ADVANCED METHODS FOR JOINT MT/MV PROFILE STUDIES OF ACTIVE OROGENS: THE EXPERIENCE FROM THE CENTRAL TIEN SHAN

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1. Introduction

Areas of active orogenesis are places where the multi-disciplinary geological-geophysical studies can substantially extend understanding of the fundamental geodynamic processes. The geoelectromagnetic branch of these investigations may and has to be an important source of information on the crustal tectonics, petrophysics, thermal and fluid regimes of the interiors. However the complex structure of orogens introduces rigorous requirements to the methods of study, including reasonably detailed observation grids and precise processing, effective analysis of the data, defining the dimensionality of the interpretational model, and finally, high resolution and stable inversion tools.

The geoelectric investigations of Tien Shan region held by the “Naryn” Working Group (the authors of the paper) during last years were concentrated on the development of rational joint system of magnetotelluric (MT) and geomagnetic (MV) soundings, which could satisfy the above mentioned demands and reliably reconstruct the heterogeneous conductivity structure of the orogen, still being formed since Cenozoic activization.

The main efforts were done to make our methods more robust to the principle difficulties of the geoelectric investigations in the mountains, which include irregular observation grids, the influence of the topography, strong near surface heterogeneity of conductivity distribution; multi-level anomalous geoelectric structure of crust and upper mantle of orogen. The prominent principles of the elaborated complex of MT/MV sounding in such areas are the following:

- synchronous observations;
- integration of MT/MV data sets with “synchronization” of data of different field campaigns;
- multi-site processing with attention to accuracy of additional component and long periods estimates of transfer function (TF);
- modern schemes of invariant analysis robust to galvanic distortions;
- effective inversion procedure with detailed model parameterization, providing adequate reconstruction of both smooth and sharp conductivity boundaries and accounting for the topography;
- using all the variety of local and inter-station TFs for the inversion.

In a case of elongated orogens they should be extended by:

- construction of quasi-2D ensembles of data for profile inversion with accounting for 3D distortions;
- specific inversion strategy based on successive partial and multi-component profile inversions considering different sensitivity to targets and “immunity” to 3D distortions of the different data components.

The paper describes application of this approach to the analysis and interpretation of MT/MV data at the 700-km “Naryn” transect providing the geoelectric cross-section of Central Tien Shan along 76°E line.

2. Integration of the data ensembles along regional transect “Naryn”

20 years of data acquisition of RS RAS (Research Station of Russian Academy of Sciences) in Tien Shan region have brought the data set of about 800 soundings (Rybin et al., 2001, Fig.1a), with tens of broad-band and long-period MT sites (CES2, MT-PIK, MT-24 and LIMS equipment) being spread, in particular,

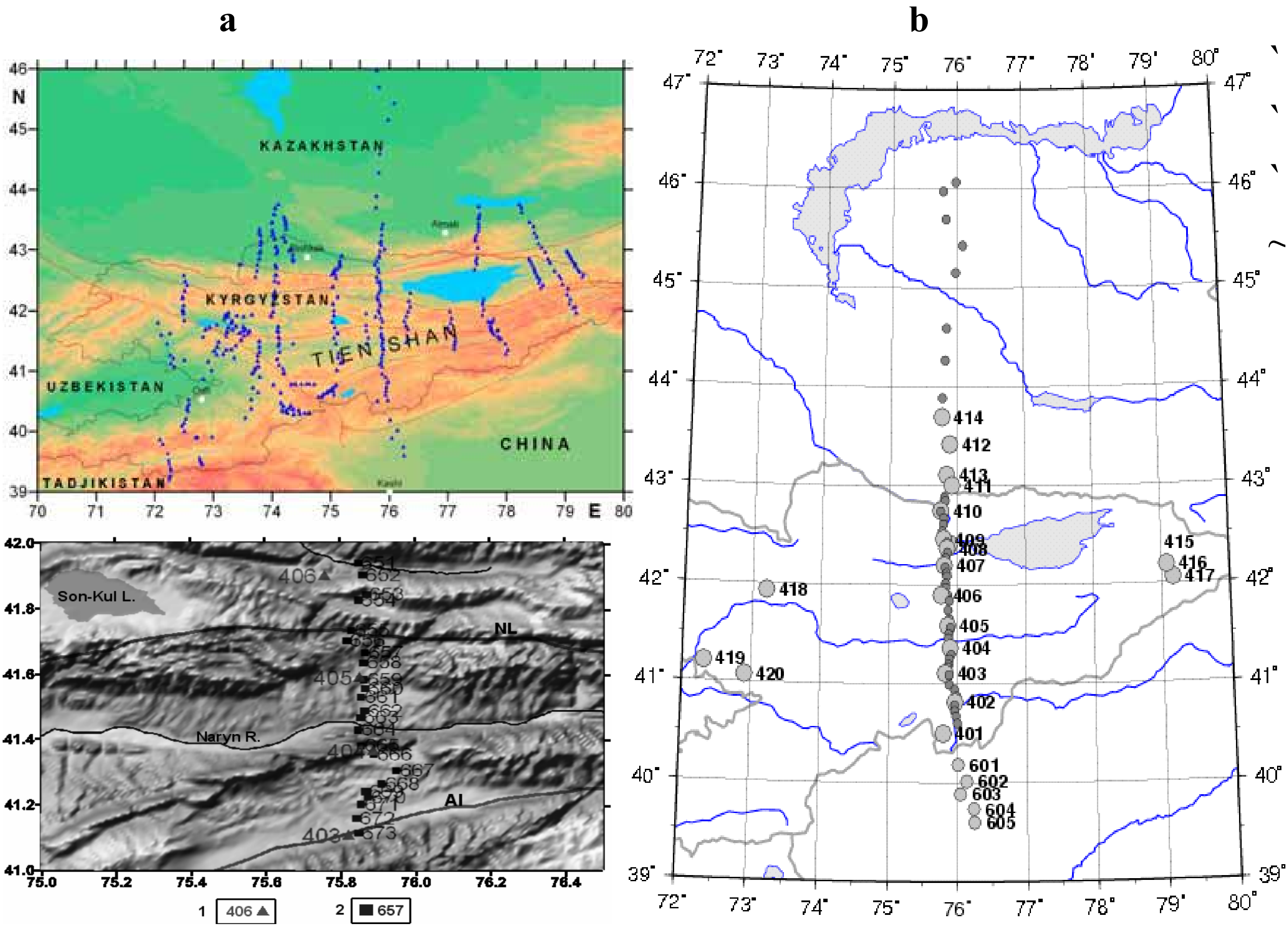

Fig. 1. The schemes of MT/MV sites locations at the territory of the Tien Shan region conducted by staff of Research Station of Russian Academy of Sciences (Bishkek, Kyrgyzstan): (a) the overall sketch of prospecting and long-period soundings with different MT instruments (CES-2; MT-PIK and LIMS) in 1986-2003; (b) MT/MV soundings along "NARYN" transect (dark grey circles – prospecting soundings with CES-2 and MT-PIK; big light grey sites with numbers – long-period soundings with LIMS); (c) the profile segment of detailed prospecting soundings with "Phoenix"-MTU-5 in 2005. Sites: 1 – LIMS; 2 - MTU-5. Major fault zones: LN - Nikolaev Line, AI – Atbashi-Inilchek.

