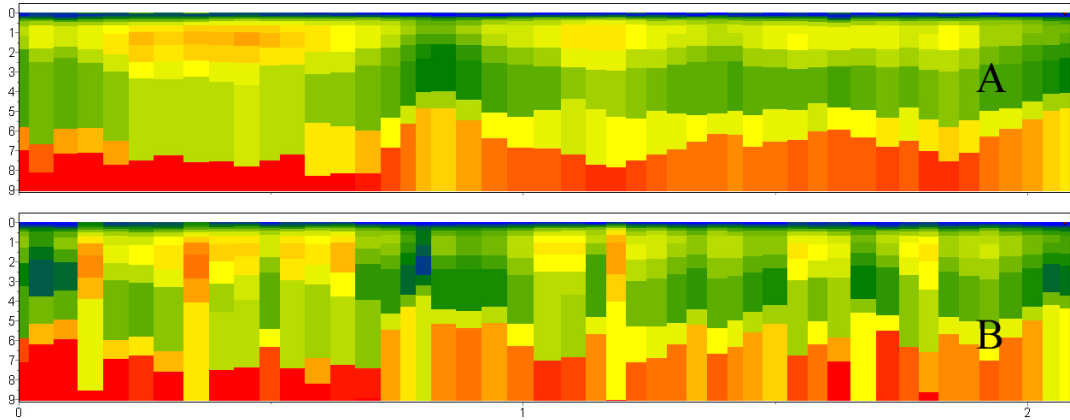
Fig. 18 Results of 1.5D inversion algorithm (A) compared to results of standard 1D inversion (B)

Field data interpretation

«ZONDMT1D» program allows solving 1D forward and inverse problems of MTS. Program automatically selects resistivity values and layer thicknesses. It is also possible to fix parameters, specify their variation limits and define weights of certain measurements. Interpretation mode is available when data file is read.

Data inversion

This option is used for quick data inversion of one or all profile stations. Newton's method is used for minimization of least-square misfit between calculated and observed curves. Right-click the button 🏦 on the toolbar. A pop-up menu will be shown, where it is necessary to choose for which items inversion will be performed: *current* - the current point, *to end* - from the current point to the end, *to start* - from the current point to the beginning of the profile. After selecting points, left-click the button 🏦.

Information on current relative misfit between calculated and observed curves is shown in the status bar. Inversion stops when current relative misfit between calculated and observed curves or number of iterations reach predefined values (for more information read Program setup dialog).

Inversion gives non-unique solution since calculated curves can be identical for different models. So it is necessary to take into account a prior information on geoelectrical section when

specifying starting model. If a prior information is reliable it is advisable to fix known parameters or limit their change range in starting model and to add geological boundaries.

Program objects

Interactive interpretation is performed in the following objects: **Model editor, Section, Parameters table**, visualization is performed in the following objects: **Pseudosection**, **Profile plot**, **Graph of theoretical and experimental curves**. These objects appear automatically as soon as data is loaded.

Model editor

It serves to display observed and calculated sounding curves and to visualize and edit parameters curve of calculated model.

Model editor window is shown in figure 19. Red and blue lines with filled circles are experimental curves of apparent resistivity (left red axis) and impedance phase (right blue axis) versus root of period (top axis). Bottom horizontal axis corresponds to depth (in kilometers) for calculated model which is displayed in red solid line.
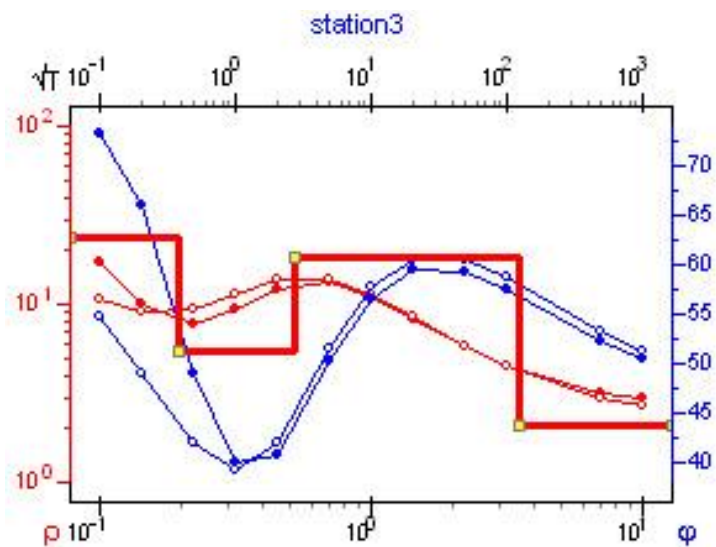

Fig. 19 Model editor window

Graphical parameters of observed, calculated and model plots are specified in graphics editor dialog (right click+SHIFT on plot). Axis parameters are specified in axes editor (right click+SHIFT on axis).

Window can contain one, two or three similar graphs which allow editing models at three neighboring stations at once.

Model parameters can be changed via mouse. In order to do that place mouse cursor on model curve (cursor shape must change at that moment) and with left button pressed drag selected part of curve. Green circle on selected curve indicates active layer.

Alteration of vertical curve pieces positions corresponds to alteration of model geometry (that is thicknesses [right click] and depths of layers tops [left button]).

Alteration of horizontal curve pieces positions corresponds to alteration of model layer parameters.

Double click in object area to run context menu which contains the following options:

Print preview	Run print dialog.
Display legend	Display/hide legend.
Setup	Run object parameters setup dialog.

Setup option runs *curve parameters setup dialog* (fig. 20).

Fig. 20. Curve parameters setup dialog

Field **Marks Style** – sets positions of graph's marks.

Value *Left points* – to the left of graph.

Value *All points* – from point to point.

Value *Right points* – to the right of graph.

Field **Curves shift** – sets shift (in percent of logarithmic decade) between adjacent curves (is used in ZondTEM and ZondVMD programs).

Data Editor (Graph of theoretical and experimental curves)

It is displayed if **Standard** style is selected (tab **Window**).

Double click in object area to run context menu which contains the following options:

Print preview	Run print dialog.
Display weights	Display/hide point weight.
Display legend	Display/hide legend.
Setup	Run object parameters setup dialog.

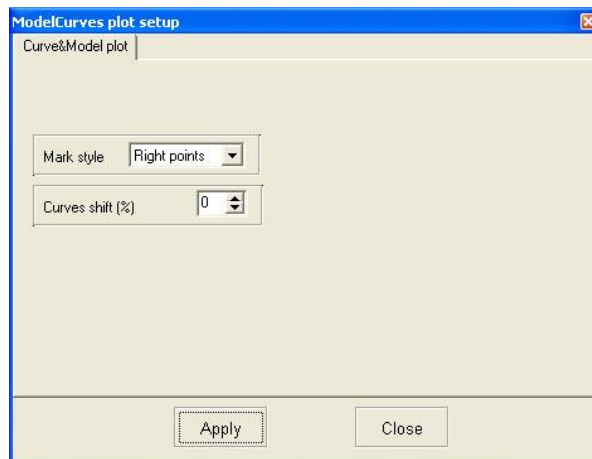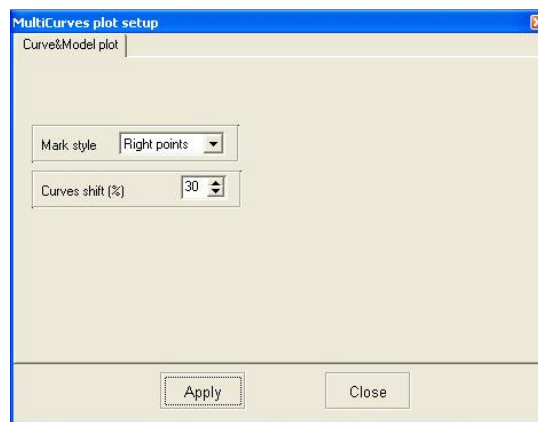Setup option runs curve parameters setup dialog (fig. 21).

Fig. 21 Curve parameters setup dialog

Field **Marks Style** – sets positions of graph's marks.

Value *Left points* – to the left of graph.

Value *All points* – from point to point.

Value *Right points* – to the right of graph.

Field **Curves shift** – sets shift (in percent of logarithmic decade) between adjacent curves.

Options button runs complementary context menu.

Change orientation option changes positions of sounding curves for adjacent points: top-down and left-right.

MultiCurves Plot Setup option (fig. 21) runs curve parameters setup dalog described above.

Set MultiCurves Plot number option sets number of adjacent sounding stations to display their curves simultaneously (from 1 to 3).

Right click in points of observed curves to run context menu which allows specifying weights of observed data:

Good point	Set weight 1 to active point.
Bad point	Set weight 0.5 to active point.
Very bad point	Set weight 0 to active point.
Good points >>	Set weight 1 to active point and to all points to the right of it.
Bad points >>	Set weight 0.5 to active point and to all points to the right of it.
Very bad points >>	Set weight 0 to active point and to all points to the right of it.
Good points <<	Set weight 1 to active point and to all points to the left of it.
Bad points <<	Set weight 0.5 to active point and to all points to the left of it.
Very bad points <<	Set weight 0.5 to active point and to all points to the left of it.
Delete point	Delete point.
Delete point>>	Delete point and all points to the right of it.
Delete point<<	Delete point and all points to the left of it.
Edit data	Edit curves.

Left click on curve point with ALT button pressed to display weight. Right click on curve point with ALT button pressed to hide weight.

Point weights are very important for model parameters inversion. Points with zero weight are not taken into account. Weight is calculated in the following way: = 1-dispesion/(observed value). Data weight can be specified in data file and is saved in project file.

Edit data option is used to edit sounding curves manually. When this option is selected dialog window **Edit data** appears (fig. 22).
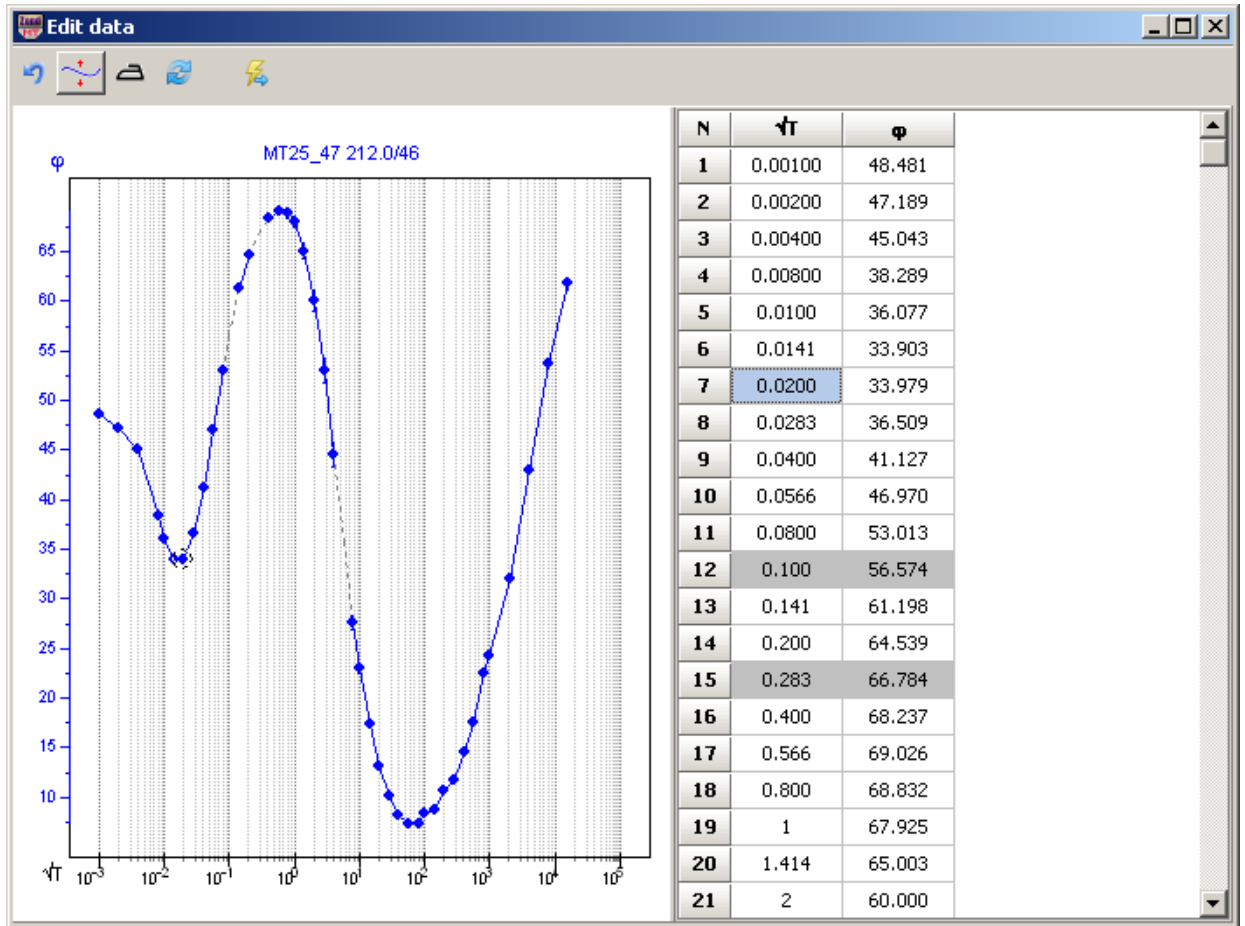
Fig. 22 Sounding curves setup window **Edit data**

Window toolbar contains the following buttons:

	Cancel previous action.
	Move sounding curve point.
	Smooth curve
	Refresh.
	Start inversion.

The window consists of two parts. Editing curve is displayed graphically in the left part. Table which contains roots of periods and values of editing parameter (impedance phase or apparent resistivity) are shown in the right one. Right click with ALT button pressed to delete point on the curve. Deleted point will be highlighted in grey in the table then. Left click with

35

ALT button pressed to recover point. After editing, press [icon] button in the toolbar to start inversion.

Model table

Tab Model table

Window with editing table is used to change model parameters via keyboard. Table contains 3 columns. Each table row contains properties of one layer only.

First column contains resistivity values of layers, the second one – thickness and the last one – depth to layer top with sounding station elevation taken into account. The cell is light grey on default (color can be specified) if parameter variation limit is set. The cell is dark grey on default (color can be specified) if layer parameter is fixed.

