ELECTROMAGNETIC SOUNDINGS: THEORY AND APPLICATIONS

PROCEEDINGS OF THE INTERNATIONAL WORKSHOP IN MEMORY OF PROFESSORS MARK N. BERDICHEVSKY AND PETER WEIDELT

 MOSCOW
 2010
Two outstanding scientists in the field of EM physics Professors Mark N. Berdichevsky and Peter Weidelt passed away in 2009. The Russian and German scientists arranged an International Workshop on EM Sounding in memory of the deceased scientists in Moscow – Zvenigorod in June, 2010.

The Workshop’s program envisages reports on a wide range of studies in the field of electromagnetic soundings, with the priority of Mark Berdichevsky and Peter Weidelt pioneer lines of research in the basic theory and the approaches to EM data interpretation. These contributions introduce scientists and engineers to recent advances in theory and practical applications of electromagnetic methods in studying the Earth's interior.

Editorial board:

Yu.P. Sizov, T.A. Vassilyeva and A.G. Goidina
Prof. Mark Berdichevsky
02.04.1923 – 11.08.2009

Prof. Peter Weidelt
27.02.1938 – 01.07.2009
INTERNATIONAL WORKSHOP
ON ELECTROMAGNETIC SOUNDINGS
IN MEMORY OF PROFESSORS MARK N. BERDICHEVSKY
AND PETER WEIDELT
Moscow-Zvenigorod, June 10-17, 2010

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Free University of Berlin
Geoelectromagnetic Research Centre IPE RAS
Moscow State University, Faculty of Geology
Shirshov Institute of Oceanology RAS

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Heinrich Brasse
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Ivan Varentsov
## SCHEDULE

<table>
<thead>
<tr>
<th>Data</th>
<th>Sections* / Chaired by</th>
<th>Reports Presentation numbers</th>
<th>Presentation time</th>
<th>Posters numbers and presentation time</th>
</tr>
</thead>
<tbody>
<tr>
<td>June 10 Thursday</td>
<td>1 / Heinrich Brasse and Nick Palshin</td>
<td>1.1 – 1.12</td>
<td>10.00–14.00</td>
<td>–</td>
</tr>
<tr>
<td>June 11 Friday</td>
<td>2 / Bueent Tezkan and Ivan Varentsov</td>
<td>2.1 – 2.12</td>
<td>10.00–14.00</td>
<td>2.13 – 2.15 14.00-14.20</td>
</tr>
<tr>
<td></td>
<td>3 / John Booker and Michael Zhdanov</td>
<td>3.1 – 3.8</td>
<td>16.00–18.20</td>
<td>–</td>
</tr>
<tr>
<td>June 12 Saturday</td>
<td>4 / Tomasz Ernst and Anatoly Rybin</td>
<td>4.1 – 4.14</td>
<td>10.00–14.00</td>
<td>4.15 – 4.19 14.00-14.20</td>
</tr>
<tr>
<td></td>
<td>5 / Andreas Hoerdt and Pavel Pushkarev</td>
<td>5.1 – 5.8</td>
<td>16.00-18.10</td>
<td>5.9 – 5.15 18.10-18.40</td>
</tr>
</tbody>
</table>

*) Sections:

1. Memorial
2. Basic theory
3. Marine EM studies
4. Deep EM studies
5. Prospecting EM studies
### SCIENTIFIC PROGRAMME

**June, 10** (Thursday)
Moscow State University, Geological Faculty

Section 1. Memorial (Chaired by Heinrich Brasse and Nikolay Palshin)

<table>
<thead>
<tr>
<th>No/time</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.1/10.05</td>
<td>Bogoslovsky V.A., Dmitriev V.I., Golubtsova N.S., Khmelevskoy V.K., Pushkarev P.Yu., Yakovlev A.G.</td>
<td>Mark Berdichevsky and his role in scientific geophysical school of Geological Faculty of Moscow State University</td>
</tr>
<tr>
<td>1.2/10.20</td>
<td>Hoerdt Andreas</td>
<td>Peter Weidelt – the helpful authority</td>
</tr>
<tr>
<td>1.3/10.35</td>
<td>Kulik Sergei N.</td>
<td>Mark Berdichevsky – a kievan</td>
</tr>
<tr>
<td>1.4/10.50</td>
<td>Zhdanov Michael S.</td>
<td>Prof. M.N. Berdichevsky and the creation of modern magnetotellurics</td>
</tr>
<tr>
<td>1.5/11.10</td>
<td>Berdichevsky Mark N., Dmitriev Vladimir I. and Zhdanov Michael S.</td>
<td>Problems and prospects of magnetotellurics</td>
</tr>
<tr>
<td>1.6/11.30</td>
<td>Zhamaledinov Abdoullhay A.</td>
<td>Mark Berdichevsky and Leonid Vanyan – two outstanding researchers of the Earth’s crust and upper mantle electrical conductivity</td>
</tr>
<tr>
<td>1.7/11.45</td>
<td>Rokitsiansky Igor I., Tereshyn A.V.</td>
<td>Electromagnetic sounding of the Moon</td>
</tr>
<tr>
<td></td>
<td><strong>12.00</strong> Coffee break</td>
<td></td>
</tr>
<tr>
<td>1.8/12.20</td>
<td>Varentsov Ivan M.</td>
<td>Compact and adaptive parameterization in the inverse problems of deep geoelectrics: from EMSLAB to EMTESZ in touch with Mark Berdichevsky</td>
</tr>
<tr>
<td>1.9/12.40</td>
<td>Rybin Anatoly K. and NARYN WG.</td>
<td>Mark Berdichevsky and EM studies of the Tien Shan deep structure and dynamics: results from 80-90’s</td>
</tr>
<tr>
<td>1.10/13.00</td>
<td>Sokolova Elena Yu. and NARYN WG</td>
<td>Mark Berdichevsky and EM studies of the Tien Shan deep structure and dynamics: recent approaches to joint interpretation of MT/MV data in high mountains</td>
</tr>
<tr>
<td>1.11/13.20</td>
<td>Berdichevsky Mark N., Fainberg Eduard B., Singer Bension Sh.</td>
<td>Possibilities and limitations of the dynamic correction method in MT soundings</td>
</tr>
<tr>
<td>1.12/13.40</td>
<td>Spichak Viacheslav V., Bezruk Igor A. and Goidina Alexandra G.</td>
<td>Neuronet based technique for construction of 3D geoelectric models from profile and array archive MT data</td>
</tr>
<tr>
<td><strong>14.00</strong></td>
<td>Lunch</td>
<td></td>
</tr>
<tr>
<td><strong>15.00</strong></td>
<td>Excursion through Moscow State University</td>
<td></td>
</tr>
<tr>
<td><strong>16.00</strong></td>
<td>Transfer to Zvenigorod</td>
<td></td>
</tr>
<tr>
<td><strong>20.00</strong></td>
<td>Ice-Breaker in Zvenigorod</td>
<td></td>
</tr>
</tbody>
</table>
June, 11 (Friday)
Zvenigorod, Moscow Region, “Zvenigorodsky” RAS Pension

Section 2. Basic theory (Chaired by Buelent Tezkan and Ivan Varentsov)

<table>
<thead>
<tr>
<th>No/time</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.1/10.00</td>
<td>Junge Andreas</td>
<td>The magnetotelluric phase tensor: theory and practice</td>
</tr>
<tr>
<td>2.2/10.20</td>
<td>Booker John R.</td>
<td>The magnetotelluric phase tensor revisited</td>
</tr>
<tr>
<td>2.3/10.40</td>
<td>Weckmann Ute</td>
<td>Electrical anisotropy vs. 3D</td>
</tr>
<tr>
<td>2.4/11.20</td>
<td>Spitzer Klaus</td>
<td>Three-dimensional EM forward modeling using vector finite elements on unstructured grids</td>
</tr>
<tr>
<td>2.5/11.40</td>
<td>Persova Marina G., Soloveichik Y.G. and Trigubovich G.M.</td>
<td>3D interpretation of EM sounding data based on numerical 3D modeling: theory and practice</td>
</tr>
</tbody>
</table>