on the regional transect "Naryn" (Fig.1b). The first simultaneous observations for 19 long-period MT/MV soundings were done on this profile with LIMS equipment in 1999 – 2001 in collaboration with geophysicists from Californian University of Riverside, presenting the results of their interpretation in (Bielinski et al., 2003). The broad-band observations of NS RAS in 2005 with "Phoenix"-MTU-5 stations working out in the details the segment of the profile around Nikolaev Line fault zone (Naryn basin) were also held synchronously (Fig.1c).

LIMS and "Phoenix" soundings were processed by "Naryn" WG with the modern tools supplying the estimates of both local and inter-station TFs. These tools (Varentsov et al., 2003; Varentsov et al, 2005) are based on the new remote reference (RR) and multi-RR schemes, which sort the partial TF estimates in the final averaging with the account for several criteria of the homogeneity of the horizontal magnetic field. This technique, mRRMC scheme– multi Remote Reference with Magnetic Control, was originated and has benefited in the frames of the EMTESZ-Pomerania project (Sokolova et al, 2005b). The progress was made also at "Naryn" profile: the estimates of the additional impedance components were improved and long-period responses stabilized for LIMS data (Sokolova et al, 2005a) as well as for broad-band "Phoenix" ones (especially for the estimates in so-called "dead" period range).

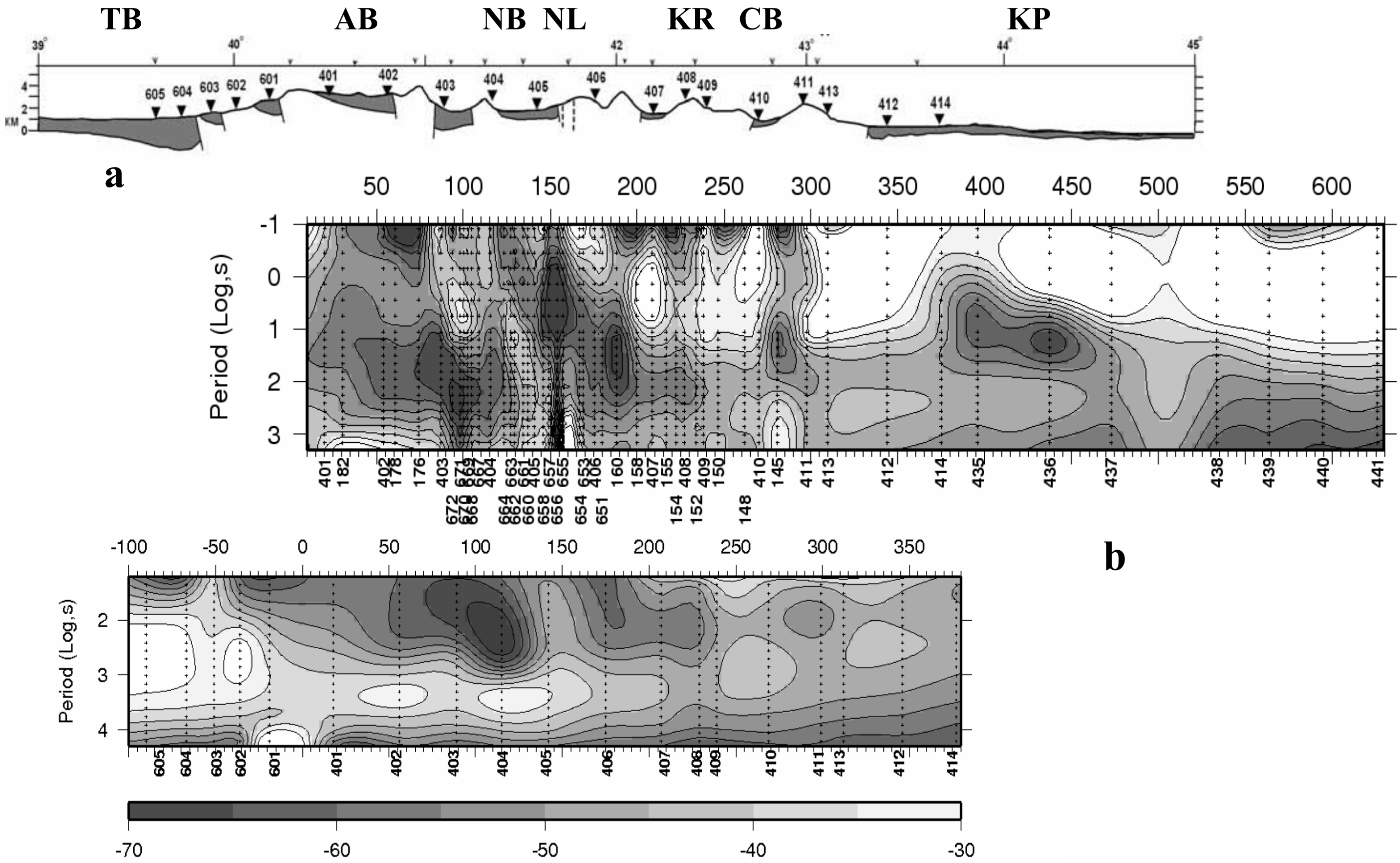

Fig. 2. Pseudosections of Zyx ("longitudinal" impedance) phase along "Naryn" line and relief profile with sedimentary basins and abbreviators of the main geomorphologycal features of Central Tien-Shan and surroundings (TB – Tarim basin, AB – Atbashi basin, NB – Naryn basin, NL – Nikolaev Line fault zone, KR – Kyrgyz range, CB – Chu basin, KP – Kazakh plate): (a) - **MT** ensemble (CES-2, MT-PIK, MT-24+ LIMS and «Phoenix» soundings); (b) - **LMT** ensemble (LIMS soundings). Coordinates along profile are given from x=0 (Kyrgyz-China border) in km and phase scale palette – in degrees.