Right click on table cells to run context menu (fig. 23). If you right click on the first row (table heading) then selected menu option will be applied to specified parameter of all layers (cell is changed into col then). If you right click on the first column then selected menu option will be applied to all parameters of specified layer.
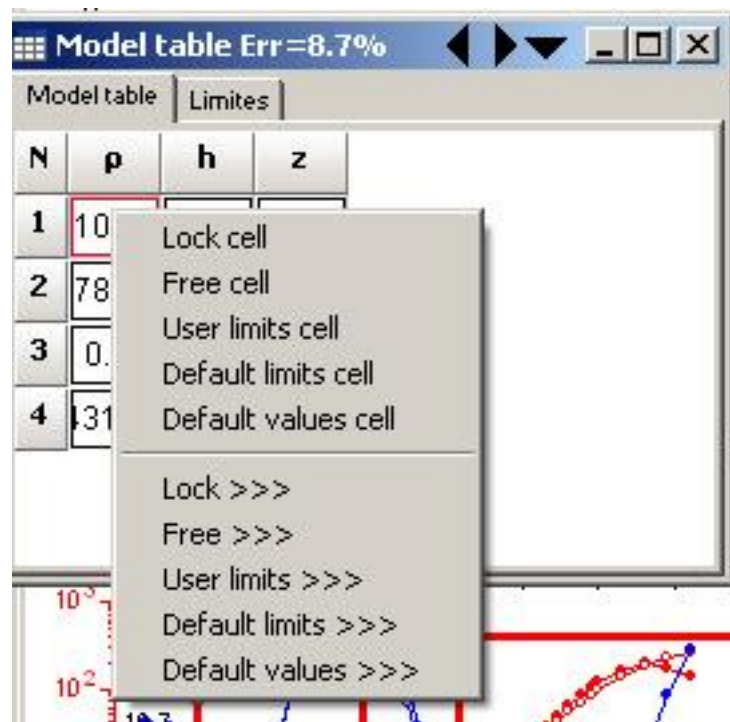

Fig. 23 Model parameters editing window in table

Lock	Fix parameter.
Free	Unfix parameter.
User limits	Set user-specified variation limits.
Default limits	Set variation limits (on default).
Default values	Set default values.
Lock >>>	Fix parameter in current model and in all following models.
Free >>>	Unfix parameter in current model and in all following models.
User limits >>>	Set user-specified parameter variation limits in current model and in all following models.
Default limits >>>	Set default parameter variation limits in current model and in all following models.
Default values >>>	Set parameter default values in current model and in all following models.

Tab Limits

This tab serves to set parameter variation limits (fig. 24). Toolbar buttons are used to select parameter type (resistivity or layer thickness) to specify limits to. **Auto** button sets limits to all parameters of selected type automatically, according to their values and specified divergence percent. Model of selected parameter (black), its lower (red) and upper (blue) variation limits are shown in the graph.
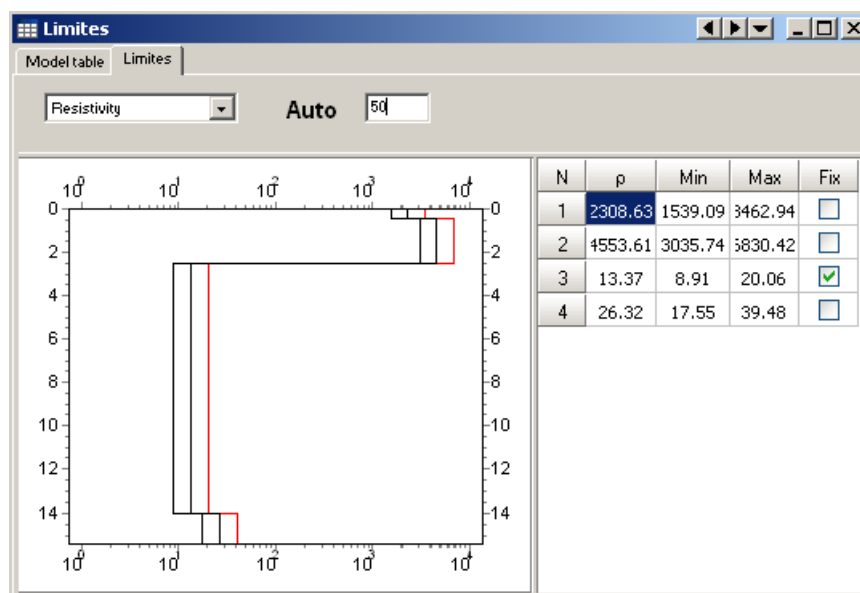

Fig. 24 Tab **Limits** of model parameters table

Lower and upper limits of model parameters are edited via mouse. Variation limits can be edited in the table situated to the right of the graph.

Use ▼ button in the top right corner of the window to run complementary context menu (fig. 25).
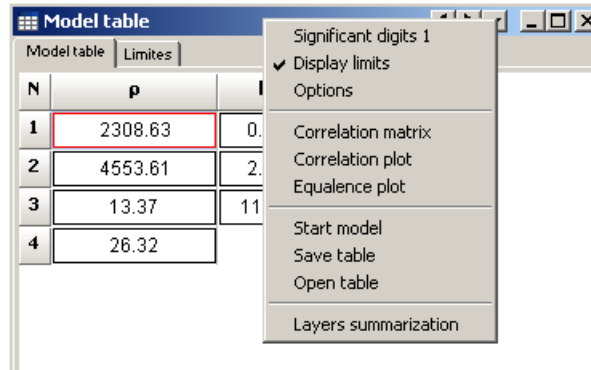

Fig. 25 Model parameters table menu

Layers summarization dialog is used to convert multilayered models obtained by Smooth or Focused inversion into simpler geological models which contain less layers. Multilayered model which consists of 14-20 layers is convenient at the beginning of interpretation (fig. 26).
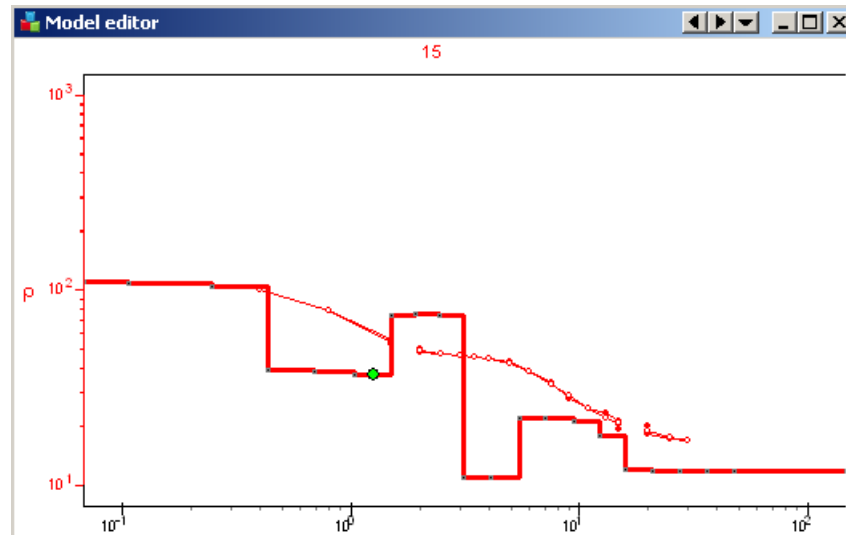

Fig. 26 Example of multilayered model

It is advisable to consider results of Smooth and Focused inversion as starting approximation for further more conscious interpretation. They give understanding of

approximate geoelectrical subsurface structure. Layer summarization dialog helps to obtains simpler model (fig. 27) which is displayed in black line above initial model.
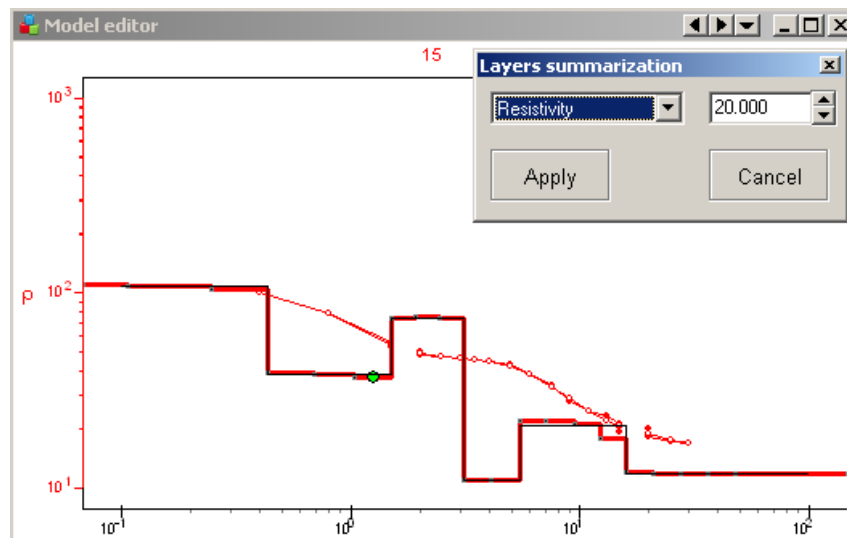

Fig. 27 Dialog **Layers summarization** (red line – multilayered model, black line – integrated model)

When specified in the field contrast parameter is achieved, two layers are merged.

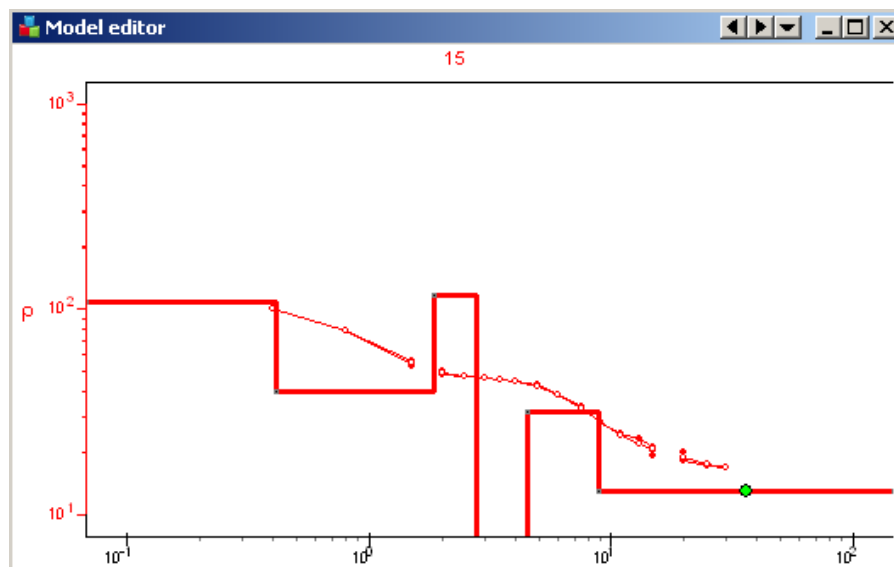After that some parameters can be fixed and standard inversion or manual fitting is performed (fig. 28).

Fig. 28 Inversion results after usage of Layers summarization function

Equivalence analysis. In electrical exploration uniqueness theorem of inverse problem is proved if there are no mistakes in continuous measurements. In practice measurements are conducted within finite intervals with certain discretization and besides they contain mistakes. Presence of mistakes and incomplete data turn theoretical solution unique into practical solution non-uniqueness which means equivalence of different inverse problem solutions. Two geoelectrical sections are considered equivalent if relative data discrepancy does not exceed accuracy of field measurements or inversion misfit. Practically equivalence principle means that some section parameters cannot be defined during interpretation if some other section parameters are not known. Equivalence principle effect complicates data interpretation. Fixing certain parameters (on the basis of a prior data) can solve the problem.

Equivalence principle analysis is based on two approaches – information-statistical for all model parameters by means of correlation matrix of coupling creation and direct calculation of equivalence domain for couple of section parameters with visualization.

One more option of equivalence analysis is creation of equivalent models cloud that is set of model curves which give similar theoretical curves.

Usually statistical estimation of equivalence for all parameters is performed first, then certain pairs of parameters with high correlation coefficients are studied.

Use **Correlation matrix** (fig. 29) option to run correlation matrix. Main diagonal of correlation matrix contains ones. If correlation coefficient modulo is significantly less than unity then section parameters which were used to calculate it influence data differently and are defined with high accuracy. Thus their separate estimation is made possible.

If correlation coefficient modulo of parameters is close to unity then these parameters are jointly indefinable. In this case it is recommended to fix one of equivalent parameters if it is possible to receive independent information on it. In case of strong parameter correlation of adjacent layers it is advisable to fix one of correlative parameters or merge these two layers in one that is to simplify the model.

Fig. 29 Window **Correlation matrix**

Last two columns of the table show confidence intervals for each parameter. Confidence intervals are considered reliability criterion for parameters definition and are connected with summarized sensitivity of section parameters. In case of large confidence interval parameter value is considered unreliable.

When assessing the confidence interval width, the absolute values of the resistivity and thickness of the layers should be considered. In this example, the confidence interval for ρ1 is about 30 Om*m with the absolute value being 300 Om*m. It means, value is determined with an error of about 5%, which is quite acceptable. For ρ5 confidence interval width is about 200 Om*m at absolute value 500 Om*m. It means, error is rather large and is about 25%.

Double click on matrix cell to run correlation map (**Correlation plot**) of selected pair of parameters (fig. 30).

Correlation map of parameters pair represents isolines map of discrepancy between theoretical data of current and calculated model. Assuming that current parameter values are centers of equivalence field, a few more forward solutions for parameters close to current point are calculated and maximum error of discrepancy between them and central point is estimated. In order to create correlation map for two parameters they are assigned set of values in certain range, data discrepancy with current model is estimated and contour map is generated. If parameter distribution is logarithmic then all above-mentioned actions are performed using parameters logarithms. Contours of maximum error values which represent equivalence principle domain geometry and range validity are shown in the equivalence map. Isometric equivalence domains indicate that there is no correlation between parameters estimations, oblong domains

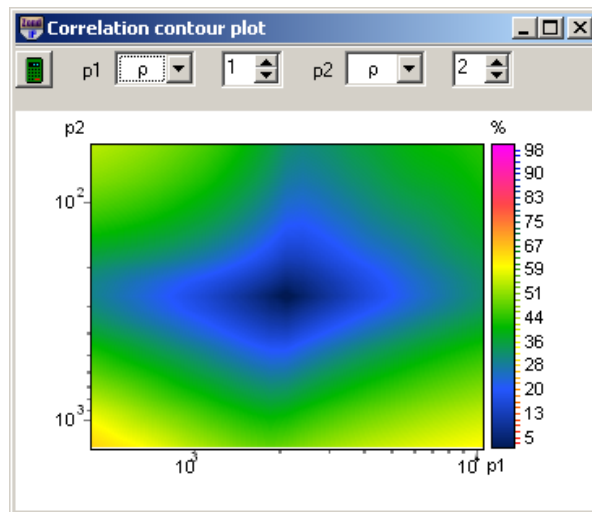mean the opposite. Correlation analysis promotes successful revealing of equivalence between two parameters.

Fig. 30 Window **Correlation counter plot**

Color bar links misfit value to color.

Field *p1* - sets type of first parameter for correlation analysis.

Field *p2* - sets type of second parameter for correlation analysis.

Following fields specify indexes of these first and second layers parameters, for which Field *p1* sets type of first parameter for correlation analysis performance.

▣ - create correlation map.

Use **Equivalence plot** option to run equivalence model cloud plot window. It implements quite resource-intensive algorithm of equivalence model access scan within specified error range using curve-fitting method (fig. 31).
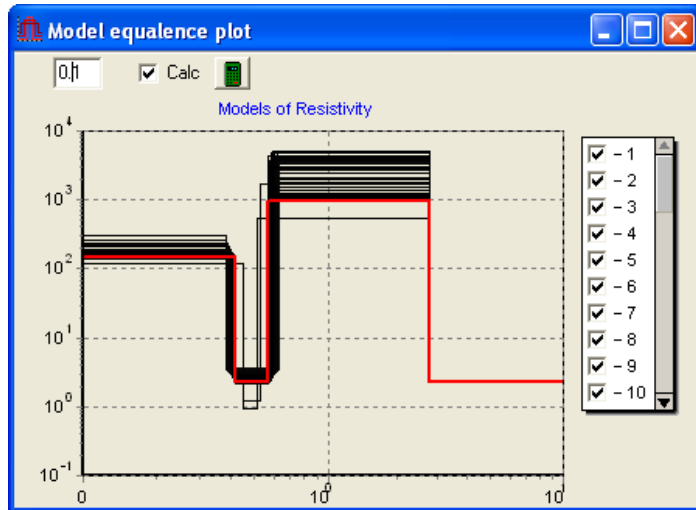
Fig. 31 Window **Equivalence plot**

Minimum error values to consider model equivalent to current (field 0.1) must be specified. If Calc option is not ticked then equivalence models are calculated for model inversion error. Usually default values are specified so that they exceed current inversion error. Parameter for calculation is chosen then (Resistivity). After that access scan can be started [icon]. Algorithm result in set of model curves. It is possible to disable any curves on the legend right of the image. Use scrolling to proceed from one curve to another.