12.00 Coffee break

<table>
<thead>
<tr>
<th>No/time</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.6/12.15</td>
<td>Jozwiak Waldemar, Ernst Tomasz, Jankowski Jerzy and Nowozynski Krzysztof</td>
<td>MV studies in Poland and their tectonic implications</td>
</tr>
<tr>
<td>2.7/12.30</td>
<td>Kovacikova Svetlana, Varentsov Ivan M., EMTESZ and KIROVOGRAD WGs</td>
<td>Quasi-3D inversion of horizontal MV responses</td>
</tr>
<tr>
<td>2.8/12.45</td>
<td>Pushkarev Pavel Yu. and Ivanov Pavel V.</td>
<td>Possibilities of interpretation of MT data obtained on a single profile over 3D structures</td>
</tr>
<tr>
<td>2.9/13.00</td>
<td>Burakhovich Tatiana K. and Kulik Sergei N.</td>
<td>Longitudinally inhomogeneous structures: MV and MT parameters</td>
</tr>
<tr>
<td>2.10/13.15</td>
<td>Zhdanov Michael S., Green Marie, Gribenko Alexander V., Cuma Martin and Wilson Glenn</td>
<td>Large-scale 3D inversion of EarthScope MT data from the northwestern United States</td>
</tr>
<tr>
<td>2.11/13.30</td>
<td>Hachay Olga A.</td>
<td>The development of Peter Weidelt’s ideas in the theory of interpretation of EM data</td>
</tr>
<tr>
<td>2.12/13.45</td>
<td>Aleksandrov Pavel N. and Aleksandrov Aleksandr N.</td>
<td>Source-wise approximation in 3D problems of electrical prospecting</td>
</tr>
</tbody>
</table>

14.00 – 14.20 Posters presentation

<table>
<thead>
<tr>
<th>No/Time</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>2.13.</td>
<td>Cherevatova Maria, Vagin S. and Smirnov M.</td>
<td>Two-dimensional inversion of the impedance tensor determinant with damped least squares solution by singular value decomposition</td>
</tr>
<tr>
<td>2.15</td>
<td>Yegorov Igor</td>
<td>Numerical-analytical approach to solve 3D geoelectric inverse problems</td>
</tr>
</tbody>
</table>

14.20 Lunch
### Section 3. Marine EM studies (Chaired by John Booker and Michael Zhdanov)

<table>
<thead>
<tr>
<th>No/time</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.1/16.00</td>
<td>Jegen Marion</td>
<td>Development and application of marine electromagnetics at IFM-GEO MAR, Germany</td>
</tr>
<tr>
<td>3.2/16.20</td>
<td>Brasse Heinrich</td>
<td>Explaining exotic transfer functions at the South and Central American margins</td>
</tr>
<tr>
<td>3.3/16.40</td>
<td>Schwalenberg Katrin</td>
<td>Marine CSEM for submarine gas hydrate exploration</td>
</tr>
<tr>
<td>3.4/17.00</td>
<td>Hördt Andreas, Bhatt K.-M., Weidelt P.</td>
<td>Effects of ocean movement on marine EM data</td>
</tr>
<tr>
<td>3.7/17.50</td>
<td>Kruglyakov Mikhail S.</td>
<td>The impedance method in the remote sounding problems</td>
</tr>
<tr>
<td>3.8/18.05</td>
<td>Trofimov Igor L., Popova Irina V. and Korotaev Sergei M.</td>
<td>Effects of small scale forms of ocean floor on EM responses in application to MV studies in the Arctic Ocean</td>
</tr>
</tbody>
</table>

**19.00 Dinner**

**20.00** Free discussion, memories & photo


**June, 12 (Saturday)**

Zvenigorod, Moscow Region, “Zvenigorodsky” RAS Pension

### Section 4. Deep EM studies (Chaired by Tomasz Ernst and Anatoly Rybin)

<table>
<thead>
<tr>
<th>No/ time</th>
<th>Authors</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.1./10.00</td>
<td><strong>Korja Toivo</strong>, Palshin Nickolay A., Varentsov Ivan M. and Smirnov Maxim Yu.</td>
<td>Electrical conductivity of the upper mantle beneath Fennoscandia</td>
</tr>
<tr>
<td>4.2./10.20</td>
<td><strong>Pavlenkova Ninel I.</strong></td>
<td>EM data on the nature of seismic waveguides and destruction zones in the continental lithosphere</td>
</tr>
<tr>
<td>4.3./10.40</td>
<td><strong>Szarka Laszlo</strong>, Kiss J., Práčser Erno and Ádám Antal</td>
<td>About geophysical crustal anomalies due to hypothetical magnetic phase transition</td>
</tr>
<tr>
<td>4.4./11.00</td>
<td><strong>Ritter Oliver</strong>, Rybin Anatoly K., Munoz G., Batalev Vladislav, Sass P.</td>
<td>MT data from the Tien Shan and Pamir continental collision zones, Central Asia</td>
</tr>
<tr>
<td>4.5./11.20</td>
<td>Batalev Vladislav, Bataleva Elena, and <strong>Rybin Anatoly K.</strong></td>
<td>Xenolith constraints on conductivity of the Tarim – Tien Shan junction zone</td>
</tr>
<tr>
<td>4.6./11.30</td>
<td><strong>Bai Denghai</strong>, Varentsov Ivan and Sokolova Elena</td>
<td>Deep geoelectric model of the Eastern Tibet derived from joint inversion of long-period MT/MV data with implications to recent Yushu earthquake</td>
</tr>
<tr>
<td>4.7./11.45</td>
<td><strong>Smirnov Maxim</strong>, Korja Toivo and Egbert Gary</td>
<td>MT array data processing in the EMMA project</td>
</tr>
</tbody>
</table>

**12.00** Coffee break

| 4.8./12.15 | **Novák Attila**, Szarka László and Ádám Antal | EM imaging in geophysics with tensor invariants: from the near-surface to Transdanubian deep structures |
| 4.9./12.30 | **Belyavsky Viktor V.** | Application of impedance tensor invariants in the study of the Earth’s crust and upper mantle |
| 4.10./12.45 | **Surina Olesia** and Dyakonova Aza G. | Electro-gravitational model of the Middle Trans-Ural region |
| 4.11./13.00 | **Walia Devesh**, Gokarn S.G., Selvaraj C. and Sanabam S.S. | Geoelectric structure over the Arakan-Yoma Fold Belt, Surma Basin |
| 4.12./13.15 | **Moroz Yury** and Moroz Tamara | The research of magnetotelluric field in the Baikal region |
| 4.13./13.30 | **Maksymchuk V.**, Ladanivsky Boris and Kobzova Valentina | Studies of structure and recent geodynamics of the Antarctic peninsula by EM methods |
| 4.14./13.45 | **Hachay Olga A.** and Khachay Yury | The role of deep geoelectrics for defining the mechanisms and structure of convection in the Earth’s mantle |

**14.00 – 14.20** Posters presentation

<p>| 4.15 | <strong>Borzotta E.</strong> | Use of MV results to improve the distortion diagnostics in deep MT soundings |
| 4.16 | Horodsky Y., Klymkovych T., <strong>Maksymchuk V.</strong>, Kuznetsova V. | The results of Wiese vectors continuous observations in the Transcarpathian region |</p>
<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>4.17</td>
<td>Moroz Yury and Moroz Tamara</td>
<td>On dynamics of magnetic tipper and horizontal tensor from the Magadan and Petropavlovsk-Kamchatskii observatory data</td>
</tr>
<tr>
<td>4.18</td>
<td>Popova Irina, Nesteruk O. I., Spichak V.V., Goidina A.G., Matyukov V.E. and Rybin A.K.</td>
<td>Application of neural network time series data prediction for the forecast of seismic events</td>
</tr>
<tr>
<td>4.19</td>
<td>Zaitsev Georgy N. and Kushnir A.N.</td>
<td>MT and MV observations in the region of high seismic activity (Dnestrovskiy water basin, Ukraine)</td>
</tr>
</tbody>
</table>

**14.20** Lunch

**Section 5. Prospecting EM studies (Chaired by Andreas Hoerdt and Pavel Pushkarev)**

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.1/.</td>
<td><strong>Hallbauer-Zadorozhnaya Valeria,</strong> Binley A.M. and De Beers F.</td>
<td>Characterising pore size distributions in sandstones: a comparison of approaches</td>
</tr>
<tr>
<td>16.00</td>
<td><strong>Tezkan Buelent</strong></td>
<td>2D joint inversion of DC and RMT data: a case study on groundwater contamination</td>
</tr>
<tr>
<td>5.2/.</td>
<td><strong>Kulikov Viktor A., Varentsov Ivan M., Yakovlev Andrey G., and Yakovlev Denis V.</strong></td>
<td>2D inversion of MT/MV data in mining application: a case study on drilled deposit</td>
</tr>
<tr>
<td>16.20</td>
<td><strong>Nurmukhamedov A.G., Alekseev Dmitry A., Pankratov Oleg V., and Yakovlev Andrey G.</strong></td>
<td>3D geoelectrical model of Mutnovsky geothermal field</td>
</tr>
<tr>
<td>5.3/.</td>
<td><strong>Antaschuk K.M., Pertel M.I., Saraev A.K., Denisov R.V., Nikiforov A.E., and Romanova N.E.</strong></td>
<td>The experience of MT/AMT survey for geothermal exploration on the Kamchatka peninsula</td>
</tr>
<tr>
<td>16.40</td>
<td><strong>Stefaniuk Michal,</strong> Maj E., Sito L., Slys M., and Wojdyla M.</td>
<td>Recognition of hydrocarbon deposits in Polish Carpathians based on EM methods</td>
</tr>
<tr>
<td>5.4/.</td>
<td><strong>Martin Tina</strong> and Niederleithinger Ernst</td>
<td>Resistivity and electromagnetic methods in nondestructive testing</td>
</tr>
<tr>
<td>16.55</td>
<td><strong>Sizov Yury P.</strong></td>
<td>Reason of the temperature dependence of the HF EM field damping impulses of the georadar probe</td>
</tr>
</tbody>
</table>