The old prospecting data on the profile were revised for the selection of conditional ones and combined with the results of new synchronous MT soundings. The multi-component data set at the heterogeneous grid was compiled from the impedances (Z), tippers (Wz) and first estimated inter-station horizontal magnetic tensors (M) in the overall period range 0.01-20000 s. The M - estimates (16-1500, 2000s) connected the horizontal field in 17 sites observed in 1999, 2001 and 2005 via single base in S. 410. As an example, the subsets of this data ensemble are presented in Fig.2 by phases of longitudinal impedances in prospecting (**MT**) and long-period (**LMT**) ranges with indication of sounding sites location, the relief profile, sedimentary basins and abbreviators of the main geomorphologycal features of Central Tien-Shan. Because of irregularity of observation grids in both period ranges and different coverage by the data of different parts of the profile the further analysis and inversion of the data were held separately for two mentioned subsets.

3. Invariant analysis and construction of quasi-2D data sets

For estimation of strike and dimensionality parameters new schemes of invariant analysis were applied according to *Caldwell et.al, 2004* (CBB scheme, based on phase tensor transformation), *Berdichevsky and Dmitriev, 2008* (complex dimensionality criterion, combining several robust impedance and tipper SKEWs) and *Varentsov 2007a* (tipper and M tensor SKEW and strike estimates).

Due to the application of these effective schemes, robust to galvanic distortions, and high precision estimates of all the components of TFs (including additional ones) reliable strike and dimensionality parameters were obtained. Fig. 3 compares Swift's and angle CBB Skew pseudo section for LMT data ensemble and shows, first, robustness of CBB estimates to static galvanic distortion and, second, several areas with increased CBB values depicting the data 3D-distorted in different degree by near surface or

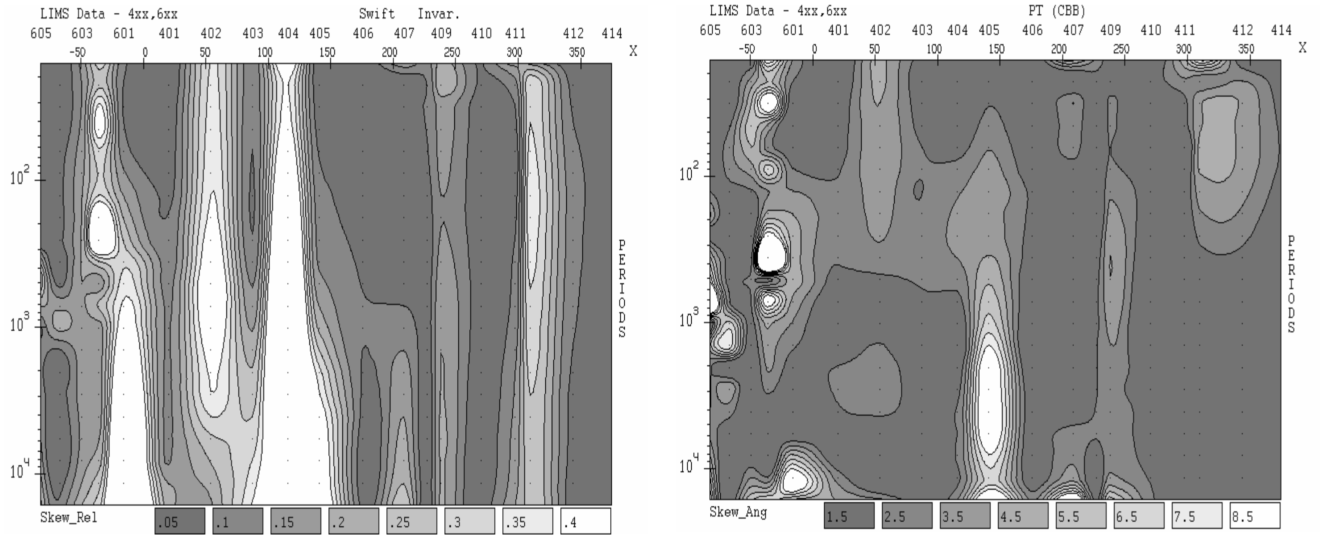

Fig. 3. Pseudosections of Skew estimates for **LMT** data ensemble: amplitude impedance Skew according to *Swift, 1983* (left) and phase tensor angle Skew according to *Caldwell et al., 2004* (right).

crustal inhomogeneties. The most prominent one, marked at rather long periods by Skew values above threshold for 2D structures (~6°), is located around S.405 on the border of Naryn basin near the crossing of the Nikolaev Line fault zone (NL, the main structural margin of Tien Shan, separating its Northern, *Caledonian*, and Middle, *Hercinian*, parts, see Fig.2). The described behavior of CBB SKEW is generally corresponds to the spatial-period distribution of **LMT** magnetovariational SKEWs.

In **MT** ensemble the northern part (Kazakh plate) of the profile with mostly small (1-2D) values of impedance SKEWs differs from mountainous one, where local areas of 3D distorted data are often depicted. Here large SKEWs are characteristic for tipper data at periods less then 10s, while for longer ones mosaic picture of small and increased values are common.