Table graphical parameters setup dialog (**Options**)

Option **Lock** sets fixed parameter cell color.

Option **Range** sets cell color for parameter with specified variation limits.

Option **Free** sets cell color for parameter without specified variation limits.

Option **Min** sets color of parameter minimum limit.

Option **Max** sets color of parameter maximum limit.

Option **Active** sets frame color of active cell.

Option **Font** sets cell font.

Option **Cell height** sets cell height.

Section

Current object visualizes geoelectrical section variations along profile. Graph is created in profile coordinate versus depth axes. Color bar represents correlation between displayed parameter value and color (fig. 32).

If mouse cursor is located within geological section then use slider to select and highlight layer which is located below it. Cursor shape changes when it is reaching boundary of layers which can be edited then. To do that drag selected boundary with left button pressed. If right button is pressed then selected boundary along with underlying boundaries are dragged. Double click on layer to run its parameter setup window.
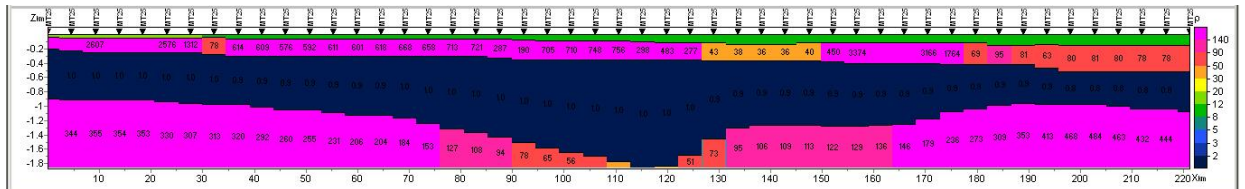

Fig. 32 Geoelectrical section window

Right click in the top (to decrease) or in the bottom (to increase) part of the axis changes maximum vertical axis value.

Double click in the object area runs context menu with the following options:

Log data scale	Use logarithmic scale in color bar.
Display labels	Display labels (parameter values) on axes.
Display ColorBar	Display color bar.
Refresh section	Regenerate section.
Setup	Run object setup dialog.
Print preview	Print section.
Save picture	Save section as graphics file.
Output settings	Run output graphics scale parameters setup dialog.
Layered section	Display section as layers.
Layered section [topo]	Display section as layers with topography.
Contour section	Display section as contours.
Smooth section	Display smooth section.
Add background	Add background image.
Remove background	Delete background image.
Increase bottom	Increase maximum vertical axis value.
Decrease bottom	Decrease maximum vertical axis value.
Set bottom	Set maximum vertical axis value manually.

Model interpolation	Interpolate all models between two selected sounding stations.
Bad data interpolation	Interpolate models (with large fitting error) between two selected sounding stations.
Column percent	Set model columns width

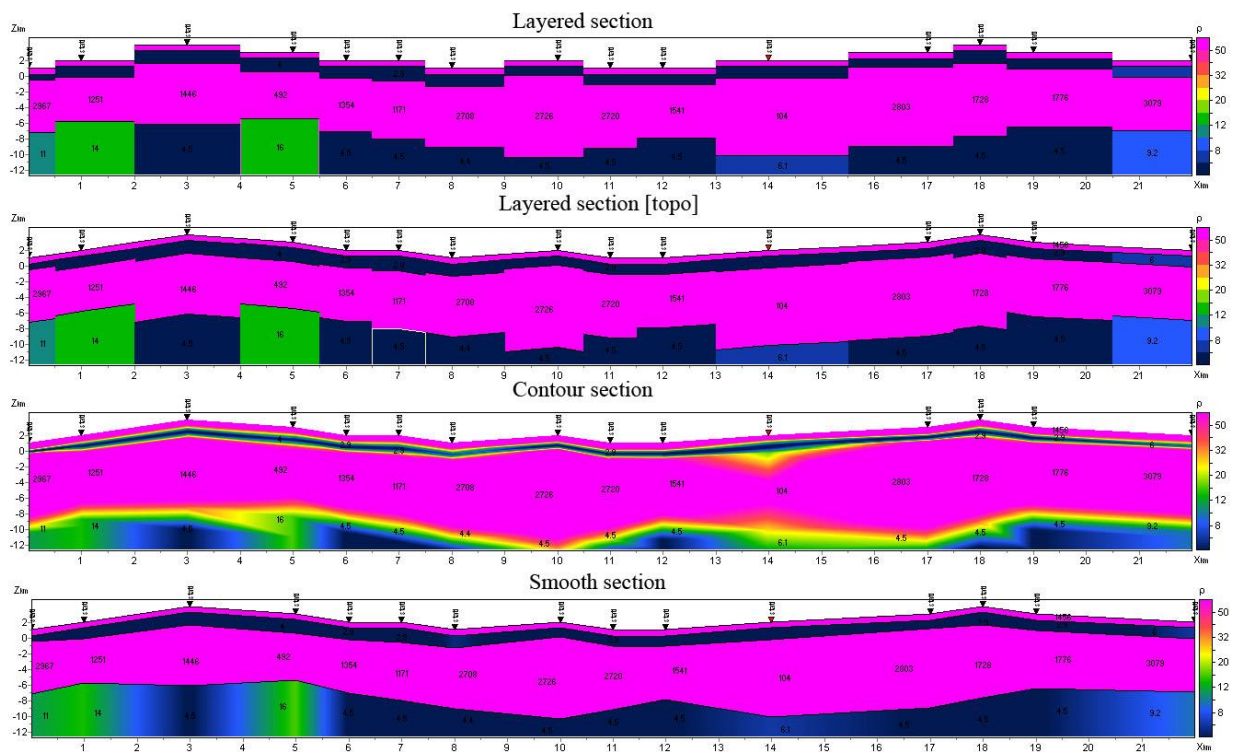Figure 33 shows four versions of geoelectrical section visualization.

Fig. 33 Options of geoelectrical section visualization

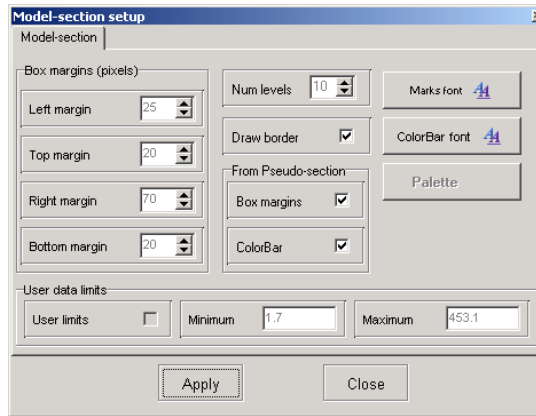Option *Setup* runs section parameter setup dialog (fig. 34).

Fig. 34 Geoelectrical section parameters setup dialog

Field Box margins

Field *Left margin* – sets image indent (in pixels) from window left edge.

Field *Right margin* – sets image indent (in pixels) from window right edge.

Field *Top margin* – sets image indent (in pixels) from window top edge.

Field *Bottom margin* – sets image indent (in pixels) from window bottom edge.

Field *Num levels* – sets number of colors. Levels are set using uniform linear or logarithmic step depending on data type.

Button **Palette** – runs section layers color setup dialog (more).

Button **ColorBar font** – runs color bar font setup dialog.

Button **Marks font** – runs layer marks font setup dialog.

Field User data limits

Option *User limits* – specifies whether to use minimum and maximum data values or specified in [*Minimum*] and [*Maximum*] fields values for color bar definition.

Field *Minimum* – sets minimum value for color bar definition.

Field *Maximum* – sets maximum value for color bar definition.

Field *From pseudosection*

Option *Box margins* – specifies to use *Box margins* field values which correspond to pseudo section.

Option *ColorBar* – specifies to use corresponding to pseudo section color bar.

Dialog **Output settings** allows specifying vertical scale, horizontal scale, print resolution in dpi and font size if Automatic box is not ticked (fig. 35).
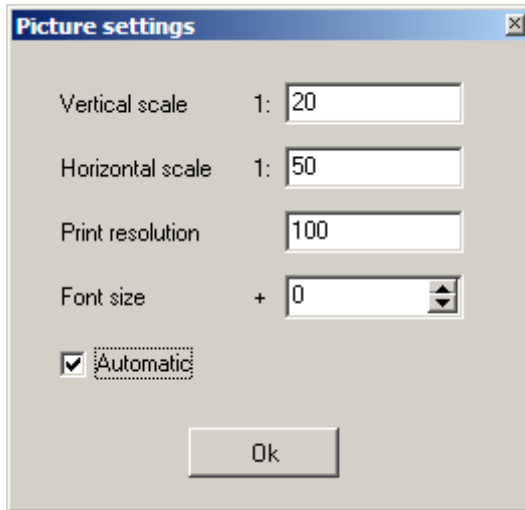
Fig. 35 Output picture settings window

Option **Add background** is used to insert background in model. This function can be useful if a prior information (geological section along profile) or data obtained by other methods are present or to compare inversion results at different stages. Background picture file must be in bmp format. When this option is selected, window appears to specify position of output file. Background is displayed above model and background layer is transparent (fig. 36, 37).
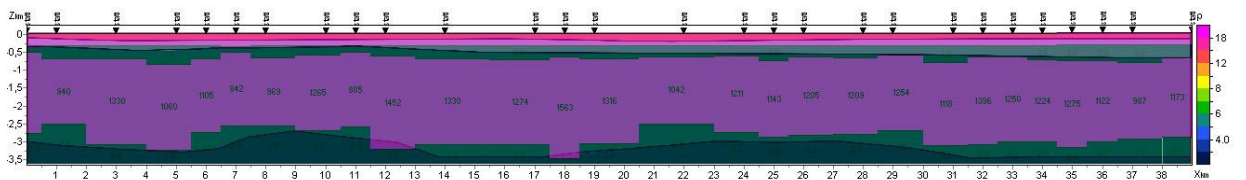

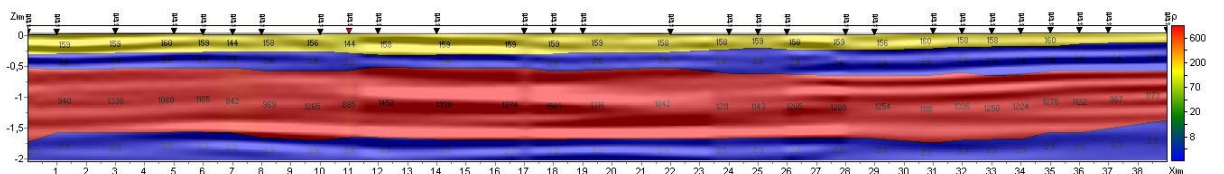Fig. 36 Example of geological section background

Fig. 37 Example of seismic section background

Pseudosection

Current object visualizes variations of observed values along profile as contour map (fig. 38).
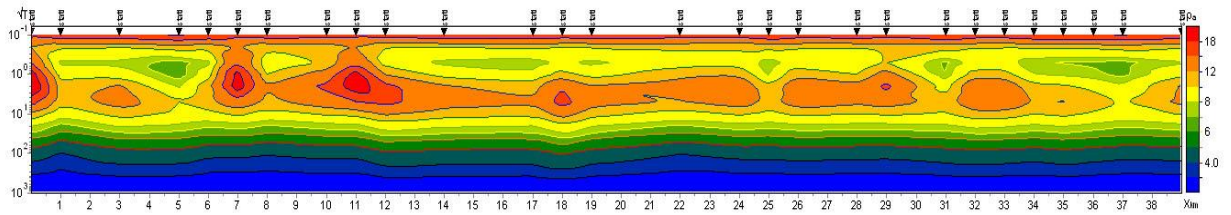
Fig. 38 Example of apparent resistivity pseudo section

Graph is created in profile coordinate versus depth axes. Color bar represents correlation between displayed parameter value and color.

Double click in object area runs context menu with the following options:

Setup	Run object parameters setup dialog.
Print preview	Print pseudo section.
Log data scale	Use logarithmic scale for color bar.
Smooth image	Smooth pseudo section.
Display labels	Display labels of measurement points.
Display ColorBar	Display color bar.
Save picture	Save pseudo section as graphics file.
Save XYZ file	Save pseudo section as Surfer file.
Apparent resistivity display	Display apparent resistivity pseudo section.
Phase display	Display impedance phase pseudo section.

Tab **Setup** is used to adjust pseudo section parameters (fig. 39).
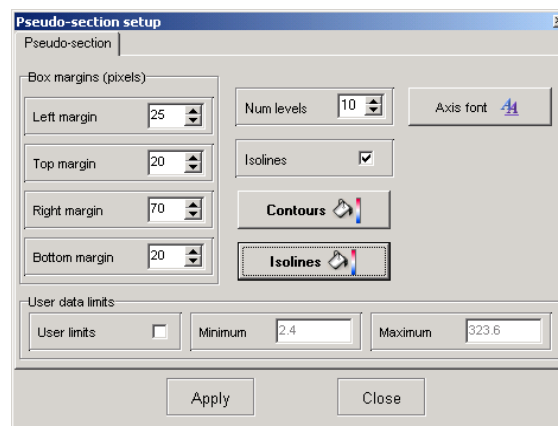

Fig. 39 Pseudosection parameters setup window

Field **Box margins***:*

Field *Left margin* – sets image indent (in pixels) from window left edge.

Field *Right margin* – sets image indent (in pixels) from window right edge.

Field *Top margin* – sets image indent (in pixels) from window top edge.

Field *Bottom margin* – sets image indent (in pixels) from window bottom edge.

Field **Num levels** – sets number of contour intervals. Contour intervals are set using uniform linear or logarithmic step depending on data type.

Option **Isolines** – specifies whether isolines are created or not.

Button **Contours** – runs contour filling color setup dialog (more).

Button **Isolines** – runs isoline colors setup dialog.

Button **Axis font** – runs color bar font setup dialog.

Field **User data limits**

Option **User limits** – specifies whether to use minimum and maximum data values or specified in [*Minimum*] and [*Maximum*] fields values for contour intervals definition.

Field *Minimum* – sets minimum value for contour intervals definition.

Field *Maximum* – sets maximum value for contour intervals definition.