**18.10-18.40** Posters presentation

<table>
<thead>
<tr>
<th>Time</th>
<th>Speaker(s)</th>
<th>Title</th>
</tr>
</thead>
<tbody>
<tr>
<td>5.9</td>
<td>Aleksanova Elena, Alekseev Dmitry A., Yakovlev Andrey G.</td>
<td>Magnetotelluric studies in the salt-dome tectonic settings in the Pre-Caspian depression</td>
</tr>
<tr>
<td>5.10</td>
<td><strong>Stefaniuk Michal,</strong> Wojdyla M.</td>
<td>Results of MT structural investigations in the Polish Eastern Carpathians</td>
</tr>
<tr>
<td>5.11</td>
<td><strong>Hallbauer-Zadorozhnaya Valeria,</strong> Chirenje E., Nyabeze P.</td>
<td>Application of DC resistivity and TDEM to water ingress investigation</td>
</tr>
<tr>
<td>5.12</td>
<td>Khmelevskoy Viktor K.</td>
<td>Magnetotellurics and radio wave interference soundings</td>
</tr>
<tr>
<td>5.13</td>
<td>Kuksenko V.S. and Makhmudov Kh.F.</td>
<td>Mechanoelectric effects in rocks</td>
</tr>
</tbody>
</table>
19.00 Dinner

20.00 Closing discussion, memories & photo

June, 13. Zvenigorod, Moscow Region, “Zvenigorodsky” RAS Pension

10.30 Seminar excursion (town and monastery)
14.00 Lunch
15.00 Transfer to Moscow

June, 14. Alexandrovka, Kaluga Region, Geophysical base of Moscow State University

07.30 Transfer from Moscow
13.00 Field geophysical excursion (instruments and technologies)
18.30 Transfer to Moscow

June, 15-17. Borok, Yaroslavl Region, Geomagnetic observatory, Institute of Physics of the Earth, Russian Academy of Sciences

June, 15
08.00 Transfer Moscow – Borok
10.00 Excursion in Sergiev Posad
12.30 Excursion and lunch in Uglich
16.00 Visit to Borok observatory
19.00 Dinner

June, 16
09.30 Transfer Borok – Pereslavl-Zalesskii
10.30 Excursion in Myshkin
13.30 Excursion and lunch in Rostov Velikii
18.00 Excursion in Pereslavl-Zalesskii
20.00 Dinner

June, 17
10.00 Visit to the Institute of Program Systems, Russian Academy of Sciences
12.30 Excursion and lunch in Pereslavl-Zalesskii
16.00 Transfer to Moscow
Session 1: Memorial

MARK BERDICHEVSKY AND HIS ROLE IN SCIENTIFIC GEOPHYSICAL SCHOOL OF GEOLOGICAL FACULTY OF MOSCOW STATE UNIVERSITY

Moscow State University

Studies of natural electromagnetic (EM) field and its applications to reveal geological structures are closely connected with history of Moscow State University (MSU), which was established in 1755. The founder of MSU, academician M.V. Lomonosov (1711–1765) experimented with atmospheric electricity and found out that electric field can originate in the ground “without thunder and lightning”. Now self–potential and magnetotelluric fields are used in geophysical exploration.

Professor A.I. Zaborovsky (1894-1976) started to teach geophysics at the Physics and Mathematics Faculty of MSU in 1928, and later created Geophysical Faculty of Moscow Geological Prospecting Institute in 1930. In 1944, due to his efforts, Chair of Geophysical methods was founded at the Geological Faculty of MSU. In the first Russian textbook on geophysics (1932) he wrote about possibilities to solve geological tasks using natural electric fields.

A great scientist, academician A.N. Tikhonov (1906-1986), who created Faculty of Computational Mathematics and Cybernetics of MSU, developed modern mathematical background of several geophysical methods (gravimetric, magnetometric, electromagnetic, geothermal). In 1950 he suggested to use the impedance (ratio of orthogonal electric and magnetic components of natural alternative field) to study deep layers of the Earth. Later he also proved the uniqueness of 1D plane wave inverse problem. On the basis of these results, magnetotelluric (MT) method was developed, making possible the study of conductivity distribution from shallow to upper mantle depth. A.N. Tikhonov and his followers elaborated theory of ill-posed problems of mathematical physics, which was a very important achievement of mathematical science. This theory is applied in inverse problems of geophysics, which are solved taking prior geological and geophysical information into account.

Outstanding followers of A.N. Tikhonov in EM studies of the Earth are MSU professors M.N. Berdichevsky and V.I. Dmitriev.

Mark N. Berdichevsky was born on April 2, 1923 in Kiev, in the family of adjunct professor of Kiev Polytechnic Institute. In 1940 he graduated school and entered Geological Faculty of Kiev University. In 1941, in the first days of the Great Patriotic War, he was called to the Soviet Army. After the war, in 1946, he moved to Moscow and entered Geological Faculty of Moscow University, which he graduated in 1949 with the specialization “geologist-geophysicist”.

From 1949 to 1969 Mark N. Berdichevsky worked in All-Union Research Institute of Geophysical Exploration (VNIIGeofizika) of the Geological Ministry of the USSR. In 1953 he defended candidate’s (equal to Ph.D.) thesis “Electric prospecting with the telluric current method”, which was a further development of his university graduation thesis. In 1967 he defended doctor’s thesis “Electrical prospecting with the magnetotelluric profiling method”. Both theses were published as his first two monographs.

In 1969 he became a professor of Chair of Geophysical Methods of Geological Faculty of MSU. Since that time, all his life, until decease in 2009, was connected with MSU, where he gave lectures on EM methods and field theory. He devoted much time to personal teaching, among his followers there are more than 40 candidates and several doctors of science.

Intensive research activity of Mark N. Berdichevsky was aimed at the development of EM exploration methods. He made a great contribution to theory and practice of deep geoelectrics and to its establishment as a powerful division of geophysics, based on highly developed methods and
providing unique information about the Earth’s interior. Magnetotellurics was his life-work, he knew its history and present state perfectly and foreseen ways of its future development.

In 1957-1960 Mark N. Berdichevsky was a scientific supervisor of MT exploration in Western Siberia. The result of this exploration was the discovery of the world’s largest Urengoy gas field. How was it happening? In June 1960 combined MT expedition of VNIIGeofizika and Tomsk Territorial Geological Department (TTGU) met in Salekhard to analyze the results and give recommendations for further geophysical work and drilling. One of the authors of this paper, V.A. Bogoslovsky, took part in this meeting, being at that time a chief of helicopter MT team. As a result, a geological structure (uplift) was revealed, it was named Urengoy swell, and later it was confirmed by seismic method. In 1963 TTGU approved a plan of drilling, based on results of several geophysical methods. MT was a new method, and most attention was given to seismic and gravimetric results. But one of the boreholes, after long discussion, was planned to be drilled on Urengoy swell. Just this borehole was the one that revealed Urengoy gas field, which for many years was one of the basic sources of gas in the country.

Mark N. Berdichevsky wrote more than 400 papers and 8 monographs. In 2008 Springer publishing house issued (in English) a book by M.N. Berdichevsky and V.I. Dmitriev “Models and methods of magnetotellurics”. A year later (in 2009) Nauchnyi Mir publishing house issued a Russian version of this monograph. Analyzing the main achievements of Russian and foreign magnetotellurics, the authors of the book construct integrated conception, which opens a way to efficient interpretation of magnetotelluric and magnetovariational data. To our deepest regret, this was the last book by Mark N. Berdichevsky.