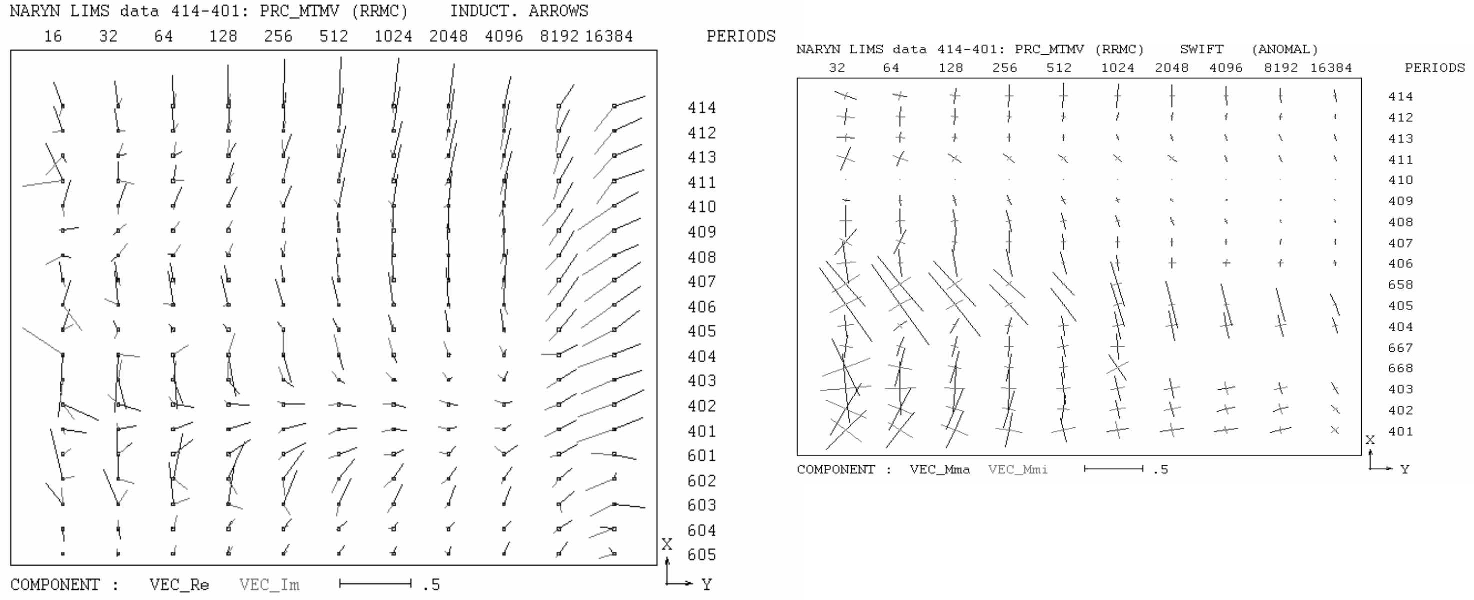

Fig. 4. The induction vectors (in Wiese convention, left panel) and diagrams of main directions of anomalous horizontal magnetic tensors (according to *Varentsov, 2007a)* (right) for LMT ensemble of data at "Naryn" profile. The horizontal axes on the panels give the periods, the vertical ones – the sounding sites with geographical North (X) at the top.

The strike of geoelectric structures was examined with a help of induction vector period-spatial behavior and the analysis of main axes of extreme diagram ("ellipses") of phase tensors and anomalous horizontal magnetic tensors (according to *Varentsov, 2007a*) (Figs. 4, 5). For the periods more then 256s the sublatitude strike corresponding to the regional tectonics was revealed (with exception of S.405 near NL zone), that is also shown by sector histograms of extremal axes for phase tensors "ellipses" in the range 256-10000s (LIMS data). For shorter periods substantial influence of sedimentary valleys configuration is reflected in the deviation of these axes and induction vectors from regional strike (compare Fig.5a and 5b as well as corresponding histograms, estimated in 5b only for "Phoenix" data in the range of 10-1500s).

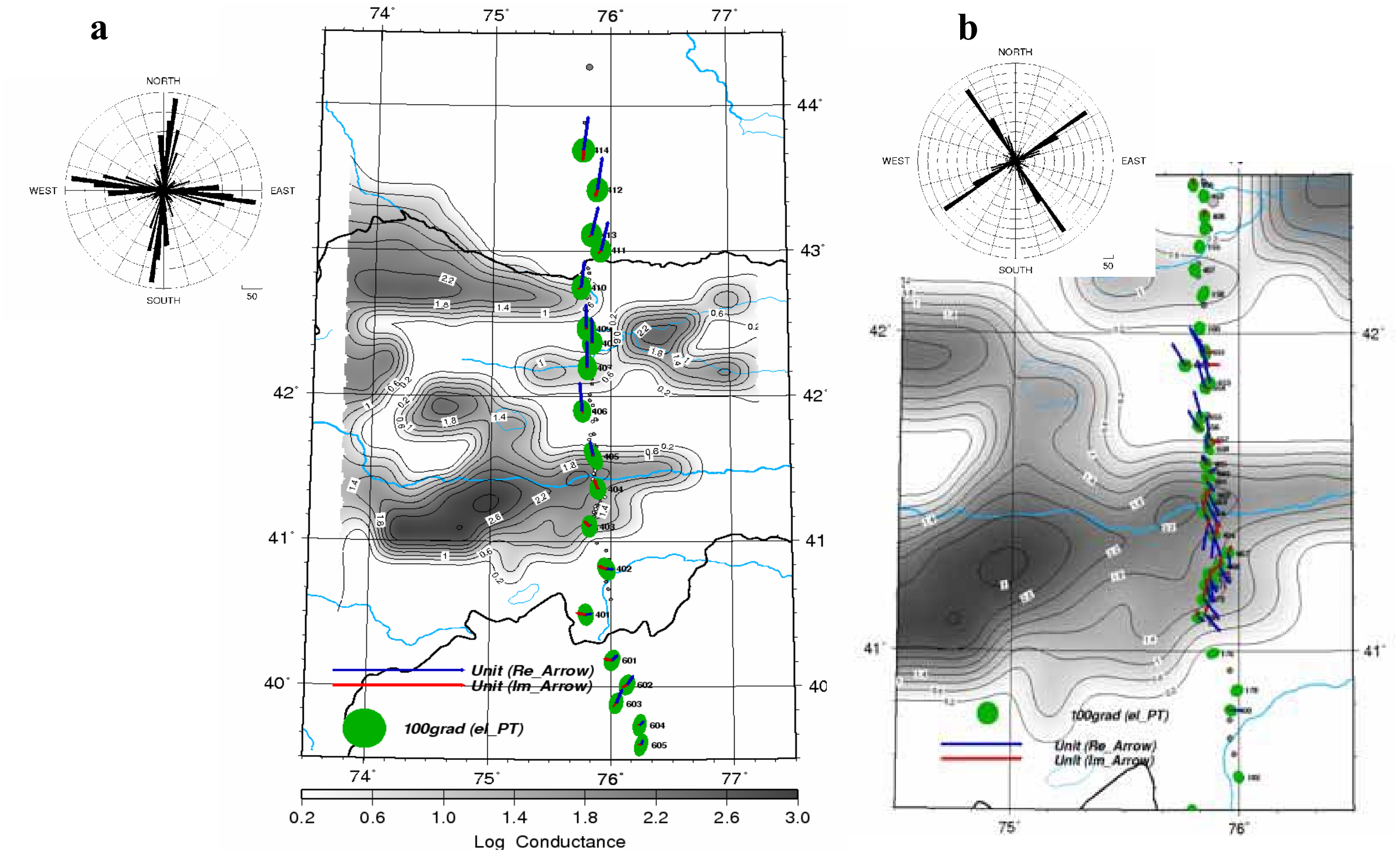

Fig. 5. Induction vectors, extremal direction "ellipses" of phase tensors with corresponding angle sector histograms on the map of total conductance of sedimentary cover (in log Sm, *Melnikova, 1991*): (a) - for LIMS data at T=2048s; (b) – for "Phoenix", CES-2 and LIMS data at Naryn Basin segment of the profile at T=256s. The scale of induction vectors is shown by unit arrows; the scale of main values of phase tensors – by circles with radii of 100° and scales of histograms – by length of segments in number of samples.