Profile plot

Current object visualizes profile graphs (theoretical and experimental) for different periods (fig. 40) (available for **Standard** and **Vision** styles only).
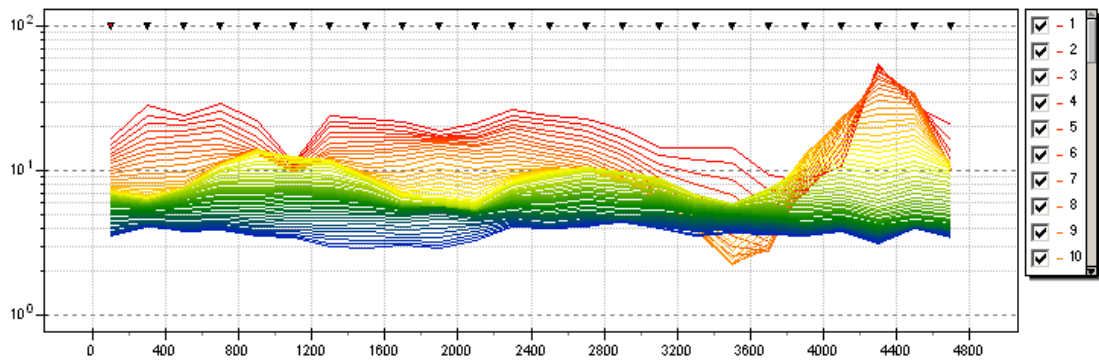

Fig. 40 Profile plot window

Curve color corresponds to certain period. This tool is useful for analyzing raw data and for profile graphics visualization on a single spacing, which will correspond to a single investigation depth. Figure 40 shows that between PC 800 and 1200 there is graphs inconsistency for high (red lines) and low periods (blue lines). It indicates the presence of local relatively more conductive object (heterogeneity) in the upper section. It should also be noted that, in general, graphic profiling should contain no sharp spikes of individual points. If there is one outlier on a graph, which is not present in the graphs on other periods, most likely this point should be removed.

On default theoretical curves are represented by solid curves, experimental curves – by solid curves with circles in measurement points. Color specified in current object setup dialog corresponds to each curve. Labels on experimental curves mean numbers of pseudo depth for which curves are created.

Graphical parameters of observed and calculated curves can be specified in setup dialog. Axis parameters can be set in axes editor (right click+SHIFT on axis).

When you left click on curve, curves for other periods disappear until you release the button. Plots can be shifted vertically by mouse dragging with right button pressed. Left click on curves list with SHIFT button pressed to display one curve only. Use scroll wheel to proceed to the next plots. Use again left click on curves list with SHIFT button pressed to display all curves.

Left click on curve point with ALT button pressed to display point weights. Right click on point with ALT button pressed to hide them.

Double click in object area runs context menu with the following options:

Setup	Run object parameters setup dialog.
Print preview	Print graphics plan.
Display calculated	Display theoretical curves.
Delete invisible	Delete invisible graphs.
Apparent resistivity display	Display apparent resistivity graphs.
Phase display	Display impedance phase graphs.

Option **Setup** is used for profile plot setup (fig. 41).
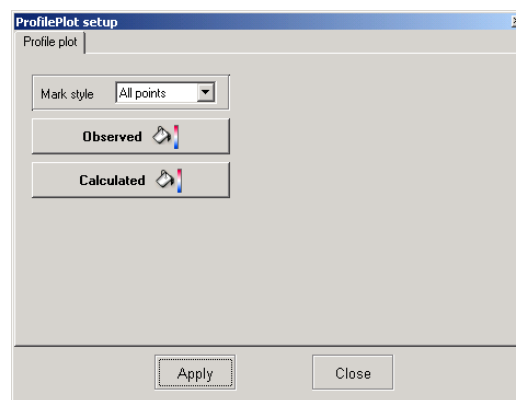
Fig. 41 Profile plot parameters setup dialog

Option **Marks style** – specifies marks style.

Value *Left points* – to the left of the plot.

Value *All points* – from point to point.

Value *Right points* – to the right of the plot.

Buttons **Observed** and **Calculated** – runs graphics parameters setup dialog for observed and calculated curves.

Advanced program options

Work with CSAMT and CSRMT data (modifications with a controlled source).

When working with controlled source it is often necessary to take into consideration geometry of source and receiver devices. If source data do not have this information, it can be set in the menu **Options/Controlled source settings**. After selecting this menu, Controlled source settings dialog appears, in which it is necessary to define corresponding settings (Fig. 42). The measurement scheme described in the section Data file format.
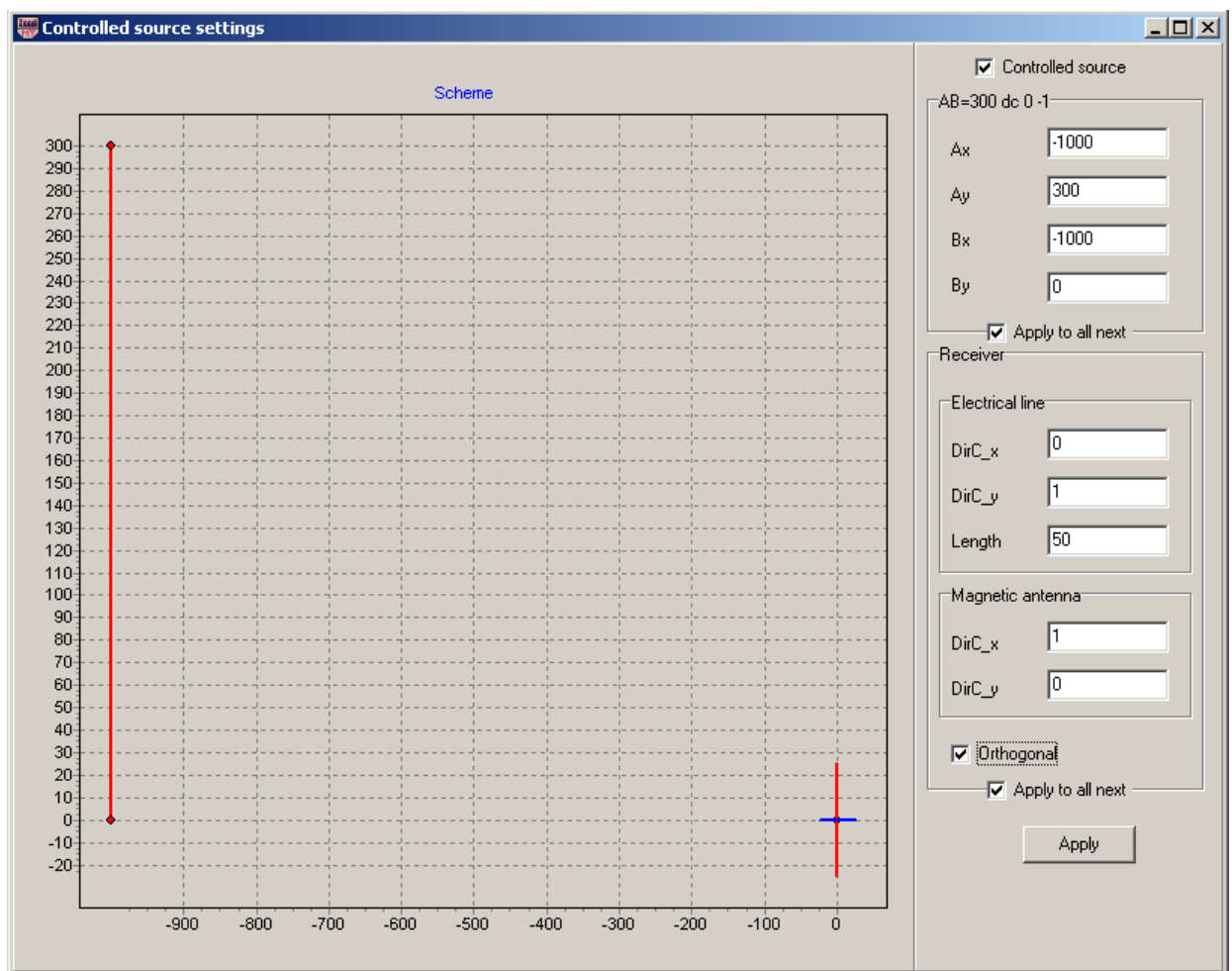
Fig. 42 Dialog window Controlled source settings of source and receiving equipment

Tick Controlled source if the measurements were performed using a controlled source.

The coordinates of supply circuit beginning (Ax Ay) and the end (Bx By) are specified in respective windows. At the same time, as coordinates specifying, length of the supply line (AB) and the direction cosine (dc) will be automatically calculated the in the field.

Field **Receiver** is intended for receiving equipment geometry placing. In the Electrical line field it is necessary to set the receiving lines direction cosines (DirC_X and DirC_Y) and their length (Length). Since source length typically greatly exceeds receiver line length, it is possible to set longer length to display lines in the diagram.

When selecting Orthogonal it is enough to fill a value of at least one direction cosine. The rest will be filled automatically, based on the current placing.

Otherwise, it is necessary to specify direction cosines of the magnetic sensors in the windows DirC_y and DirC_x in the Magnetic antenna field.

Select Apply to all next, if the given parameters are correct for all sensing points. If it is not selected, then, after clicking Apply, they will be applied only to the current sensing point.

Work with areal data and 3D visualization

Select **Options/Set lines/coordinates** in the main menu to set several profile lines. **Line settings** window appears then. See *Setting of profile line or profiles for areal data* for details. Use ▭Line1 ▾ window in the main window toolbar to switch profiles.

Option **Plane data** (**Options/Plane data)** is used to create areal distribution maps of selected parameter (resistivity, apparent resistivity, elevations, etc.) depending on depth or period. Figure 43 shows example of areal resistivity distribution map.
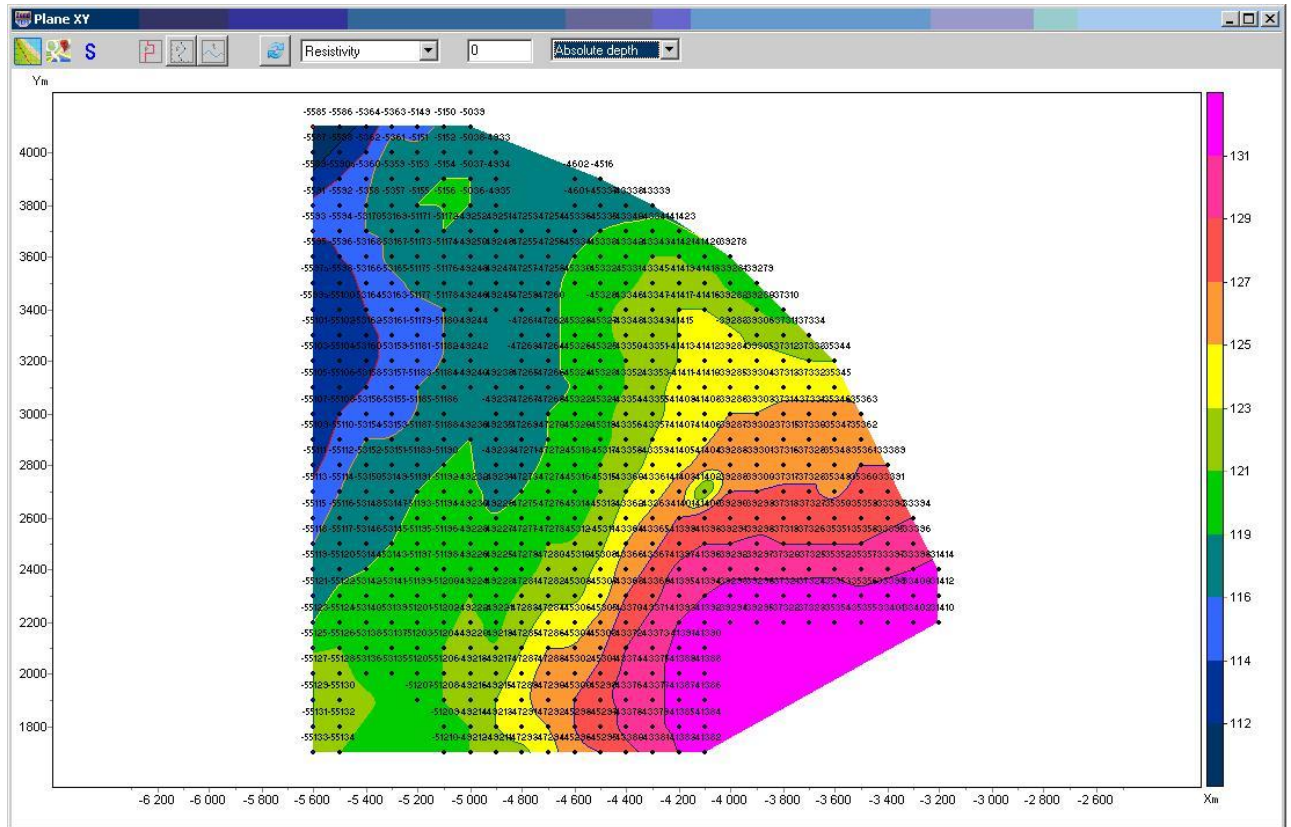
Fig. 43 Window **PlaneXY**. Resistivity contour map

Window toolbar contains the following buttons:

	Load map raster file as background.
	Load Google map
S	Export areal scheme of parameter distribution in Golden Software Surfer and run the application
	Create contours for model parameters (resistivity, conductivity or thickness).
	Create contours for measured parameters (apparent resistivity or impedance phase).
	Create contours for elevations.
	Redraw current plan.

When plotting model parameters there are two windows in the toolbar which are used to select one of parameters and specify depth to display it at. Depth counting method is specified in the right window: Depth from topo – depth values are counted off the ground, Absolute

depth – absolute depth values are used, Layer index – contour map is generated for specified layer.

When plotting contours of measured parameters, layer number corresponds to initial data period grid.

Option 3D section (Options/3D section)

Current option is meant for 3D visualization of profile interpretation results. If this option is selected **3D sections viewer** window appears. Window toolbar contains the following buttons:

	Print preview.
	Rotate 3D model.
	Display horizontal map. Plan depth from the surface is set in kilometers in the window to the right .
	Press this button to set equal scale for all axes. Window to the right appears then. It allows specifying scale ratio for each axis.
	Vertical axis Z setup.

Window **3D section viewer** contains three tabs.