The book shows that during 60 years of development magnetotellurics passed a long way. Naturally, the authors raise a question: “What’s next?” Or, as the epigraph to Russian version of the afterword says: “Which way shall we sail?” Here the authors provide 10 basic conclusions, on which, according to their opinion, researchers should rely.

“Which way shall we sail?” Ahead, along the way, directed by Mark Berdichevsky.

**PETER WEIDELT – THE HELPFUL AUTHORITY**

A. Hoerdt

Technical University, Braunschweig, Germany

Peter Weidelt passed away unexpectedly on July 1, 2009 during a private visit to Turkey. In 1999, he received the Conrad Schlumberger award of the EAGE for his fundamental contributions to electromagnetic induction phenomena. He leaves behind his wife and two children.

Peter Weidelt studied physics, mathematics and geophysics at the University of Göttingen, where he graduated in 1970 with a dissertation on inverse problems of EM induction. He stayed in Göttingen as a research scientist and lecturer until 1978. A research fellowship at the University of California, San Diego, in 1973, and a guest lectureship at the department of Earth Sciences at the University of Aarhus, Denmark, were important stations in his scientific career. In Denmark he wrote his “Aarhus lecture notes”, which became widely distributed and famous among researchers and teachers in this field. From 1978 to 1984 he worked on ore exploration with EM methods at the Federal Institute for Geosciences and Natural Resources in Hanover, interrupted by a visiting professorship at the University of California in
Berkeley in 1982. In 1984 he accepted a professorship for geophysics and meteorology at the TU Braunschweig.

Peter was recognized worldwide as a brilliant theoretician in electromagnetic induction methods. His research interests included forward modelling and inversion in all three dimensions, for both active and passive EM methods. He was excited to work on fundamental concepts such as exact solutions, mathematical proofs and extremal models. He always had the practical application of his results in mind; recently he contributed to the understanding of the so-called “airwave” in marine electromagnetics, laying the foundation to improve the method for oil exploration. Peter was also known for his warm personality and his helpfulness, witnessed by numerous acknowledgements in scientific papers. It was common for scientists from all over the world to ask him for help when they had difficult questions or theoretical problems. He would ask for some time and get back with the solution a few days later, usually a handwritten treatise or even a piece of code, always correct, elegant and perfect.

Even after his retirement in 2003, Peter was very active. He was working on a book, co-supervised PhD students, reviewed for scientific journals and the German Science Foundation and helped colleagues with his insight. He also continued to travel around the world to visit colleagues, maintaining particularly strong relationships with scientists from India and Russia. In late June he travelled to Turkey to visit a friend, relax, and work on his book. On the morning of July 1, he suffered from a heart attack while swimming in the sea.

We feel deep sorrow for a brilliant, warm-hearted and helpful colleague who is no longer with us. Peter leaves a huge gap.

MARK BERDICHEVSKY – A KIEVAN

S.N. Kulik

Subbotin Institutes of Geophysics, NAS of Ukraine, Kiev

Childhood, adult life and scientific life of Mark Naumovich Berdichevsky were very closely related to Ukraine and Kiev. But it was also geoelectric researchers of Ukraine who were tightly connected in their scientific work to the outstanding scientist. He was a leading scientist in the world who was working not only on developing theoretical foundation of geoelectric methods, magnetotelluric sounding and telluric currents, but who was also organizing and heading the majority of experimental projects of electro-investigations and deep geoelectric studies of the Earth crust and upper mantle. This field was growing rapidly in post-war Ukraine. Mark Naumovich contributions to all results of Ukrainian geoelectric were both crucial and significant.

Mark Naumovich is a kievan, he was born in Kiev, he loved Kiev, he followed closely all Ukrainian developments, and he was always trying to visit Kiev. His childhood years passed in Kiev, he lived in Pechersk, one of the oldest parts of Kiev. His father was a professor of Kiev Polytechnic Institute. Mark Naumovich studied in school that was on a slope of Kreshatik valley between Lyuteranska and Kruglouniversitetskaya streets right on the bring of the ravine from where one can see Bessarabka and Bessarabka market, the starting point of Kreshatik street. Berdichevsky’s lived in the house that was close to the theater of Ukrainian dramaturgy named after Ivan Franko and Russian theater named after Lessya Ukrainka. It’s not far from Bankovskaya street where administration of Ukrainian President is located nowadays. This part of Kiev is called Lipki.

He had many friends not only in his school; he was also part of the group of young poets whose members were, among others, Naum Korzhavin and Semen Gudzenko. His schoolmate, Maryasin Il’ya Lazarevich, wrote that they graduated from high school in 1940 and all those in their graduation class who were born in 1922 were called to serve the country and all those born in 1923 entered the University and institutes and had time to finish their first year of studies. But the war started and Mark Naumovich went to the frontline. He came back to Kiev only in 1945 after he was
wounded. Kiev was heavily destroyed, almost half of his classmates perished in the war and it was clear that Kiev became a special city for Mark Naumovich when he wrote

Ты не вейся, черный ворон, над мою головой.
Я вернулся в древний город, искалеченный войной.
Снял шинель, отбросил ранец и заплакал от тоски.
И пошел, как иностранец, возвращенью вопреки.


Mark Berdichevsky returned to the University and to the department of Geology for his sophomore year. Their class was just formed anew and students didn’t have time to get to know each other. One of his classmates, Evgeny Gerasimovich Korovnichenko, who later went on defending his thesis and teaching class of seismic investigation in the Kiev University, told me that Mark Naumovich was always a special figure, a war veteran, a senior friend. He loved to read poetry and was writing poems himself. Evgeny Gerasimovich remembered that Mark Naumovich was frequently seeing standing with somebody, often with some girl, by a window in corridors of second or third floor of the Red building (occupied by department of geology at the time) and they read poetry to each other. For his junior year Mark Naumovich moved to Moscow and entered Moscow University.

But his connection with Kiev was not broken, a new generation of Kiev geoelectric scientists grew up and Mark Naumovich was following closely all theoretical and applied research in Ukraine. His magnetotelluric method for deep studies and investigations in the Earth was applied here in sixties and seventies, the method of which he was one of the founder and to development of which Mark Naumovich devoted so much effort.

During the following 40-50 years here in Ukraine there were obtained results that allowed complex interpretation of geophysical data and lead to building models of tectonosphere of the Earth crust and upper mantle of Ukraine.

The main result of the studies of the Earth Crust and upper mantle of Ukraine was the development of a three dimensional model of distribution of geoelectric parameters.

Deep magnetotelluric studies of the territory of Ukraine started in 60-th in Carpathian region, Dneper – Donetsk depression and Crimea along main profiles of deep seismic sounding under
leadership of A.P. Bondarenko and A.I. Bilinsky. As a result of this work simultaneous studies of natural electromagnetic field of the Earth in the long period range were done for the first time. The studies of various regions of Ukraine by the method of magnetovariational profiling were begun at the same time under the leadership of I.I. Rokityansky in the Institute of Geophysics. Later, the territory of Ukraine was investigated by methods of DMTS (Institute of Geophysics NAS of Ukraine) and of MTS (ministry of geology of Ukraine).

Further on, when modern measuring instruments and methods of analysis and interpretation of obtained values of transfer functions were begun to be used the 3D models of western Ukraine, its central and eastern parts were built. The most studied was Precambrian Ukrainian crystal shield. Anomalies of high electric conductivity are located here; in some cases they characterize suture zones. Those structures are the most important tectonic modules.

The majority of zones of higher electric conductivity of different nature that were discovered on the territory of Ukraine within the Earth crust spatially coincide with the regions of metallogenic formations. Overall, the data on ore mineralization on the territory of Ukraine allowed defining several basic types of provinces of development of natural resource deposits:

1. Precambrian metallogenic regions (province of Ukrainian shield) – iron, titanium, chromium, aluminum, nickel, cobalt, tin, niobium, zirconium, vermiculite, graphite, disthene, sillimanite, piezo quartz, talc, fluorite.

   Korosten and Chernvotsy-Korosten anomalies of electric conductivity in the western part of USh spatially conform with Sushano-Perzhany, Ovruch, Korosten and Zhitomir zones.

   Deposits of apatite and pyrophyllite, showings of rock crystal, zirconium, titanium, gold, silver, tin are found in the boundaries of Ovruch zone.

   In the Korosten metallogenic region the main areas of known color-metals deposits, graphite deposits and deposits of rare metals (such as zirconium, molybdenum) are present mainly in the western part.

   In the gneisses of Zhitomir zone 14% graphite deposits are often found.