These figures also demonstrate the long period effects of inhomogeneous source in tippers data (Fig. 4) as well as marks of regional 3D distortions of Z and M at long period (Fig. 4,5a) for southern part of the profile, which are probably caused by borders of Tarim Basin in its NW corner or crustal anomaly there.

Despite the fact that the presence of the impedance and tipper distortions, caused by near surface and/or crustal inhomogeneties of limited strike, was revealed in **MT** and **LMT** ensembles, the regional quasi-2D behavior of the profile data sets was generally approved and the validity of 2D approach for the interpretation was confirmed for both data ensembles with exceptions of high (<10s) and long (>8000s) period tippers obviously strongly distorted by near surface or source heterogeneities.

Quasi 2D ensembles of TFs for profile inversion in broad-band (**MT**, 0.1-1500s) and long-period (**LMT**, 16-20000s) ranges were compiled from the impedances (Z), tippers (Wz) and horizontal magnetic tensors (M) estimates (the letter ones are present only in **LMT** range). Each component of the data was rotated according to the regional strike (0°) and supplied with a specific mask of weights, reflecting data accuracy and a quantitative measure of local 3D distortions calculated via invariants SKEWs and Strikes Fig. 6. demonstrates the data (tippers ReWzx and Mxx component of tensor M), corresponding error bars estimated in processing routine and resulted weights just described above. The latter will serve as penalties in the inversion, suppressing the influence of the 3D distorted data and thus concentrating the inversion procedure on the recovering of the regional 2D structures.

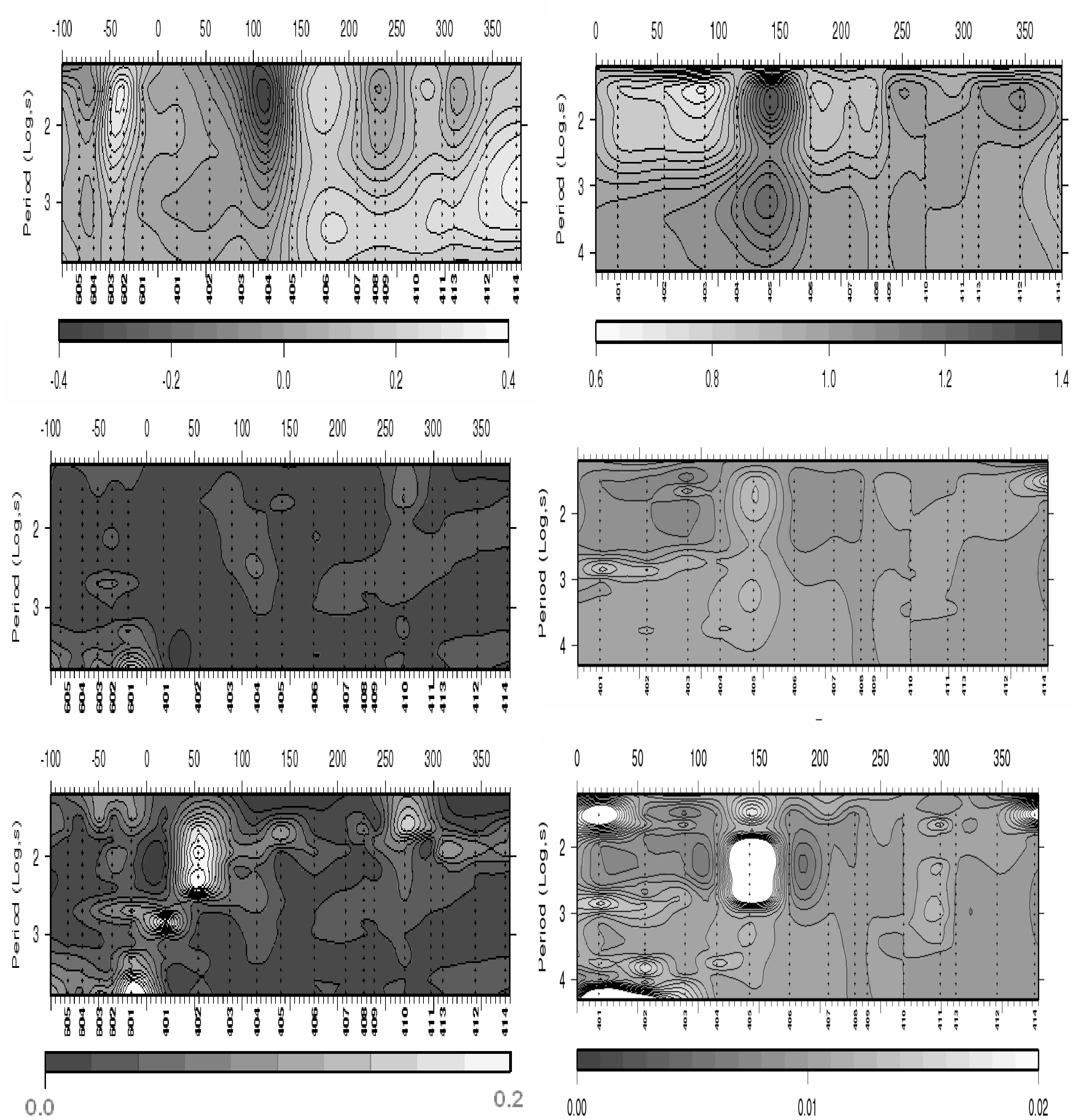

Fig. 6. The pseudosections of LMT ensemble components (top row), estimation error bars (middle row) and 2D inversion penalties, calculated on the results of invariant analysis (bottom). The panels of left column present data for ReWzx and right column - for Mod Mxx. The scale palettes for middle row panels are the same as for the correspondent bottom ones.