Tab *Lines* (fig. 44) is used to edit coordinates of profile beginning and end and to set profiles for 3D visualization. There is a table to the left which contains profile names and coordinates of profile beginning and end. Tick box in the last column (V – visible) to display profile in 3D. Profile plan is displayed in the right window. Active profile is highlighted in red. Axes properties can be edited by right click with SHIFT button pressed. See Axes editor for details of axes parameters setup.
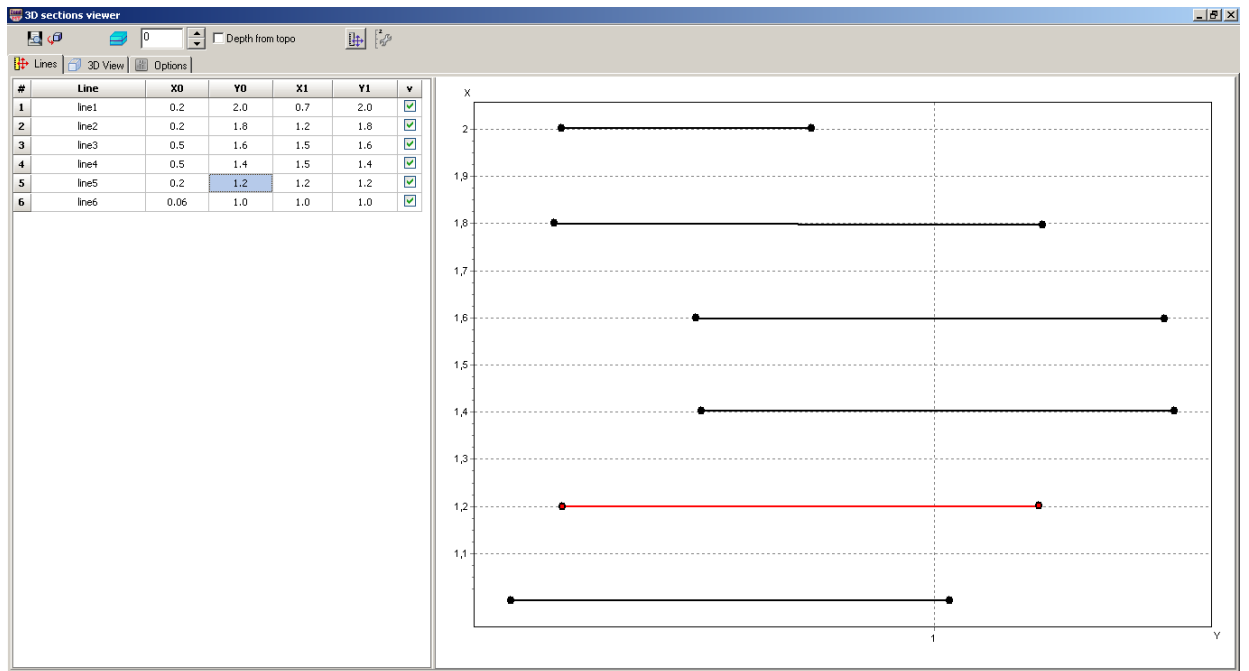
Fig. 44 Window **3D section viewer**, tab **Lines**

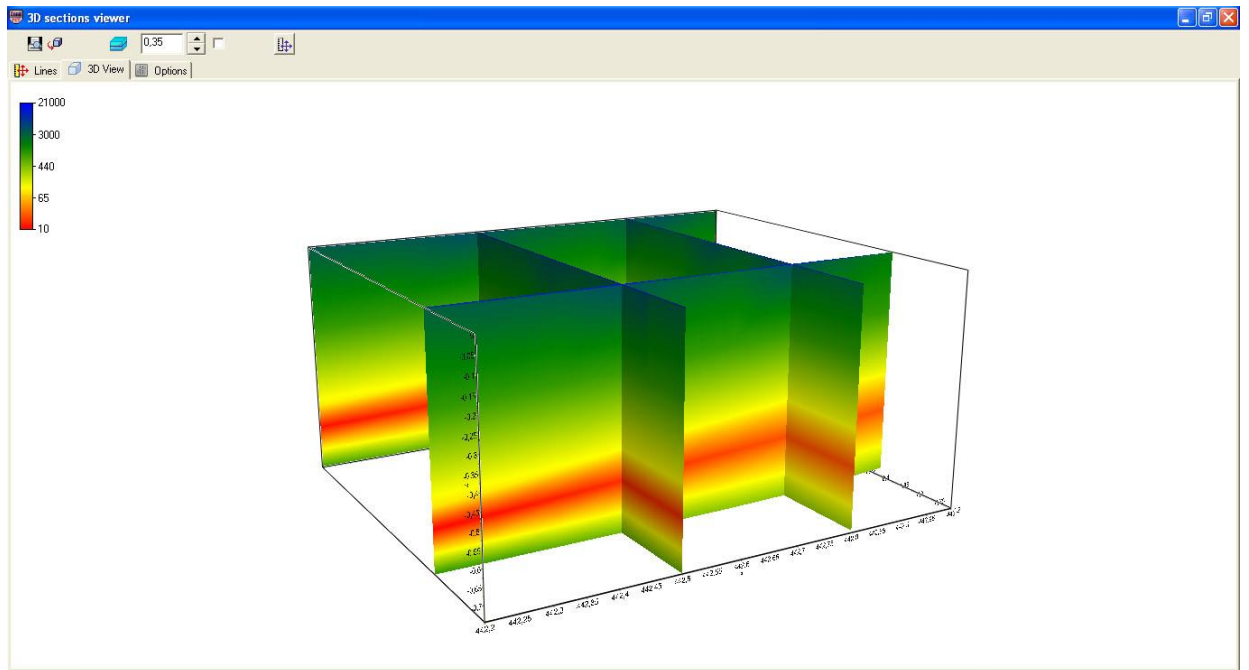Tab *3D view* (fig. 45) is used to view 3D model.

Fig. 45 Window **3D section viewer**, tab **3D view**

Tab **Options** (fig. 46) is used to set image parameters.

Field *Color scale* allows specifying filling parameters. **Palette** button runs filling setup dialog ([more](#)). Field *Color scale limits* is used to specify color bar minimum and maximum values manually or select automatic mode of range definition by ticking certain box.
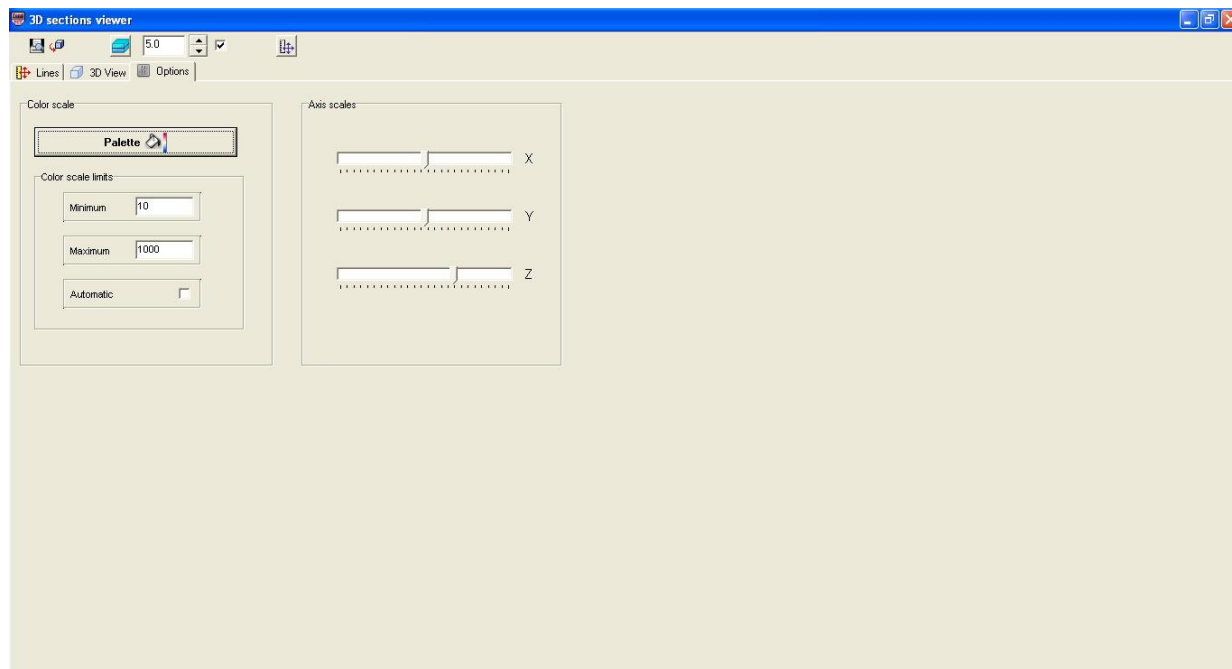

Fig. 46 Window **3D section viewer**, tab **Options**

Field *Axis scale* is meant for axes scale definition. Scales can only be set with pressed button in window toolbar.

A priori data input

A priori data (borehole data) availability helps to increase reliability of received geoelectrical sections significantly. «ZONDMT1D» program has integral module which is used to visualize a priori data graphically in sections.

Lithology file creation and insertion

Choose **Options/Create/Edit borehole data** option in the main menu to create stratigraphy file. Dialog window of the module **Add borehole data** (fig. 47) appears.
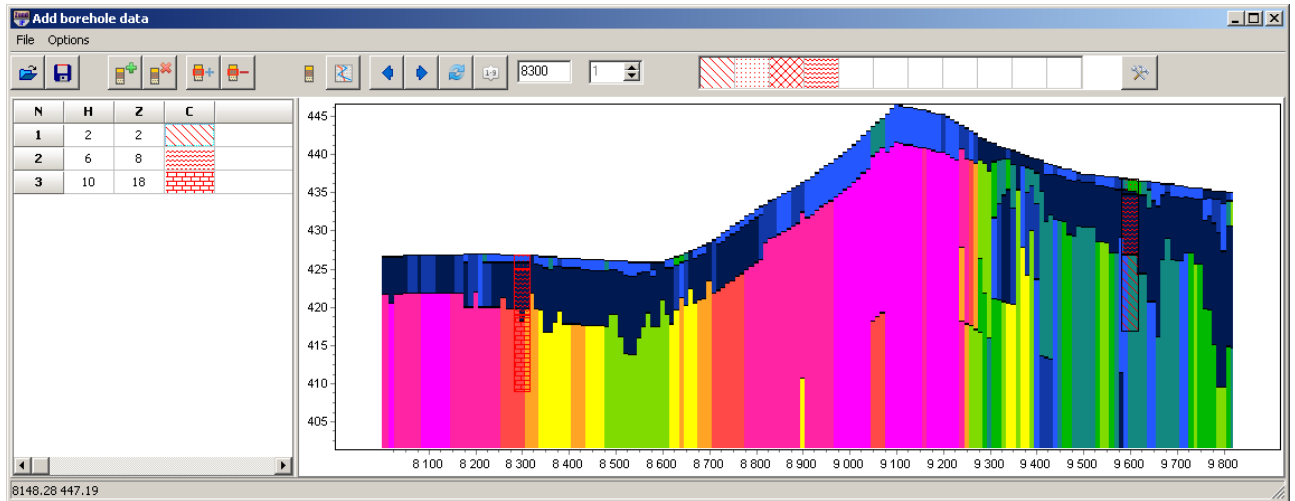
Fig. 47 Dialog window of lithology file creation **Add borehole data**

Dialog window toolbar contains the following buttons:

	Open lithology file.
	Save lithology file.
	Create new borehole.
	Delete borehole.
	Add new layer to borehole.
	Delete layer from borehole.
	Load logging data.
	Return to previous borehole.
	Proceed to next borehole.
	Refresh window.
	Sort out boreholes by coordinate.
	Select fill color of borehole display window (red in example).
	Advanced options.

The main toolbar also contains fields used to specify horizontal coordinate of borehole (offset from profile beginning) - **horizontal position** and elevation - **Position from surface**.

Vertical and horizontal coordinates are set in kilometers. Empty square windows are used to create set of filling patterns.

The module consists of two windows. **Data window** is located on the left. It contains table with the following columns: **N** – number of layer, **H** – layer thickness in kilometers, **Z** – layer bottom depth in kilometers, **C** – type of pattern. Borehole data is displayed graphically in the right window.

Press ![button] button in the toolbar to start creating lithology file. New table appears in **Data window**. Use ![button] button to set number of layers, then edit table by specifying thickness and layer bottom depth and select pattern type according to lithology. Double left click on **C** column to run pattern setup dialog **Pattern Color Editor** (fig. 48). There is a wide range of lithology pattern in the program. Use option **Color** to select pattern color.
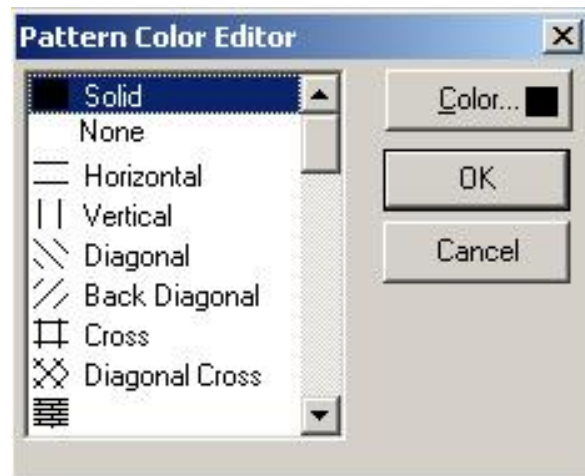
Fig. 48 Pattern Color Editor window

When borehole data is entered, press ![button] button to display borehole graphically. Then specify horizontal and vertical coordinate of borehole in kilometers in the toolbar and after that borehole is displayed according to its coordinates. Active borehole is displayed in red in graphics window.

Palette can be saved to make work with large number of boreholes more convenient. In order to create palette select pattern in pattern column of **Data window**, then right click on pattern domain in the main toolbar. Set of patterns can be created in this way. To save it press ![button] button and select **Save default palette.** Saved set of patterns can be used while creating new lithology and logging data file (![button] - **Load default palette**).

Function **Set percent,** run via button [icon], serves to change scale of borehole data graphical representation.

When data file is saved a few files are created: ***.crt** – module project that can be loaded in «ZONDMT1D» program and ***.txt** – file for each borehole, file names correspond to horizontal and vertical coordinate. See Appendix 2 for details on lithology data file format.

Use **Options/Load borehole data** function to add borehole data. Borehole data is displayed in geoelectrical section and in model editor window (fig. 49).
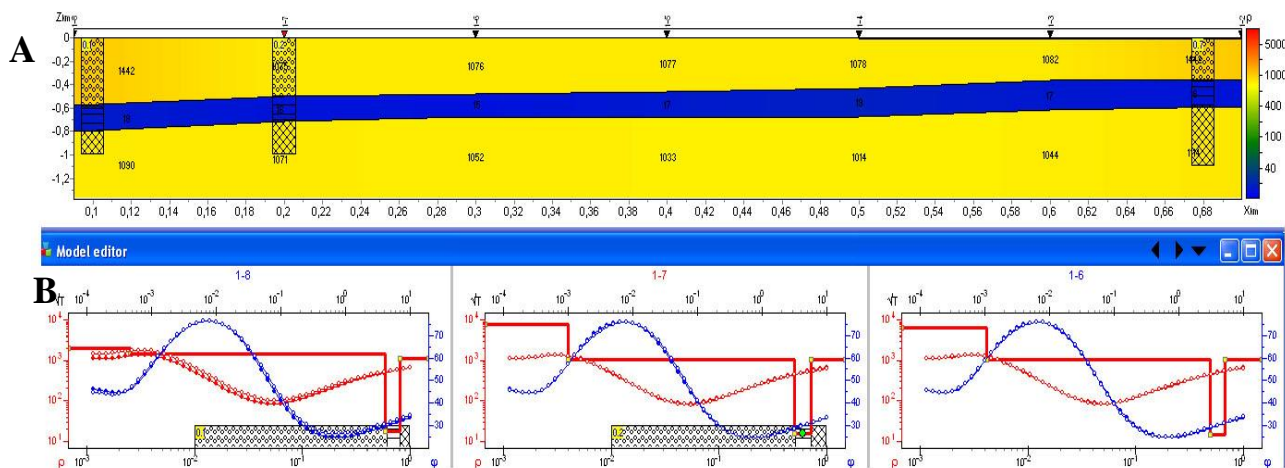
Fig. 49 Display of lithology data in geoelectrical section (A) and in model editor (B)

Logging data can also be added. Click button [icon] to do it. Logging data can be added to the existing lithological column.

Set boundaries dialog

Use **Options** menu to call boundaries setup dialog **Set boundaries**. It allows taking into account prior geological information. Menu with the following buttons appear when this tab is selected:

[icon]	Enable/Disable editing boundaries mode	Enable/Disable editing boundaries mode.
[icon]	Add new boundary	Add new boundary.
[icon]	Delete boundary	Delete all boundaries.
[icon]	Save boundaries to file	Save boundaries to file.
[icon]	Load boundaries from file	Load boundaries from file.