   In the eastern part of USh Gajvoron-Dobrovelichkov, Kirovogradian and Presovanian anomalies of electric conductivity coincide spatially with Krivorozhian-Kremenchug, Orekhov-Pavlogradian, Priazovian facial zones.

   Pobuzh metallogenic region is known for numerous showings of graphite and sillimanite in gneisses, iron ore, corundum and others. Significant graphite deposits are found in the village of Zaval’e.

   Metallogenic properties of Krivorozhian-Kremenchug facial zone are characterized by formation of rich deposits of iron, ore mineralization and points of mineralization of copper which are the leading natural resources. To the lesser extent other deposits are also present such as gold, silver, zinc, lead, nickel, cobalt, aluminum, arsenic, molybdenum, zirconium, germanium, rare earth metals, asbestos, apatite, marble, graphite.

   Aside of poor in iron ore there are also some showings on the territory of Orekhov-Pavlogradian zone of higher concentration of copper, molybdenum, cobalt, antimony, silver, bismuth, nickel, titanium, zirconium, hafnium, yttrium, tantalum, niobium.

   In general Preazovian block is a rare-metal and iron-ore containing region. Leading metals here are iron, zirconium, titanium, molybdenum, aluminum. From non-ore minerals graphite and vermiculite are present. Eastern parts of Preazovian differ from western part by larger set of found natural mineral resources and deposits of non-ore minerals – graphite and vermiculite.

2. Regions of Riphean-Paleozoic and Meso-Cenozoic metallogeny which are represented by platform formations (Don-Dnepor metallogenic belt, Volyn-Podolian metallogenic provinces, Pre-black-sea metallogenic region) have deposits of iron, titanium, zirconium, aluminum, copper, nickel, gold, germanium, diamonds as well as deposits of sulphur, polymetal and large accumulation of manganese.

   Showings of copper, titanium-magnetite and, possibly, diamonds are associated with rocks of trapp formation in Volyn (Volynian anomaly of electric conductivity).
Specifics of Podolian metallogenic zone (part of the Chernovtsy-Korotenian anomaly of high electric conductivity) is simultaneous complex presence within its boundaries of fluorite, lead-sulphide, zinc and copper as well as showings and areal of dispersion of cinnabar, gold, realgar and other natural mineral resources.

Endogen mineralization found in the Southern-Donbass metallogenic zone (Donbass anomaly of high electric conductivity) is characterized by diversity of composition and defereent conditions of forming. Endogen showings of magmatic type are related to iron-titanium ore mineralization, contact-metasomatic (skarn) type is represented by garnet, malacolite, epidote, vesuvianite, magnetite, amphibole. Vein hydrothermal formations are represented by pyrite, galenite, sphalerite, chalcopyrite.

Ore of Nagolnyy Ridge are complex in its composition. The most common minerals are pyrite, arsenopyrite, sphalerite, galenite, chalcopyrite, boulangerite, gold; main vein minerals are quartz and ankerit.

3. Regions of Late Paleozoic (Hercynian) and Meso-Cenozoic (alpine) metallogeny (Carpathian and Crimean-Caucasus metallogenic provinces, Donetsk metallogenic region) are characterized by abundance of mineralization of mercury, lead, zinc, arsenic, antimony, tellurium, gold, silver, alunite, barite.

Vygorlat-Guta zone is characterized by endothermic mineralization of mercury, bismuth and tellurium hosted in the rocks of Pliocene andesitic formation and coincides spatially with Carpathian conductivity anomaly.

Natural mineral resources of Crimea are represented by depositions of the exogenic group – iron, aluminum, magnesium and sulphur as well as the endogenic group – mercury, lead, zinc and copper.

Analysis shows that all conductivity anomalies of consolidated Earth crust fully or partially spatially coincide with various metallogenic zones or provinces.

PROFESSOR M.N. BERDICHEVSKY AND THE CREATION OF MODERN MAGNETOTELLURICS

M.S. Zhdanov

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Professor Mark Naumovich Berdichevsky is the father of modern magnetotellurics. He developed the foundations of magnetotelluric (MT) method, including the telluric current and magnetotelluric profiling methods, the tensor representations of MT data, the distortion theory, the deep geomagnetic sounding method, and many others. M.N. Berdichevsky pioneered the applications of numerical modeling and the inversion theory in magnetotellurics. Many of his ideas were well ahead of their time. In fact, Professor Berdichevsky predicted almost all theoretical and technical aspects of modern MT method decades before they become widely used in practice. Professor Berdichevsky founded the Russian school of magnetotellurics.

In the beginning

A group of methods for determining the electrical structure of the earth using naturally existing EM fields rather than fields generated by a controlled source came into use about 1960, based on theoretical concepts originally proposed by Tikhonov (1950) in the USSR, Louis Cagniard (1953) in France, and Tsuneji Rikitake (1950) in Japan.

The knowledge of the existence of telluric currents is far from recent. As early as in 1868, Sir George Biddell Airy, English mathematician and astronomer, made the first coordinated study of earth currents and their relationship to magnetic variations. In September 1862, one of the first field experiments to measure telluric currents was carried out by Lamont (1862) in the Alps. Terada (1917) appears to have been the first to measure the dependence of the magnetic field relationships on the conductivity of the ground.
The Schlumberger brothers observed telluric currents during their experiments with DC measurements on the ground as well. They were also the first to suggest that telluric currents could be used for oil and gas exploration. However, practical measurements showed significant variations and instability in telluric current behavior, which made it difficult to develop any reasonable technique for the interpretation of telluric current data. The main sources of this instability were associated with complex processes in the ionosphere and magnetosphere which were unknown at that time.

The core of the discovery made independently by Tikhonov in the USSR, and by Cagniard in France, was that the effect of processes in the ionosphere and magnetosphere could be cancelled if the electric field components of the telluric field were normalized by the magnetic field components. This was a revolutionary idea at the time, as it allowed geophysicists to transform the observed field data in the predictions of the resistivity of rock formations. This opened the way for the development of a new exploration technique called the magnetotelluric (MT) method.

Professor Berdichevsky realized the significance and power of the MT method very early in his scientific career. He developed the telluric current and magnetotelluric profiling methods, based on studying the horizontal variations of the MT field (Berdichevsky, 1960, 1968). Over the years, he became the leader of the development of the MT method not only in the former Soviet Union, but internationally. His work and the collective efforts of many of his colleagues and associates transformed the method into a practical geophysical tool.

Introduction of the distortion theory

The MT method has a long and rich history full of great discoveries and setbacks. In the 60s and early 70s, the MT method became widely used for oil and gas exploration. Originally, the interpretation of MT data was based on simple layered earth models, which made it easy to provide MT sounding curves in the form of corresponding plots of the apparent resistivities vs. the period of the observed data or square root of the period (which is proportional to the depth of investigation). The MT sounding curves were then transformed into 1D geoelectrical sections. The entire geoelectrical model was recovered by stitching together multiple 1D sections.

Electromagnetic induction workshop in Santa Fe, New Mexico, June 2002, from left to right: N.A. Berdichevskaya, M.N. Berdichevsky, O.N. Zhdanova and M.S. Zhdanov.
In real earth, however, there is always some departure from ideal one-dimensionality, or horizontal inhomogeneity. As a consequence, there is always some departure of an observed MT sounding curve from an ideal 1D curve computed for a specific layered-earth model. Such departures are called distortions to an MT sounding curve, and the observed curves in such cases are called distorted curves. Formal interpretation of these MT sounding curves in terms of 1D structure, ignoring such distortions, quite often resulted, unfortunately, in creating false geoelectrical structures of the depth sections, which sometimes were misinterpreted as potential hydrocarbon reservoirs.

Professor Berdichevsky was the first to realize the importance of accounting for the effects of horizontal geoelectrical inhomogeneities on MT data. He introduced the tensor measurements in the MT method, which soon became widely used all over the world. The transition to tensor-based data processing resulted in a major increase in the amount of information extracted from MT observations. Another major contribution of Professor Berdichevsky in geoelectrics was developing a distortion theory of MT sounding curves. His work on the distortion theory resulted in the creation of the method of deep geomagnetic sounding of the earth.