4. Methods of profile inversion and results of its minimal constrained round

The strategy of ‘‘Naryn” profile data inversion was aimed at the suppression of 3D distortions and focused on the target 2D geoelectric features. It implied reasonable choice of a staring model and the priority of phase and geomagnetic data, introduced by the logicality of partial inversions, application of a’priory weights and/or calculated penalties defining quasi-2D ensembles. The inversion round combined the successive partial inversions (starting from the geomagnetic data and step by step fixing the parameters for reliably determined conductivity blocks) and, in parallel, simultaneous weighed multi-component bi-modal inversions. The regularized 2D inversion technique (Varentsov, 2007b), which offers adaptive block and piece-wise continuous approximation of conductivity distributions and a variety of resources for the solution stabilization, was the basic tool for interpretation.

To use all the advantages of the extended **MT** data set with dense spacing, the starting model of the extensive grid was used with the windows for the detailed scanning in the areas of expected conductivity anomalies (Fig. 7). This starting model and vector of conductivity parameters were the same for both **MT** and **LMT** subsets of data, which were inverted separately. Normal sections were chosen on the 1D inversion results for MT curves at the sites of Kazakh and Tarim platforms. In this model the approximation of the real topography along profile and of sedimentary valleys was incorporated after the modeling studies, which have revealed their significant influence on the observed MT/MV responses. Fig.8 shows the responses of starting model (complete grid geometry and conductivity distribution

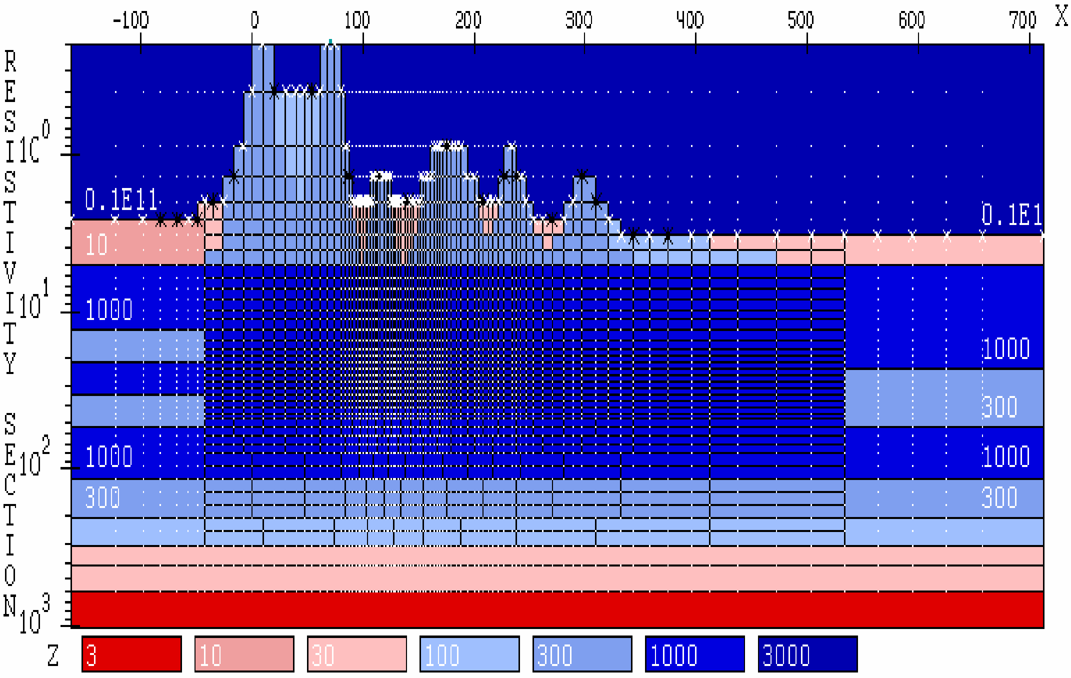

Fig. 7. The starting model of conductivity distribution (in Ohm.m) for profile inversion of **MT** and **LMT** data sets at “Naryn” transect: the grid dimension is 109x53 with ~ 2000 optimized parameters; X - distance in km with X=0 at the Kyrgyzstan-China border, Z - log depth in km with Z=0 at the relief top.

presented in Fig.7.) and of two its modifications with changed central (“anomalous”) parts (lowermost row panels): with flat surface or with topography approximation but without sedimentary valleys. The topography effects calculated for the components of **MT** data reach: 4-5° at periods of 1-2s for phases of longitudinal impedance and value of 0.1 for real part of tipper at first units up to first tens of seconds. The incorporating of “sedimentary valleys” with realistic integral conductance (about 100-150 Sm, see Fig.5) enhances the effects up to 15° or more for phases and up to 0.175 – for tippers as well as shifts them to the longer periods – up to first tens and first hundreds of second, correspondingly. The effects of topography are also significant in all the other components and spread to first second for phases of Zxy, to tens of second for Im Wzx, being quasi static for amplitudes of Zxy.