A prior data entry to inverse problem is extremely important to increase interpretation quality. On one hand it increases problem stability and on the other – decreases equivalence field and allows receiving more consistent structure. This is almost the only way to receive acceptable result in models with low-sensitive parameters.

Prior to setting boundaries it is recommended to perform **Smooth** inversion (selecting type of inversion (**Style**) in **Inversion** tab of program setup window) with enabled depth fitting (tick **Thick/depth**). See Program setup dialog for details on inversion parameters.

Boundaries must be plotted in the geoelectrical section according to borehole data or on the assumption of a priori conception of geological structure. Use left mouse button with enabled boundaries editing mode to set boundaries. Right click to close boundary. It is not recommended to use many nodes in boundaries. It is preferable to have as smooth boundaries as possible.

When boundaries are set run inversion again. It will take specified boundaries into account (fig. 50B).
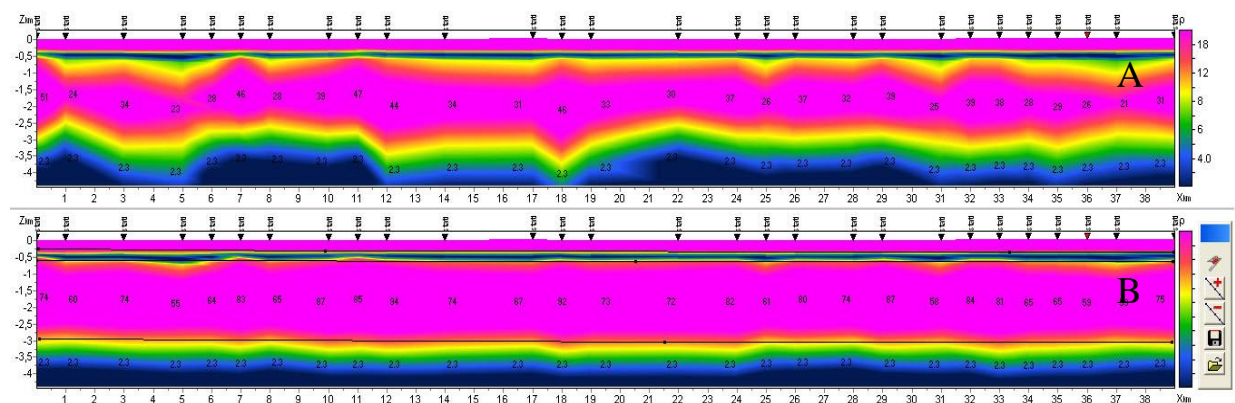
Fig. 50 Example of geoelectrical section after inversion without (A) and with (B) regard to geological boundaries

Raw data filtering

ZondTEM1D allows smoothing raw data. In the menu Options two functions are available: Denoise data and 2D smoothing. To return to raw data use Origin data in the same place. Use these functions with care, because too strong data smoothing and filtering may lead to the substantial losses of useful information.

Function *Denoise data* smoothes automatically source curves for the currently selected receiver (TM or TE), removing individual spikes on sounding curves. Figure 51 shows an example of PMT sensing data before and after denoising.
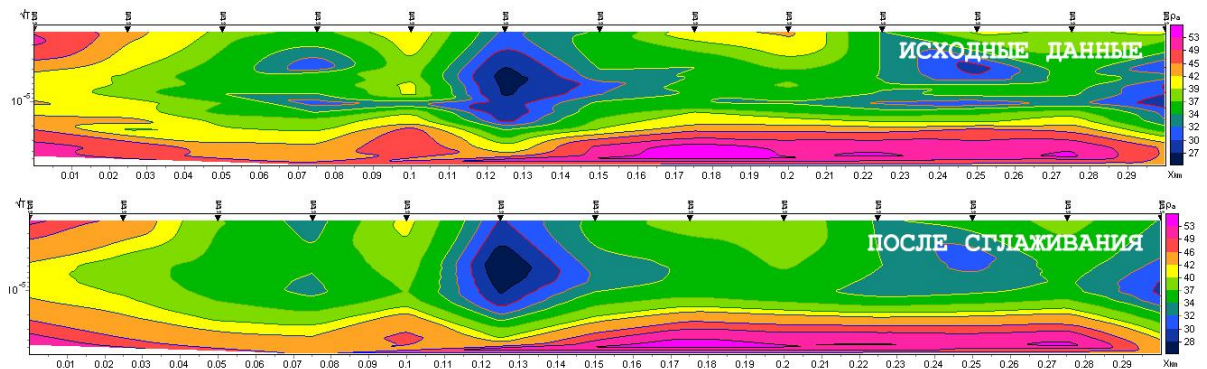
Fig. 51 Example of using *Denoise data* function for PMT. Top - the initial data below - data after smoothing.

2D smoothing function performs two-dimensional data smoothing. This function, unlike the previous one, allows data smoothing in the horizontal and/or vertical direction rather than removal of individual spikes. After selecting this option, a dialog Options (Fig. 52) appears with the following settings:
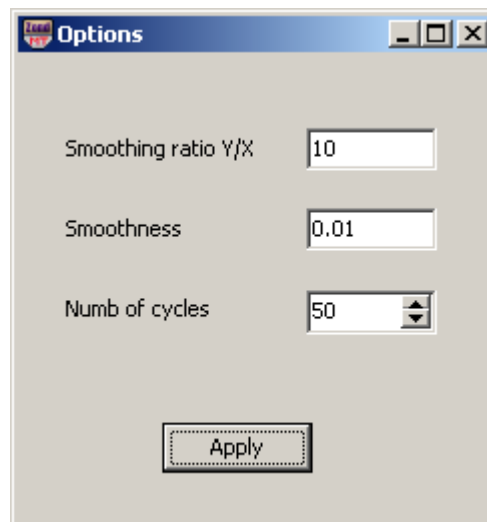
Fig. 52 Settings of 2D smoothing

Smoothing ratio Y/X - smoothing ratio on the axis X and Y. When the value of this parameter is greater than zero, the main smoothing is conducted along the vertical axis, it means along the time axis. For large values of this parameter, the result of applying function is similar

to the results after using Denoise data. For parameter values less than zero, the main smoothing is conducted along the horizontal axis. (fig. 53)

Smoothness – data smoothness degree. The larger the parameter value, the more smoothing is applied to the data.

Numb of cycles - number of calculation cycles.
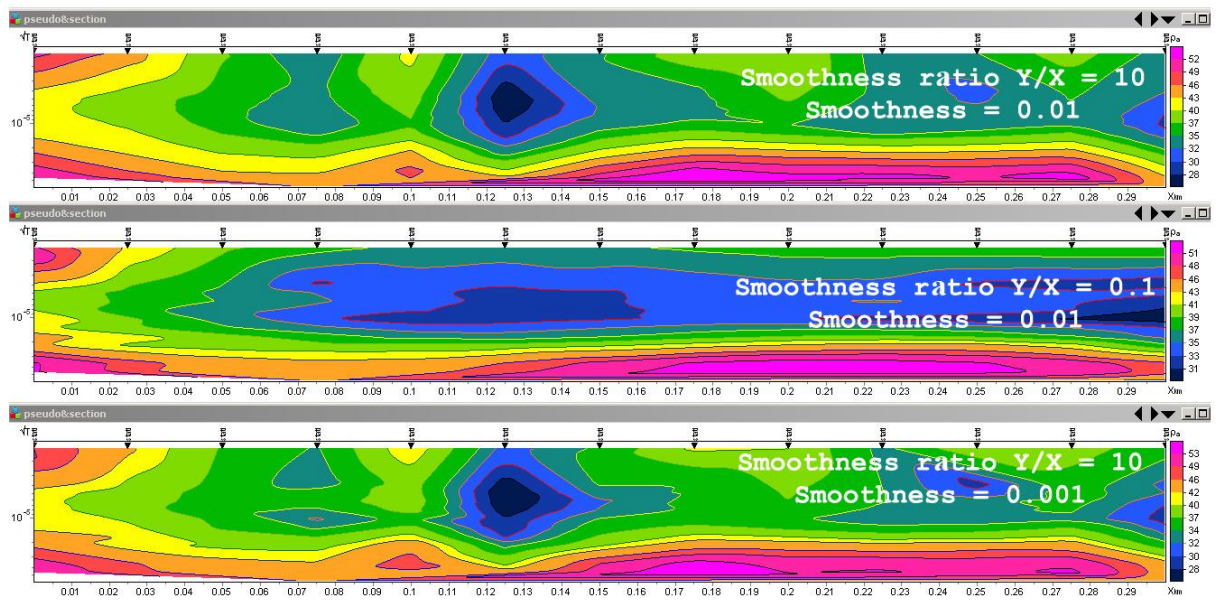
Fig. 53 Example of applying 2D smoothing function with different settings

Model smoothing

The program ZondTEM1D allows smoothing calculated geoelectrical sections (Fig. 54). To do it, select Smooth model in the menu Option. Smoothing is done automatically. During smoothing, layer boundaries and resistivity values change.
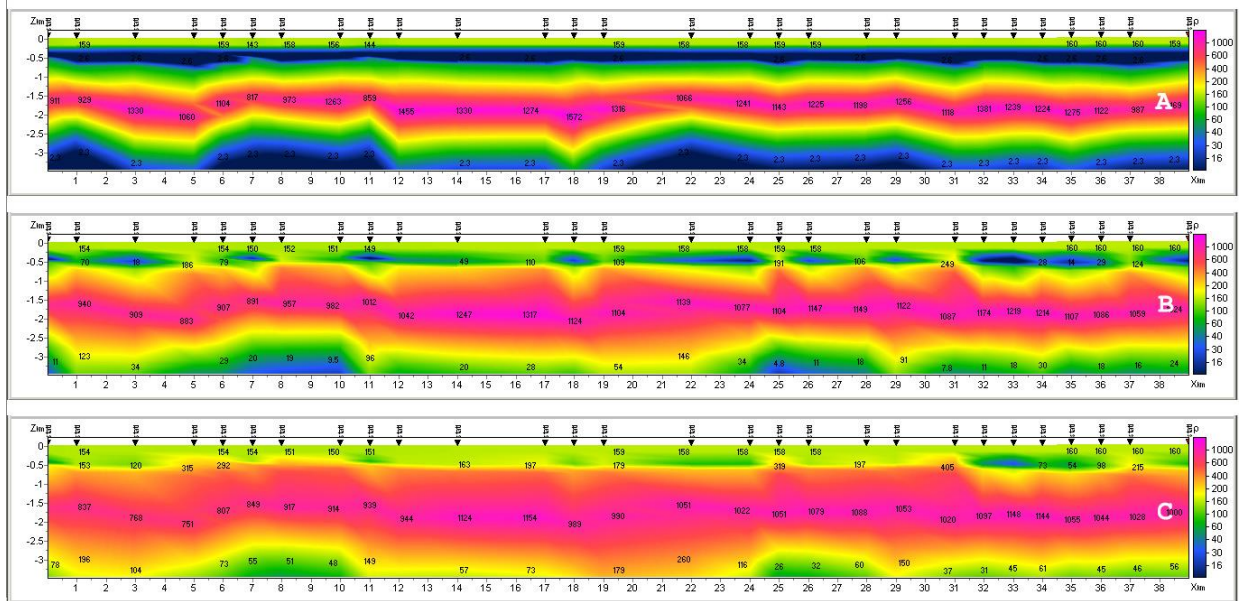
Fig. 54 Example of applying the function Smooth model. A - initial model, B - after applying the option Smooth model, C - after applying the option Smooth model twice.

Module of joint interpretation of MT (AMT, RMT) and VES data.

This module is intended for joint interpretation of AMT (MT, RMT, CSAMT, CSRMT) and VES data.

The module can be called from the **Options/VES Data** menu. The following options are available in the menu:

Load VES data	Load VES data in TXT file (file format is described follow).
Remove VES data	Remove VES data
Joint inversion	Joint inversion of VES and MT data
Display VES plot	Plot VES curves.

Text file of VES data must contain the following values (are recorded in lines):

ab/2 - current line half length

mn - length of the receiving line

app.res - apparent resistivity

The apparent resistivity curves are displayed in window VES Plot (Fig. 55). The red color shows the measured curve, blue - selected as a result of the joint inversion. It is possible to

edit axes properties. To run the editor, right-click with pressed Shift button. For details of setting axis parameters, see Axes editor.
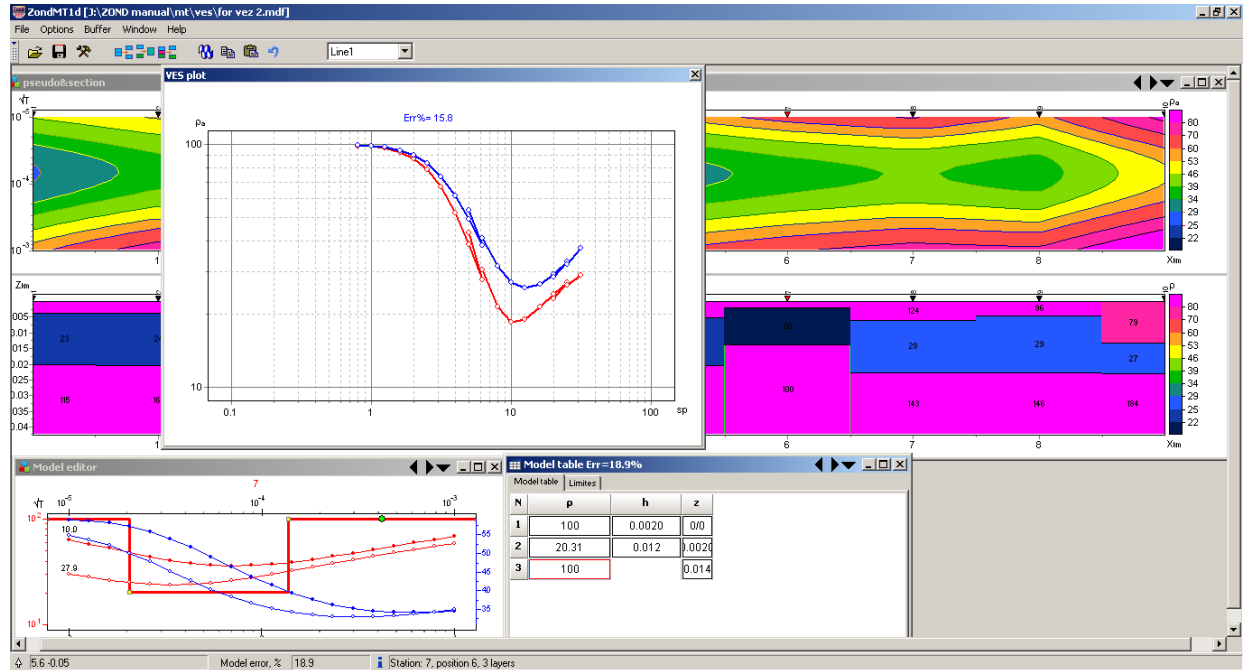
Fig. 55 Displaying of VES curves. The joint inversion results of RMT and VES data

Buffer menu for comparison of inversion results

Menu **Buffer** of the main window allows comparing inversion results using different parameters. After calculating the first model, go to the menu **Buffer** and select **Model 1**. In the appeared dialog, it is possible to specify model name, reflecting, for example, used parameters in the inversion. In this way, 1 to 5 models can be saved.