Birth of the deep geomagnetic sounding method

I met Mark Naumovich Berdichevsky for the first time in 1967. I was an undergraduate student in the Gubkin Oil and Gas University in Moscow and was working on some research projects with Dr. G. G. Obukhov, who was a research scientist in VNIIGeophysika, the leading Russian research institute for exploration geophysics at that time. I remember one morning in fall 1967, when Dr. Obukhov brought me in the lab headed by Berdichevsky. Mark Naumovich talked to me briefly about my interest in geophysics and then suggested to solve a problem related to the plane EM wave propagation in a simple model of a conductive half-space, separated by a vertical plane into two parts with different conductivities. I told him that I was not familiar with the technique of solving this kind of problems. It was completely new area for me at that time. However, Berdichevsky asked me to try anyway and left the room. I spent several hours desperately trying to solve this problem and finally come up with a solution in the form of Fourier series. When Mark Naumovich came back, I showed him the result. Apparently, he liked it, and he offered me to become his graduate student and to work on similar problems. However, at that time I had already accepted an offer from Professor K.V. Gladky to work on potential field theory after completion of my undergraduate study. Mark Naumovich suggested that I could still work with him informally, and I happily agreed. This became the beginning of our forty plus years of collaboration in EM geophysics, which resulted in multiple papers and books published together.

It was an unusual situation. Professor Berdichevsky was not my formal professor, and I was neither his formal student, nor even his research associate. However, he became my real Teacher who by his personal example, his enormous enthusiasm and love of science led me on an exciting journey in a new world of EM geophysics.

We worked with Professor Berdichevsky one day every week. It was one full day when everything else was forgotten, and the focus was on new exciting ideas about the properties of the EM field, its generation, its propagation within the earth, and its response to the internal structure of the earth, etc., etc.

For me it was a real school of the art of science. Every problem, every model, every idea was discussed multiple times, under different assumptions, under different angles, until they become crystal clear and transparent. Mark Naumovich rewrote every paper several times, trying to find the clearest definitions and explanations. He was a true scientist and he was always open to new ideas and unconventional solutions. At the same time, he had a unique ability to identify the fundamental principles that would lead to the most effective solution of the problem.

It so happened, that my wife, Olga Zhdanova, worked in the research group headed by Professor Berdichevsky at Moscow State University for many years. She also defended her Ph. D. thesis under his supervision. All this created a situation when we often met together with
Berdichevsky and his wife, Natalia Alexandrovna, who stood by his side for more than forty years.
We enjoyed close friendly relationships between our families.

As I wrote above, in the late 60s Professor Berdichevsky developed the basic principles of the
 distortion theory, which provided clear guidelines for a correction of MT sounding curves distorted
 by horizontal geoelectrical inhomogeneities. However, very quickly he realized that these
 inhomogeneities should be considered not as the sources of incorrect interpretation of MT data, but
 as the objects of interpretation instead. I was lucky to participate in the development of this theory
 (see Berdichevsky and Zhdanov, 1984).

The term “Deep Geomagnetic Sounding (DGS)” was coined by German geophysicists Ulrich
 Schmucker, who suggested using this term to describe the geophysical method based on studying
 the anomalies of the natural EM field of the Earth. We agreed with this idea, and used the term for

Professor Berdichevsky envisioned analysis of the natural EM field and its anomalies on the
 local, regional and global scales. This required different mathematical methods of field analysis,
 based on spherical or plane geoelectrical models. Another problem was related to the theory of the
 transfer functions, which constituted the cornerstone of the MT method. Professor Berdichevsky
 made fundamental contribution in the development of this theory as well.

Peter Weidelt

I remember that during one of our regular “working sessions” in the late 70s Mark
 Naumovich asked me to look at the thesis of unknown to me at that time German scientist, P.
 Weidelt. The thesis was written in German, and I could understand only mathematics in that text. I
 was impressed by the elegant style and the depth of the paper. In that thesis, P. Weidelt presented
 his famous theorem of uniqueness for a two-dimensional model with an electrical conductivity
 described by an analytic function (Weidelt, 1978). It was a beautiful result. I recall that M. N.
 Berdichevsky received this paper from U. Schmuker, who was Peter’s supervisor in Göttingen
 University. Professor Berdichevsky wrote a letter to Dr. Weidelt with some questions about his
 work, and got an enthusiastic reply. This was the beginning of the lifelong friendship between M. N.
 Berdichevsky and Peter Weidelt. They met many times at different meetings and workshops, visited
 each other in Russia and Germany. It was a wonderful example of a friendship based on common
 interest to the science and deep mutual understanding.

We became friends with Peter Weidelt as well. I visited him in the early 80s, when he worked
 in Hannover, and later in Braunschweig, when he received a prestigious Professorship at the
 Braunschweig University. He visited us in Moscow several times. We had many inspiring talks
 concerning the problems of magnetotellurics and science in general. P. Weidelt was an outstanding
 scientist with a unique ability to combine mathematics and physics in one clear picture of the
 physical phenomenon. He had a very warm personality. I remember him playing with our little
 daughter when he was in our home in Moscow. I have received the last e-mail from Peter just a few
days before his tragic death. ..

Numerical modeling as the basis of multidimensional magnetotellurics

In the early 60s, there were very limited resources available for modeling the MT field in
 inhomogeneous media. However, Professor Berdichevsky was the first who realized the importance
 and power of numerical modeling in magnetotellurics. His lifelong collaboration with Professor V. I.
 Dmitriev began with the development of the fundamental set of 2D geoelectrical models, which still
 serves as an etalon for modern methods of modeling and inversion. Mark Naumovich possessed a
 unique physical intuition, which allowed him to understand and to explain EM field behavior in
 complex geoelectrical structures. He was a real master of the MT field, who could use his deep
 insight to the properties of the field for an effective interpretation of practical data. His work
 stimulated greatly the further development of 2D and 3D numerical modeling, which became a
 main focus of my research in the Consortium for Electromagnetic Modeling and Inversion at the
 University of Utah.
Development of marine magnetotellurics

In the late 70s and early 80s, M.N. Berdichevsky became interested in marine magnetotellurics. The first experiments with marine EM field measurements were conducted by Russian geophysicists in the Arctic Ocean (e.g., Trophimov and Fonarev, 1972). In the late 1970s Scripps Institution of Oceanography conducted several deep-water marine EM experiments in the Pacific Ocean (Filloux, 1979). However, the interpretation of marine EM data was not well developed. There were significant differences in the physical conditions for electromagnetic field generation and behavior on the sea bottom and on land. Professor Berdichevsky initiated a comprehensive study of this phenomenon. The results of this study were presented in the book published in 1989 (Berdichevsky et al., 1989). This monograph provided a foundation of the modern day marine EM methods, which have become widely used for off-shore hydrocarbon exploration in recent years.

Magnetotellurics in the context of the theory of ill-posed problems

Professor Berdichevsky pioneered the application of regularization theory in the solution of electromagnetic inverse problems. One of his books, written together with V. I. Dmitriev, is entitled “Magnetotellurics in the context of the theory of ill-posed problems” (2002). As early as in the 70s and 80s he demonstrated that the theory of regularization of ill-posed problems should be considered as a cornerstone of magnetotelluric interpretation. The basic principles of MT inversion described in his latest books (Berdichevsky and Dmitriev, 2002, 2009) summarized decades of development in the field of interpretation of MT data, pioneered by Professor Berdichevsky. My ongoing collaboration with him in this field stimulated my own research on the inverse theory and regularization problems, which resulted in the development of effective methods of 3D MT inversion. Some of these methods are outlined in my recent books (Zhdanov, 2002, 2009).

Conclusion

Professor Berdichevsky is the father of modern magnetotellurics. He developed the foundations of this method and transformed it from a simple technique based on the 1D model into a comprehensive modern geophysical method of studying the inhomogeneous structures of the Earth. In some sense many aspects of this development happened to be ahead of their time. In fact, Professor Berdichevsky predicted almost all of the theoretical and technical aspects of modern MT method decades before they become widely used.

Professor Berdichevsky founded the Russian school of magnetotellurics. He was not only a teacher but also a mentor of several generations of EM geophysicists. He was a generous man, who cared very much about his students, colleagues and friends. I was privileged to have him as my mentor and friend. It was extremely gratifying for me to work together with him for many years and to see the enthusiasm and energy he has given to developing the magnetotelluric method.

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PROBLEMS AND PROSPECTS OF MAGNETOTELLURICS

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Issues raised in the report have been discussed in details by the authors of the report in recent years. A detailed article will be released in the journal “Fizika Zemli” this summer. Below we formulate the main issues discussed in the report.

1. Presently one cannot entrust the computer (even the supercomputer) with complete self-dependent automatic press-button inversion. Inversion should be conducted in the interactive mode realizing the contact between the geophysicist (a leader) and the computer (a performer). Leader suggests to perform an inversion strategy that can define the interpretation success.

2. The statement of the inverse problem calls for a normal background, which can be given as a mathematical abstraction consistent with magnetotelluric response functions obtained at the boundary of the observation area and with a priori information.