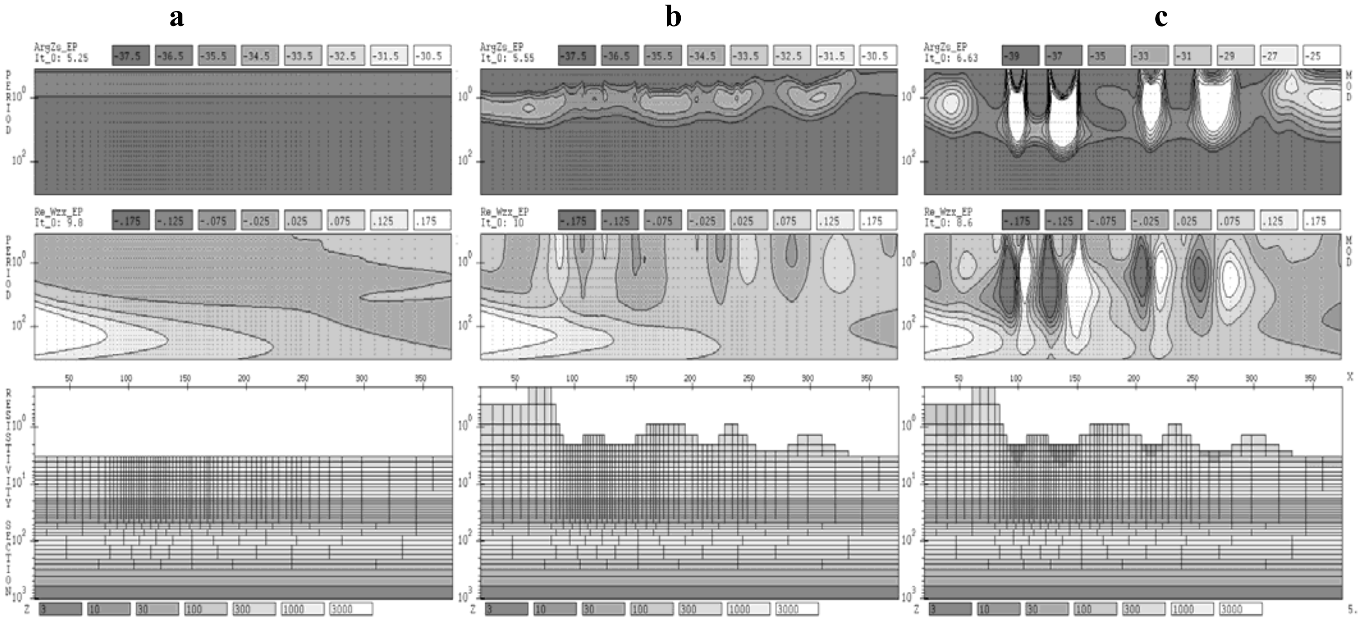

Fig. 8. 2D model studies of the topography and sedimentary cover effects on MT/MV sounding results along "Naryn" profile on the base of starting model, depicted in Fig. 7: (a) - results for "normal" structure (flat topography, different left and right normal sections); (b) – "normal" structure with topography; (c) – starting model (including topography and sedimentary valleys). The lowermost row of the panels presents the central ("anomalous") part of the models used, the following upper rows present the corresponding pseudosections of Re Wzx (middle panel) and Arg Zyx (top).

The resulting model of this "minimal constrained" round of inversion is constructed as a robust averaging of the successful partial inversion results (in a space of conductivity parameters of each model cell) for both (**MT** and **LMT**) ensembles. It provides a solution in a manner resembling the "boot-strap" approach (Efron, 1979). This model is shown in log scale of depths in Fig. 9 (with example of data fitting for tipper component of **MT** ensemble) and in natural depth scale - in Fig. 10a.

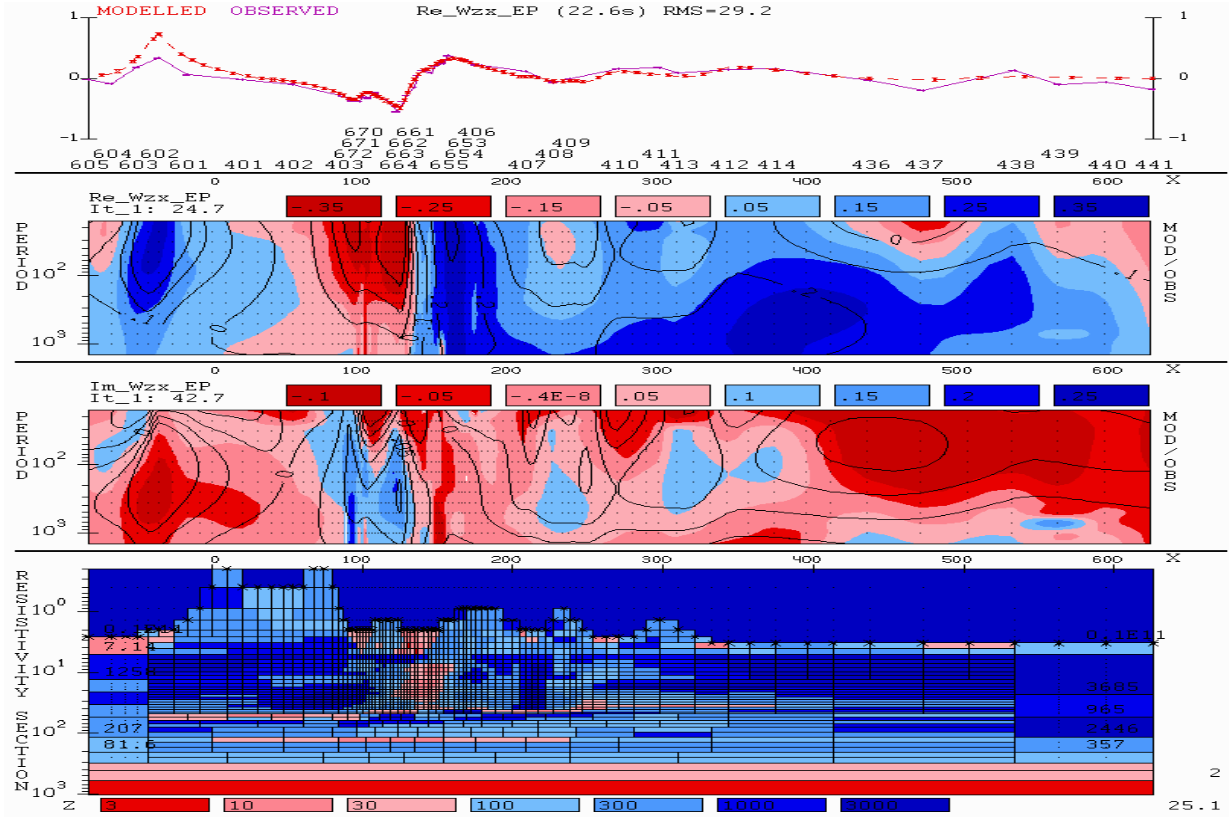

Fig. 9. The geoelectric cross-section of the Central Tian-Shan along "Naryn" profile (in log depth scale), obtained by the averaging of the results of a set of minimal constrained inversions of **MT/LMT** data (a) and data fitting on examples of Re Wzx and Im Wz components of **MT** ensemble.

The important features of resolved geoelectric structures are the low crustal conductive layer on the depth 40-50km uprising to 35km and decreasing integral conductivity in northern direction, sporadically revealed upper crustal one and the sub-vertical large-scale conductive zone in the upper and middle crust under “Nikolaev Line” tectonic unit. The application of the powerful well-focused inversion tools and representative character of data sets have permitted to obtain more resolution of the conductivity distribution along “Naryn” profile in comparison with the earlier studies of *Trapesnikov et al., 1997* as well as more stable solution compared with the results of *Bielinski et al., 2003*.