A tick will appear in front of a saved model. When clicking on the saved model, shown dialog allows loading selected model as a current (button **From Buffer**), or saving the current model as selected (Button **To Buffer**).

The option Open from the Buffer menu opens all saved models for the current measurement point in one window. (Fig. 56)
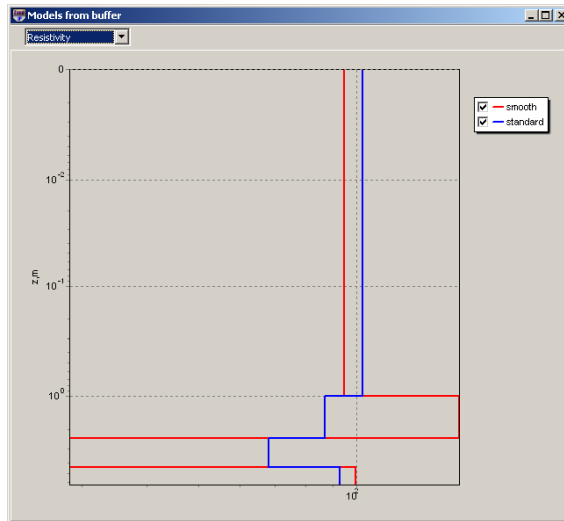
Fig. 56 Two models opened in the same window for one measurement point

Color palette setup dialog

The dialog is meant for object palette setup and can be run using **Palette** button (fig. 57). The dialog allows choosing one of default palettes (forward and inverse rainbow, grey scale, etc.) or creating own one. Right click with Ctrl button pressed to add slider to the scale. Use Delete button to remove slider. Use 🔲 button to save scale or load already existent scale using 📂 button.
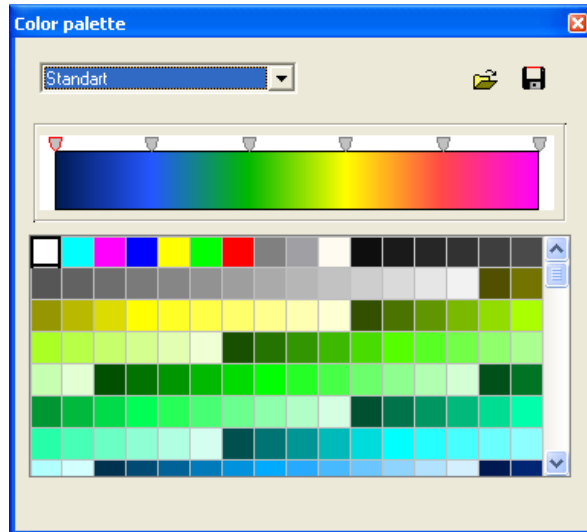
Fig. 57 Color palette parameters setup dialog

Axes editor
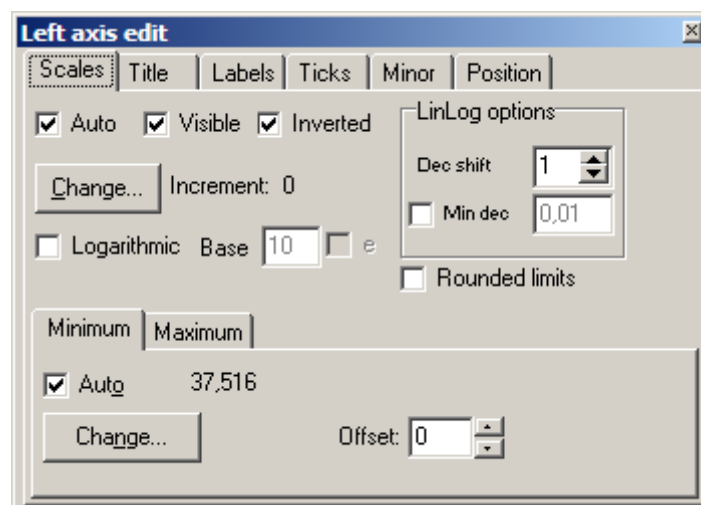
Fig. 58 Axes editor window

Axes editor is used to set graphic and scale axes parameters. Right click on necessary axis with SHIFT button pressed to run it. Pop-up menu with two fields (**options** and **default**) appears. The first one runs dialog, the second sets values on default.

First tab of **Scales** dialog contains options for axes scale parameters setup.

Option **Auto** defines how minimum and maximum axis values are chosen. If this option is ON axis limits are set automatically otherwise values from Minimum and Maximum filed specified by user are selected.

Option **Visible** shows/hides selected axis.

Option **Inverted** defines axis orientation.

Button **Increment change** runs dialog for axis label step definition.

Option **Logarithmic** selects logarithmic or linear axis scale. In case of sign-changing scale additionally use options from **LinLog options** field.

Option **Base** sets logarithm base for logarithmic axis.

Field **LinLog options** contains options for linear-logarithmic axis adjustment. Linear-logarithmic scale allows representing sign-changing or zero containing data in logarithmic scale.

Option **Dec Shift** sets indent (in logarithmic decades) relative to maximum axis limit modulo to zero. Minimum decade (prezero) has linear scale, others have logarithmic.

Option **Min dec** sets and fixes minimum (prezero) decade value if option is ON.

Option **Rounded limits** defines whether it is necessary to round minimum and maximum axis values or not.

Fields **Minimum** and **Maximum** contain options for axis limits adjustment.

Option **Auto** defines whether axis limit is selected automatically or using **Change** button.

Option **Offset** sets percentage axis limit shift relative to its actual value.

Tab **Title** contains options for axis header adjustment.

Tab **Style**:

Option **Title** sets axis header text.

Option **Angle** sets header text rotation angle.

Option **Size** sets header text indent. If 0 value is specified it is selected automatically.

 Option **Visible** shows/hides axis header.

Tab **Text**:

Button **Font** runs header font setup dialog.

Button **Outline** runs dialog for header letters outline adjustment.

Option **Inter-char spacing** sets letter spacing in axis header.

Button **Gradient** runs gradient fill setup dialog for header text.

Option **Outline gradient** specifies if gradient fill is used in outline or interior of letters.

Button **Shadow** runs axis header shadow setup dialog.

 Tab **Labels** contains options for axis label adjustment.

Tab **Style**:

Option **Visible** shows/hides axes labels.

Option **Multiline** is used for setting multiline axes labels.

Option **Round first** rounds first axis label.

Option **Label on axis** hides labels that go beyond axis.

Option **Alternate** arranges labels in two lines.

Option **Size** sets axis label indent. If 0 value is specified it is selected automatically.

Option **Angle** sets label rotation angle.

Option **Min separation %** sets minimum percentage label spacing.

Tab **Text**:

Button **Font** runs label font setup dialog.

Button **Outline** runs dialog for label letters' outline adjustment.

Option **Inter-char spacing** sets letter spacing in label text.

Button **Gradient** runs label gradient fill setup dialog.

Option **Outline gradient** specifies whether gradient fill is used in outline or interior of letters.

Button **Shadow** runs label shadow setup dialog.

Tab **Ticks** contains options for axis main ticks adjustment.

Button **Axis** runs axis line setup dialog.

Button **Grid** runs line setup dialog for main ticks' grid.

Button **Ticks** runs external main axis tick setup dialog. Option **Len** sets its length.

Button **Inner** runs internal main axis tick setup dialog. Option **Len** sets its length.

Option **Centered** centers grid of axis ticks.

Option **At labels only** displays main axis ticks only if axis labels are present.

Tab **Minor** contains options for axis intermediate ticks adjustment.

Button **Grid** runs line setup dialog for intermediate ticks grid.

Button **Ticks** runs external intermediate axis tick line setup dialog. Option **Length** sets its length.

Button **Minor** runs internal intermediate axis tick line setup dialog. Option **Len** sets its length Option **Count** sets number of intermediate ticks between main ones.

Tab **Position** defines axis size and position.

Option **Position %** sets axis indent relative to its standard position on graph (in percent to graph size or in screen units depending on selected option Units).

Option **Start %** sets axis start indent relative to its standard position on graph (in percent to graph size).

Option **End %** sets axis end indent relative to its standard position on graph (in percent to graph size).
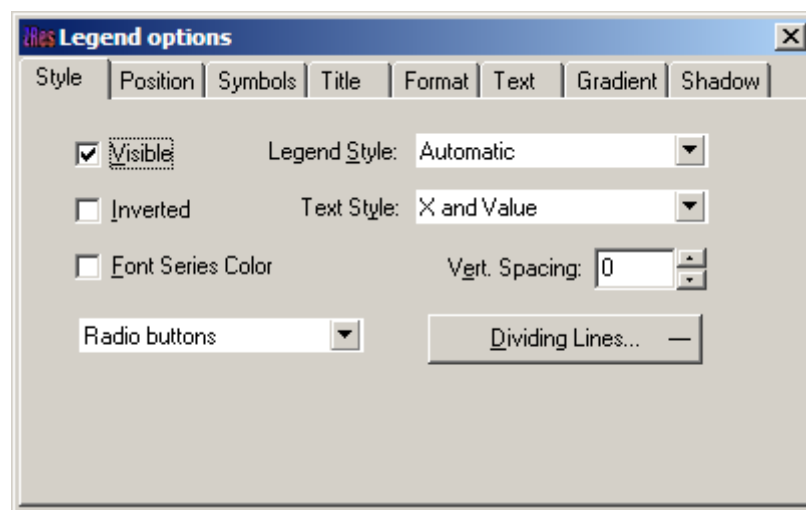
Legend editor

Fig. 59 Legend editor window

Editor allows adjusting graphic and legend interface. Right click with SHIFT button pressed on legend to the right of the graph to run it.

Pop-up window with set of tabs will appear.

Tab **Style** contains settings of legend display, allows choosing data label format and showing boundaries between legend labels, etc.

Tab **Position** serves for choosing legend position relative to graphics plan.

Tab **Symbols** sets legend symbols display parameters.

Tab **Title** specifies legend name and allows adjusting its format.

Tab **Text** serves for adjusting legend label format.

Tabs **Format**, **Gradient** and **Shadow** contain settings of legend window, its gradient fill, and shadow.

Graphics set editor
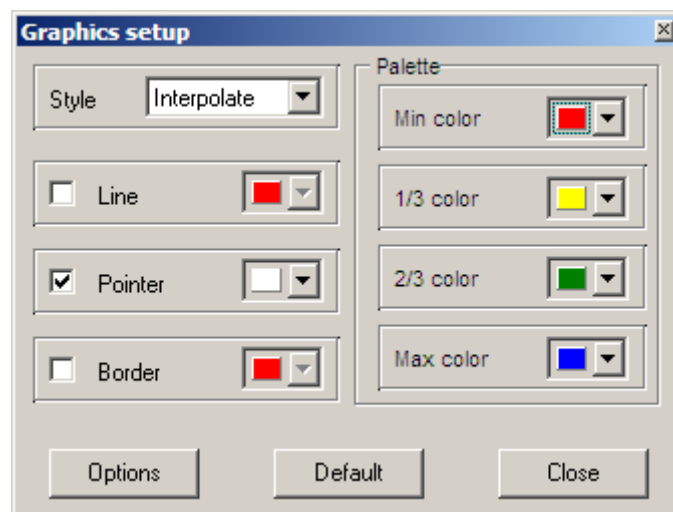
Fig. 60 Graphics set editor window

Graphics set editor serves for color adjustment of graphics set.

Option **Style** defines algorithm of graphic's color palette specification.

Interpolated palette is used if **Interpolate** is selected. It is created using colors specified in fields **min color**, **1/3 color**, **2/3 color** and **max color**. Value **const** sets the same color (option **color**) for all graphics. Value **random** assigns random colors for all graphics.

Option **Line** sets color for graphic's connecting lines. If this function is OFF palette color is used otherwise specified in **Line** field color is used.

Option **Pointer** sets color for graphic point's color fill. If this function is OFF palette color is used otherwise specified in **Pointer** field color is used.

Option **Border** sets graphic point's outline color. If this function is OFF palette color is used otherwise specified in **Border** field color is used.

Button **Options** runs graphics setup dialog.

Button **Default** returns graphics default settings.

Graphics editor
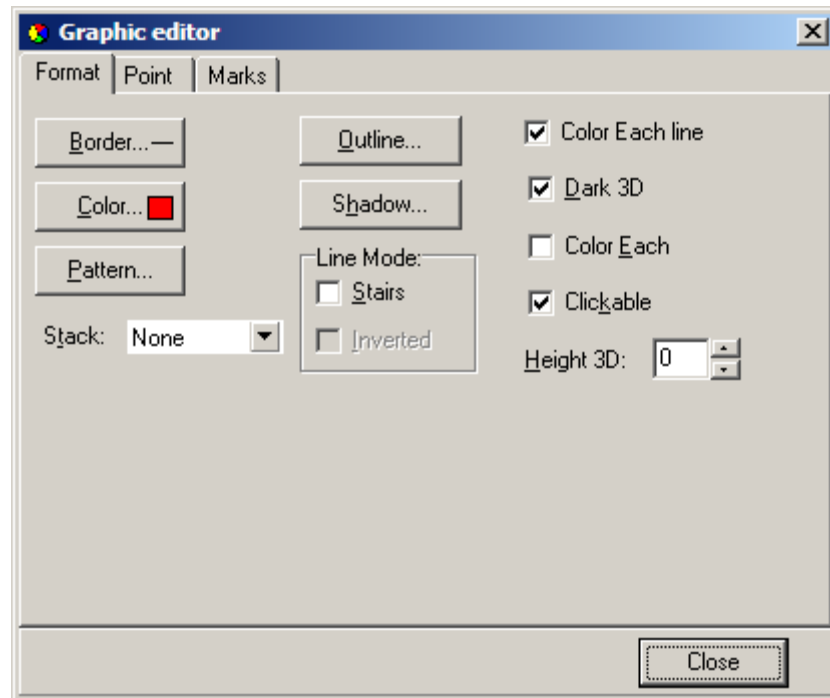
Fig. 61 Graphics editor window

Graphics editor is used for graphic interface setup. Right click with SHIFT button pressed on graphic to run it.

Tab **Format** contains connecting line settings.

Button **Border** runs connecting line parameters setup dialog.

Button **Color** runs color setup dialog.

Button **Pattern** runs filling parameters setup dialog.

Button **Outline** runs graphic's connecting line setup dialog.

Button **Shadow** runs shadows setup dialog.

Tab **Point** contains plot point settings.

Option **Visible** is used to show/hide plot points.

Option **Style** sets point shape.

Option **Width** sets point width in display units.

Option **Height** sets point height in display units.

Option **Inflate margins** defines if image size is zoomed in according to point size or not.

Button **Pattern** runs point's color fill setup dialog.

Button **Border** runs point's outline parameters setup dialog.

Button **Gradient** runs point's gradient color fill setup dialog.

Tab **Marks** contains settings of graphic's point marking.

Tab **Style**.

Option **Visible** is used to show/hide plot point marking.

Option **Draw every** allows plotting every second, third and so on marking depending on selected value.

Option **Angle** sets point marking rotation angle.

Option **Clipped** defines whether point marking is plotted or not if it is located beyond graphic borders.

Tab **Arrows** allows adjusting arrow from marking to point.

Button **Border** runs arrow line parameters setup dialog.

Button **Pointer** runs arrowhead shape setup dialog (options in tab Point).

Option **Length** sets arrow length.