3. The inverse problem is unstable. Its solution is meaningful provided it is sought within a restricted set of plausible solutions forming the interpretation model. The choice of the interpretation model should be confidently controlled by a priori information and qualitative indications derived from the field observations.

4. The magnetotelluric field is of diffusive nature. Generally it can offer only a smoothed image of the geoelectric medium. Buried sharp conductivity contrasts existing in the Earth are introduced into the interpretation model from a priori information or hypothetically. The most complete interpretation can be performed by a compromise between smoothing (Occam) and contrasting (blocky) inversions.

5. In solving an unstable inverse problem, we come up against the paradox of instability. The more restricted the interpretation model, the more stable the inverse problem and the poorer the
detailedness of its solution. On the other hand, the more stable the inverse problem, the higher its resolution. The resolution of the inverse problem and the detailedness of its solution are antagonistic. The inverse problem should be solved with optimum relation between stability, resolution and detailedness. An interpretation model with a small number of layers and structures is preferable. The additional layers and structures can be introduced providing the magnetotelluric and magnetovariational indications demand their presence. Taking advantage of blocky partition, a number of parameters defining the interpretation model should be reduced to a minimum providing a stable solution.

6. The magnetotelluric inverse problem is multicriterion. We can use tippers, magnetic tensors, impedance and phase tensors. These response functions have different sensitivity to different parameters of the interpretation model and different immunity to near-surface distortions. Being inverted simultaneously, they may come into conflict with each other impairing the inversion accuracy. The best approach to the solution of a multicriterion inverse problem is a succession of partial inversions focused upon different elements of the interpretation model. Partial inversions trade their information: the result of a previous inversion is transferred to a next inversion as a starting model. When studying media with sharp horizontal contrasts and strong geoelectric noise, it is profitable to begin with tippers and magnetic tensors which are free from static distortions and nicely resolve the geoelectric medium in the horizontal and vertical directions. It is just tipper and magnetic tensor that under complicated conditions can give a sound reliable basis for further estimates performed by phases and apparent resistivities.

7. The magnetotelluric effects are of integral nature and therefore the large compact bodies can manifest themselves as mosaic alternation of cells of higher and lower conductivity. Such a solution should be considered as one of the equivalent solutions. In agreement with geological expediency, it can be smoothed under condition that the misfits of the response functions do not increase.

8. The inversion adequacy should be estimated by comparing the modeled and measured local response functions. The model elements whose elimination does not increase the misfits of the response functions are considered as unnecessary insignificant artifacts and removed.

9. Magnetotelluric large-scale regional studies of sediments and deep studies of the Earth's crust and upper mantle are usually carried out on the long single profiles which dooms geophysicists to the quasi-one-dimensional or two-dimensional interpretation of the observation data. Admissibility of such simplifications should be verified by a priori and a posteriori analysis of lateral effects. An important part of this analysis is an appraisal and correction of interpretation errors arising due to finite strike of elongated structures considered as two-dimensional ones.

10. The main puzzle of magnetotellurics is a violation of the dispersion relations between apparent resistivities and impedance phases. We have several exotic models that expose these anomalies and occasionally we observe the violations of the dispersion relations in actual practice. But we little understand their physical mechanisms and we cannot tell with distinctness what properties of the geoelectric medium are responsible for violation of the dispersion relations. The study in this field is a challenge for all of us.

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ELECTROMAGNETIC SOUNDING OF THE MOON

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The Moon including its deep interior was intensively studied in the course of USSR – USA cosmic competition in the time interval 1959–1976. Data of lunar seismology and gravity as well as lunar geography and geology yield clear understanding that lunar crust and mantle are substantially not uniform laterally. Nevertheless having quite few seismometers and magnetometers at the Moon, only spherically symmetric 1D preliminary models of seismic velocities and electrical conductivity were obtained. Reliability of the models is not well proved.
Let us consider electrical conductivity study of the Moon by means of magnetic variation sounding (MVS) with synchronous measurements of 3 components magnetic field both on lunar surface and on lunar orbiter. Relevant for our problem magnetic field on the Moon surface consists of $B_e$ – external driving field, $B_{ip}$ – internal poloidal field caused by eddy currents induced in conducting layers of the Moon interior by external field changes $B_e$ (magnetic or TE mode) and $B_{it}$ – internal toroidal field of unipolar electric currents driven through the Moon by motional electric field $-V\times B_e$ (electric or TM mode), where $V$ is solar wind velocity. For spherically symmetric conductivity model, $B_{ip}$ is sensitive to the high conducting layers in the deep interior while $B_{it}$ is sensitive to high resistive layers which commonly expected at a shallow depth. So, the measurement of two modes would yield longitudinal conductance of the good conducting layers and transverse resistance of the most resistive layers. But the modes separation needs observations in three sites on the lunar surface. Having only one site, we should select more significant mode and neglect other. On the Earth, TM mode is small as result of lower atmosphere high resistivity ($10^{13} – 10^{14}$ Ohm·m). Moon has no atmosphere but upper layer 2-12 m thick, regolith, has resistivity $10^7 – 10^9$ Ohm·m according few samples study in the Earth laboratories. Having only this data, investigators supposed that TM mode can be neglected. Calculations show that if upper layer 100 km thick has resistivity $10^7$ Ohm·m two modes have comparable value. So neglecting of TM mode should be proved experimentally.

As was shown in works M.N. Berdichevsky and L.L. Vanyan, poloidal field from deep interior arrives to surface with geometrical attenuation, for example, field produced by currents in conducting layer at the depth $a/2$ ($a$ is the Moon radius) attenuates in 8 times and compose at the best $0.1B_i$. Practically it means that reliable information from this depth can be received only when error is much less of the quantity. An essential source of error is screening of internal fields by highly conducting plasma on the day side of the Moon. During 3 weeks of lunar month the Moon immersed in solar wind which, as it was believed, completely reflects internal fields, vanishing vertical component of magnetic field and enhancing horizontal ones in several times. For interpretation of day time measurements calculations for spherically symmetric solar wind impact were made. At the night side of the Moon, space treated as vacuum in which internal magnetic field penetrate without distortion. Real asymmetry of the moon surrounding space should be taken into account because it yields direct error in the deep conductivity estimation. The observed differences of the Moon conductivity estimations from day and night data may be explained by this factor.

The inductive response function of the Moon determined in harmonic and impulse regimes was presented in works of American [Sonett, Dyal, Parkin and others] and Soviet [Vanyan, Berdichevsky, Dolginov and others]. For harmonic regime averaged response function attains maximum value at approximately $4 \times 10^{-3}$ Hz, i.e. at period 250 s, but from other components at $3 \times 10^2$ Hz (30 s); for impulsive regime the time constant of response function decay in “e” times was received to be equal 85, 70 and 23 s in different time and place. Agreement is not very good. In the class of two-layer models with non-conducting upper layer this data are compatible with uniform spherical conductor of $5 \times 10^{-4}$ S/m at the depth 200 km and also with many other models. In these studies two important sources of error were not excluded properly: conductive mode and asymmetry of solar wind suppression of secondary internal field. The problems are difficult, progress can be expected by multi-site synchronous measurements. Concerning the upper high resistive layer, this magnetovariational study can give only global transverse resistance if TM mode will be reliable separated.

L.L. Vanyan, M.N. Berdichevsky and their colleagues were the first who presented the lunar EM data in the form of apparent resistivity (1973).
M.N. Berdichevsky’s and L.L. Vanyan’s lives and creative activity are tightly knit and can hardly be presented separately. Both of them were passionately given to magnetotellurics. They considered the magnetotelluric exploration to be a very effective method of studying deep electrical conductivity of the Earth Crust and Upper Mantle. However, they paid no less attention to electrical prospecting with controlled sources. And Vanyan was the one who gave it special attention. He elaborated a theoretical and methodological basis for frequency sounding and transient fieldtechniques. M.N. Berdichevsky was much concerned with the theory and practice of the sounding on direct currents with symmetrical and dipole installations. Under his supervision a remarkable album of theoretical apparent resistivity curves was created. It is considered as a significant supplement to A.M. Pylaev’s album. Professional versatility and global study of the Earth deep structure were common for both prominent scientists during all of their lives.