An interesting correlation of this still preliminary image of geoelectric section of Central Tian Shan with recent results of receiver function tomography, presented in Fig. 10b for the line 76ºE according to *Vinnik et al., 2006*, already may be productive for new ideas on complex geophysical model of the orogen. However the main mission of this model is to serve as a base for model sensitivity tests and checking up different hypotheses as well as to be a starting point for the next round of inversion, constrained by a’priory geological-geophysical knowledge. This final stage of interpretation of MT/MV data at “Naryn” profile is under way now as it is necessary for extracting from these data well-grounded geodynamic implications.

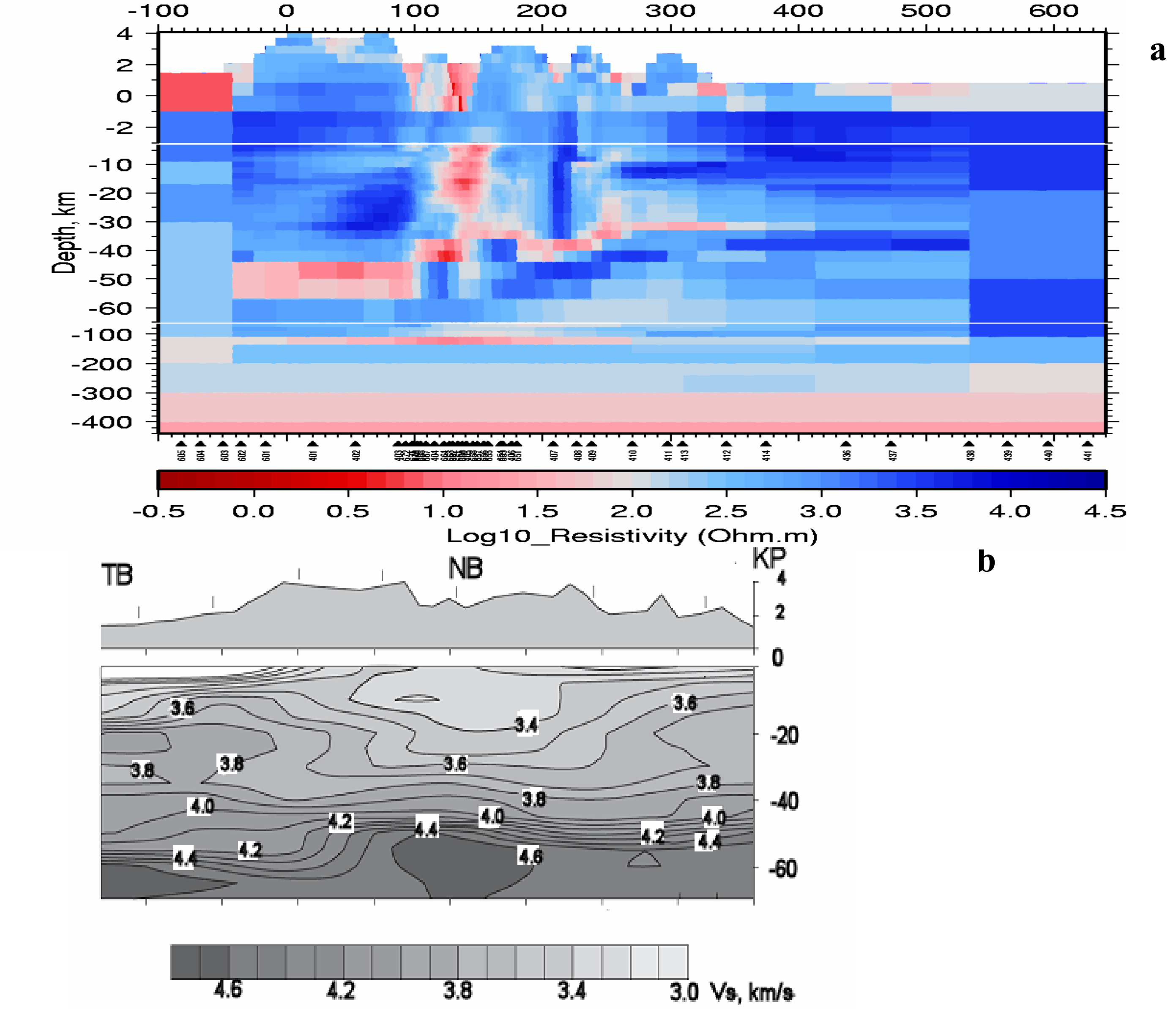

Fig. 10. The geoelectric cross-section of the Central Tian-Shan along “Naryn” profile, obtained by the averaging of the results of a set of minimal constrained inversions of **MT** and **LMT** data (a) and depth distribution of shear wave speed (Vs) along 76ºE given by receiver function tomography (b) (*Vinnik, et al., 2006).*

5. Conclusions

The paper presents recent advances in the methods of geoelectrical investigations in Tien Shan based on the original approaches in the processing, analysis and inversion of the MT/MV sounding data elaborated by the "Naryn" Working Group. We concentrate on the experience of profile studies being more economical and easily implemented in mountain surroundings then array soundings. It was demonstrated that this approach is valid for the data interpretation on the longest regional transect in Tien Shan – profile "Naryn", where abundant collection of MT/MV data has been gathered by Research Station of Russian Academy of Sciences.

The approaches, which help to overcome the problems of 2D interpretation in real situation of a mountain range (even elongated one) were in the focus. They include attention to geomagnetic data and robust schemes of invariant TF analysis, adaptive parameterization of conductivity distribution, operations with heterogeneous in space and frequency range ensembles of data, construction of quasi-2D ensembles, preventing the inversion procedure from dangerous influence of near-surface and off-profile distortions and, finally, multi-component weighed inversion, considering different sensitivity and "immunity" of data components.

We present the current model of geoelectrical cross-section of the Central Tien Shan with increased resolution, but saved stability of the main features. The model shows general correlation with recent seismic tomography data. Nevertheless it needs checking by model sensitivity tests and next round of inversion, constrained by concurring geodynamic hypotheses, as well as further approval by other geophysical-geological information.

The elaborated methods will be applied for interpretation of the data on the other MT sounding transects crossing Tien Shan before a combination of all the profile inversion results into regional prognostic volume conductivity model of the orogen, valuable for geodynamic studies of this unique area of intracontinental building.

MT studies in the mountains became "a mainstream" of modern geoelectrics and so we believe that our experience, based on the traditions of classical approaches to ill-posed problems solution, might be useful for our colleagues in other regions.

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