Option **Distance** sets distance between arrowhead and plot point.

Option **Arrow head** sets type of arrowhead. **None** – arrowhead specified by **Pointer** button is used. **Line** – classic thin arrowhead is used. **Solid** - classic thick arrowhead is used.

Option **Size** sets arrowhead size if classic arrow is used.

Tab **Format** contains graphic settings of marking frame.

Button **Color** runs frame background color selection dialog.

Button **Frame** runs frame line setup dialog.

Button **Pattern** runs background parameters setup dialog.

Option **Bevel** sets frame type: usual, elevated or submerged.

Option **Size** sets elevation or submergence level.

Option **Size** rounds frame corners.

Options **Transparent** and **Transparency** sets frame seamlessness degree.

Tab **Text**:

Button **Font** runs marking font setup dialog.

Button **Outline** runs marking letter outline setup dialog.

Option **Inter-char spacing** sets letter spacing for marking text.

Button **Gradient** runs gradient fill for marking text setup dialog.

Option **Outline gradient** specifies if gradient fill is used in outline or interior of letters.

Button **Shadow** runs marking text shadow setup dialog.

Tab **Gradient** contains gradient fill settings for frame around markings

Tab **Shadow** contains shadow settings of frame around marking.

Print preview dialog

Use **File/Print preview** function of the program main menu to run print preview dialog. Double click on any program object also runs it. Two options are available when running via main menu:

Option **Station** serves to print sounding curves and current station model (fig. 62). Model parameters are displayed as table which contains number, resistivity value and depth of top layer boundary.
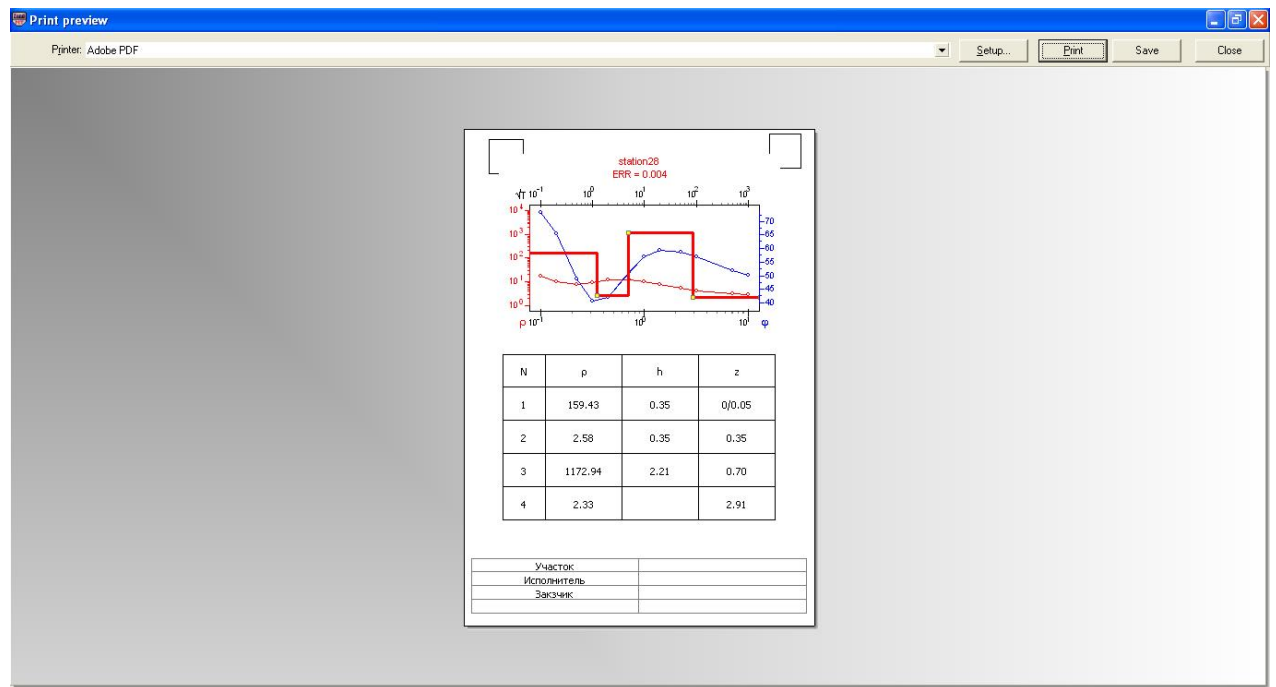

Fig. 62 Window **Print preview/Station**

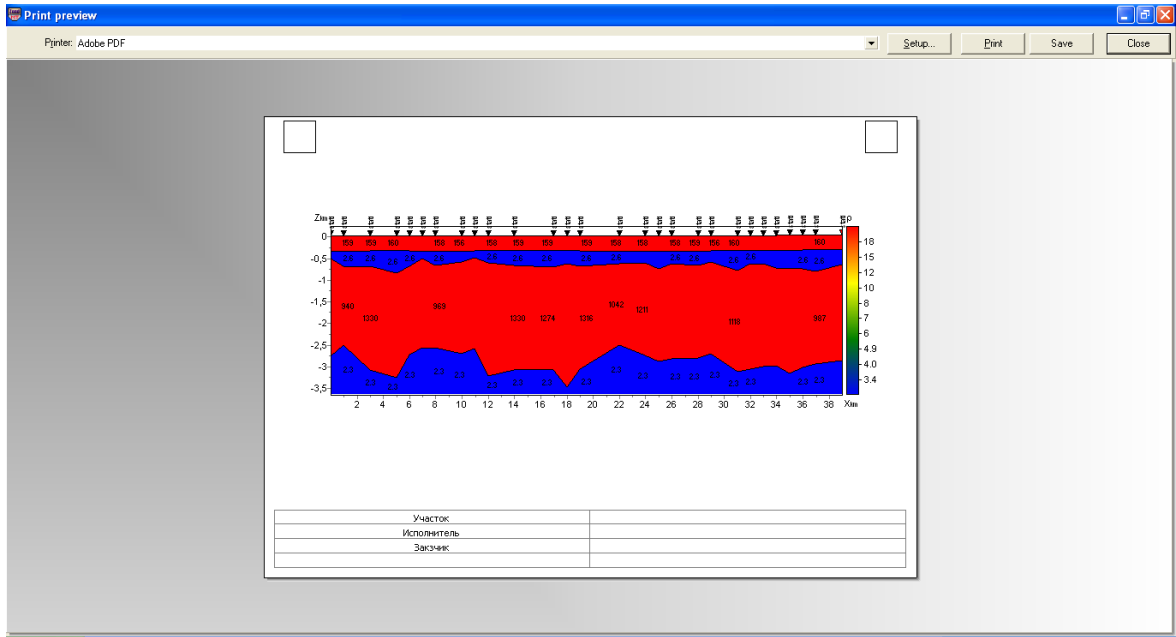Option **Section** serves to print geoelectrical section (fig. 63).

Fig. 63 Window **Print preview/Section**

Use left button to move print object in the page.

Print Preview window of the main menu contain the following buttons.

 - select printer. One of adapted printers can be chosen in opening menu.

 - print setup button. Size and page orientation, print properties, number of pages per sheet and other parameters can be set in opening window.

 - press this button to start printing when necessary parameters are specified.

 - save in bitmap files.

 - close Print preview window.

Squares in the top part of the page are designed for company seals, stamps and symbols. Right click on the square and choose raster image which you would like to insert in to opening window. Use mouse to change square size.

Editing table is located at the bottom of the page. In order to add text, right click on the table and type in necessary text in opening window. Comments can be also saved in table files using button or already saved comments can be loaded using button.

Zdconvert program serves to create data files for «ZONDMT1D» and «ZONDMT2D» programs. Sounding station data represented as table files in txt or dat format which contain frequency, apparent resistivity, and impedance phase values are necessary to work with the program. The program has three main windows (fig. A1). List of sounding sites organized as 5-column table is located in the top right window: **Filename** – name of source file, **Name** – assigned name of the station, **Used** – include/exclude station data from new file, **pozX** – distance from the beginning of profile, **pozZ** – elevation of measuring point. The former four columns can be edited.
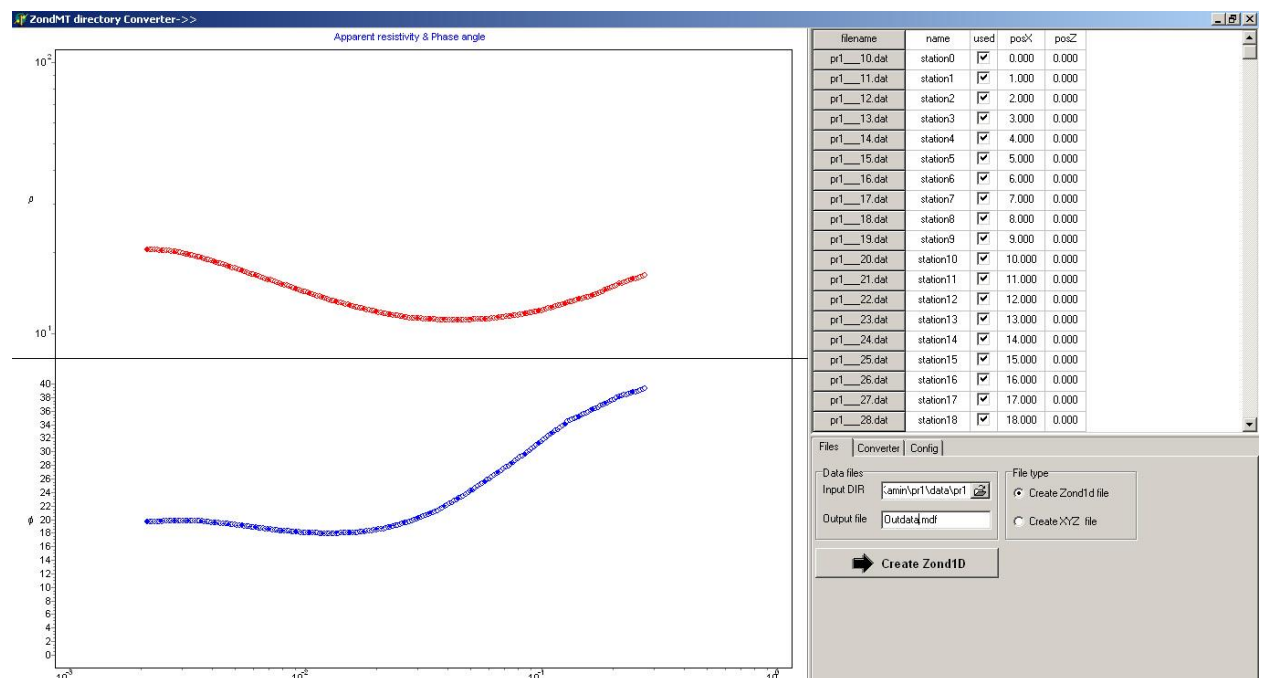
Fig. A1 Window of Zdconvert support program

Observed and smoothed curves of apparent resistivity and phase impedance for selected station are displayed in the left window of the program. Double left click on necessary axis to run vertical or horizontal axis setup dialog.

Main program menu with three tabs is located in the bottom right corner.

Tab **Files:**
Field **Data files** – contains information about directory that contains source data files and name of resultant ZONDMT1D file.

Input DIR – open directory that contains source data files.

Output File – set outbound ZONDMT1D (*.mdf) file name.

Filed **File type** – specifies type of outbound file.

Create Zond1D file – create file of 1D inversion program ZONDMT1D.

Create XYZ file – this option is used to export data of parameters (apparent resistivity and phase impedance) distribution on certain frequency that is set in pop-up window. Additional editable column **pozY** also appears in data window. It allows receiving areal parameters distribution.

Depending on selected type of outbound file **Create Zond1D** or **Create XYZ** button is located in the bottom area. After pressing this button corresponding file is created in the directory where Zdconvert program is saved.

Tab **Converter**:

Field **Range dividing** – specifies type of outbound curves filling with points. Automatic filling (**Automatic**) or filling in logarithmic frequency mesh (**Equal log-step**) is possible.

Include boundary frequencies – sets whether end points are included to outbound curves or not.

Smoothing – enable/disable smoothing options.

Frequencies number – number of points on resultant curve.

Press **Process** button to accept all specifications.

Three bottom fields serve to integrate two files of 1D inversion program for different polarizations in one 2D inversion file. Select 1D inversion files which correspond to TM and TE modes in two left windows, specify file name in the right window, and press button. 2D inversion file (*.m2d) will be created in the directory that contains source 1D inversion files.

Tab **Config** is used for source files parameters setup. Specify number of columns in data file, number of column with apparent resistivity, impedance phases and frequency values in **Columns number**, **Rho column index**, **Phase column index** and **Frequency column index** fields respectively.

Specify extensions of source data files (e.g., dat or txt) in the right window.

Turn **log_rho** option on if source data file contains decimal logarithm values of apparent resistivity.

Use button to open list of *.prd files. This list should be saved in the folder with initial data and should contain three columns: PozX, PozZ and File name (distance along profile, elevation and file name respectively).

Button is used to create list of already opened files.

Window **Step** sets step along profile between stakes in kilometers.

Appendix 2. Lithology data file format

Lithologic columns are hold in certain file formats. First type of files has txt extension.

The following file structure is used to create lithology data file:

First column contains depth (from ground surface) of layer boundary. Second column contains zeros. Third column defines layer color for visualization, forth – type of pattern

Lift of first 23 patterns which can be used for lithologic column creation is given below.
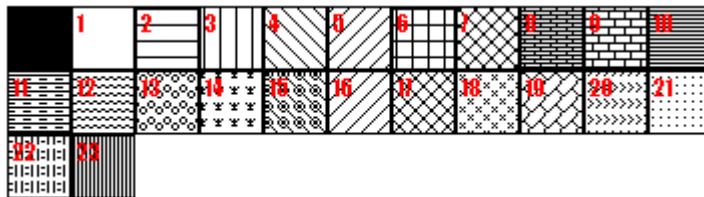
Lithologic data sample-file is given below:

0 1 0 13 Top of layer 1

4 1 0 13 Bottom of layer 1

4 1 0 19 Top of layer 2

11 1 0 19 Bottom of layer 2

11 1 0 27 Top of layer 3

16 1 0 27 Bottom of layer 3

Second type of files has *.crt extension; these are control files which specify type of data and way of visualization. Structure of CRT file for lithology data visualization for any number of boreholes is described below.

2280.txt   First line – logging or lithology data file

brhl2280   Second line – Borehole name (is displayed on borehole)

18 2 2 1 0 1 0 0   Third line contains control parameters

Data record 18 – borehole coordinate on profile.

2 – image width (in percents to profile length, usually 1 - 20).

2 – type of data visualization 0 - 3.

0 - logging data (as graph);

1 - logging data (interpolated color column), section color scale is used for visualization;

2 - lithologic column;

3 - logging data (color column), colors for data visualization correspond to model color scale, column colors are selected in compliance with model color scale;

1 - Logging data normalization parameter 0 - 2.

0,1 – the same minimum and maximum is used for all data;

1,2 - subtract average value from every borehole log;

0 - Logging method index (if different logging methods are displayed indices of all methods should be specified) 0 – n-1, where n – number of methods.

1 – Plot color.

0 – Data scale is logarithmic 0 or linear 1.

0 – Vertical borehole shift relative to ground surface.

3246.txt   Description of the following borehole on profile

brhl3246

102 2 2 1 0 1 0 0