Like most scientists of the younger generation, I first got acquainted with M.N. Berdichevsky and L.L. Vanyan as with classics of the electrical exploration theory via their major works "Electric exploration using magnetotelluric profiling" [Berdichevsky, 1968] and "Basics of electromagnetic sounding" [Vanyan, 1965]. These works became handbooks for several generations of prospectors. I got acquainted in person with M.N. Berdichevsky and L.L. Vanyan in spring 1976 at a memorable electromagnetic workshop in Zvenigorod which was dedicated to the 25th anniversary of magnetotellurics. The highlight of the workshop was a theoretical discussion on the basics of MT sounding between supporters of M.N. Berdichevsky, L.L. Vanyan and V.I. Dmitriev defending poloidal (induction) Tikhonov-Cagniard model and supporters of D.N. Chetaev standing for transverse-electric (galvanic) field excitation mode. Academician A.N. Tichonov, who was present at the workshop, remained neutral, knowing the two conceptions being hardly totally different. In Zvenigorod Mark Naumovich and Leonid L’vovich acted as leaders of the geophysical study in magnetotellurics and leaders of the study of structure and properties of the Earth Crust and Upper Mantle deep conductivity. They were also concerned with elaborating the theoretical basis for the electromagnetic sounding. In Zvenigorod L.L. Vanyan provided motivations for the program of the asthenosphere conductivity study. In 1977 this program was adopted by the International Association on Geomagnetism and Aeronomy (IAGA) and got the status of international geophysical project "ELAS". The immediate world-wide interest of geologists and geophysics in the project was due to it focusing on the study of the intermediate conducting layer in the lithosphere base as an indicator of the partial melting zone. They believed that the partial melting zone (asthenosphere) should be of low viscosity and could serve as a forcible argument for the lithosphere plates being able to slip, as was stated by the mobilist concept dominating at that time. Thus, project ELAS became a complex program with 19 participating countries.

Besides this work, Mark Naumovich paid great attention to conductivity of the whole lithosphere and, first of all, to that of the Earth crust. He knew these issues being tightly woven. When the boom about the first impressive results of the deep MTS detecting the presence of the asthenosphere all around the world subsided, it became clear that magnetotellurics, unlike the seismic prospecting, is greater subjected to lateral distortions. On the initiative and under scientific supervision of M.N. Berdichevsky the project "The Map of the Earth crust conductivity for the territory of USSR" was elaborated. In the framework of this project M.N. Berdichevsky and L.L. Vanyan actively discussed fluid and electronically conducting concepts on the nature of conductivity crustal anomalies. It became clear that the nature of the lithosphere deep conductivity is more complicated than the 1D model could show. There are also indiscernible, diffusive electromagnetic fields of the deep electromagnetic soundings, the latter being limited by the quasi stationary approach.
L.L. Vanyan was the first to evaluate the situation. As one of its solutions he set forth the idea of elaborating "normal" or, as he called them more often, "standard" models of the deep section for cool, moderate and hot types of the lithosphere. He studied the issue with much of his concern and profound analysis. A number of his major works on the issue was published.

The initiative and broad scientific background of M.N. Berdichevsky and L.L. Vanyan contributed to general interest of geologists of many countries in studying crustal conducting objects on the Russian territory and abroad. Certain compilations are provided in works of A.A. Kovtun, I.I. Rokityansky, S.N. Kulik, A.A. Zhamaletdinov and others.

In his last reports and presentations M.N. Berdichevsky mentioned the self-introduced term "insular astenosphere" all the more often. It means that the astenosphere does not spread universally, but develops in certain quite exotic areas: within the Juan-de-Fuko rifting zone in the northern Pacific Ocean, in Hawaii islands area, within the Pannonian depression and in a number of other regions. The astenosphere as the zone of the partial melting is probably out of the Precambrian shields and ancient platforms. These essential new results of deep geoelectrics (magnetotellurics), which are also confirmed by the deep seismic prospecting (DSP) data, led to working out a concept of tectonic plumes in the theoretical geology in addition to the mobilist concepts of the plate tectonics.

POSSIBILITIES AND LIMITATIONS OF THE DYNAMIC CORRECTION METHOD IN MT SOUNDINGS

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Some possibilities and limitations of the dynamic correction method are investigated on the model containing subsurface and deep layer. Conductance of the subsurface layer and normal section of the model are supposed known. Conductance of the deep layer is determined by series of dynamic correction and 1D inversion. Multi-thin-sheet program based on modified iterative-dissipative method is used for direct 3D problem solution. It is shown that thrice-repeated application of this procedure enable to determine conductance of the deep layer with acceptable accuracy.

COMPACT AND ADAPTIVE PARAMETERIZATION IN THE INVERSE PROBLEMS OF DEEP GEOELECTRICS: FROM EMSLAB TO EMTESZ IN TOUCH WITH MARK BERDICHEVSKY

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Prof. Mark N. Berdichevsky for many years had in the focus of his studies the problem of rational model parameterization in the solution of geoelectrical inverse problems. He many times discussed this topic in his monographs written together with V.I. Dmitriev and M.S. Zhdanov, in particular, in his last book (Berdichevsky, Dmitriev, 2008). He outlined the following main requirements for the successful model parameterization: the compactness, the capability to account for a priori assumptions and the adaptiveness to concentrate resources in model elements with the greatest influence on the inverted data. In mid-90’s he was surprised with the variety of possibilities to satisfy these requirements, besides of the enhanced solution stabilization capabilities, being available in our general approach for the inversion of magnetotelluric (MT) and magnetovariational (MV) data (Golubev, Varentsov, 1993; Varentsov, 2002, 2007) and with the first results of its
multi-component 2D application with the priority of geomagnetic tipper and bi-modal impedance phases (Varentsov et al., 1996) to the data from the EMSLAB project. In few years he and his team (primarily, N.S. Golubtsova and P.Yu. Pushkarev) became deeply submerged users of our 2D inversion software and started its broad use in the simplest, but at the same time the most compact “fixed geometry” mode. In this mode elementary modeling cells are integrated into fixed shape inversion cells, whose resistivities are further optimized together with resistivities of the background layered section of fixed thicknesses. The deep understanding of the EM field phenomenology helped this team to concentrate inversion cells in the investigated model parts and to achieve on this way the effective compromise of resolution and stability. On the base of this technique Mark Berdichevsky developed his strategy of successive partial inversions, which started with the tipper data inversion and then improved models with the fitting of impedance phases and downweighted apparent resistivities. This approach brought an important generalization of the EMSLAB model for the Cascadia subduction zone (Vanyan et al., 2002) in comparison with our previous results (Varentsov et al., 1996). Then the advantages of this strategy were demonstrated in many details (Berdichevsky et al., 2003) using MT/MV data set imitated for the Tien Shan geoelectric model along the NARYN transect (Rybin, NARYN WG, 2010). More synthetic data sets were investigated in (Novozhinski, Pushkarev, 2001). Other important inversion applications followed during this decade (Berdichevsky, Dmitriev, 2008). The last one was again associated with NARYN transect and brought the state-of-art successive partial 2D inversion (Berdichevsky et al., 2010) for significantly improved and extended real MT/MV data set (Sokolova, NARYN WG, 2010).

At the same time, since the end of 90’s, our team started wide-scale inversion experiments with more advanced model parameterizations, already implemented that time in our inversion software. These schemes allow the combination of the rough layered peripheral background model of fixed geometry with a series of “scanning windows” with fine parameterization (Varentsov, 2002, 2007). One approach for this fine approximation was based on the use of Strakhov’s continuous finite functions, while another one exploited Tarantola’s idea of correlated changes of inversion cell parameters controlled by a priori size estimates for the studied geoelectric structures. For a number of quite complicated synthetic data sets investigated in the above cited papers these new parameterization schemes demonstrated obvious advantages in comparison with the fixed geometry scheme. Moreover, we observed that joint multi-component MT/MV inversion solutions had resolution and stability improvements in comparison with partial inversions. It looked that the misfit functional for one data component served like a stabilizing functional for another one and vice verse. In particular, MV data stabilized the fit of impedance responses. At the same time the convergence contradictions between different data components were resolved by means of Huber’s robust data misfit metrics.

We successfully applied this advanced approach to real data in a number of research projects with simultaneous EM soundings considering the joint inversion of tippers, horizontal MV responses, impedance (or phase tensor) bi-modal phases and downweighted apparent resistivities. In the EMTESZ-Pomerania experiment (Ernst et al., 2008) interesting inversion results were obtained both for separate horizontal MV data (Varentsov, EMTESZ-Pomerania WG, 2005) and for the joint 8-component data ensemble mentioned above (Varentsov et al., 2007). Moreover, in the latter paper we investigated the inversion resolution achieved for different component ensembles of strictly 2D imitation data with various error levels calculated in complicated EMTESZ-type model with overlapping conductors in sedimentary cover, crust and upper mantle. A perfect recognition of practically all model structures both from MT, MV and MT+MV data inversions was demonstrated in this imitation study in case of percent-level data quality.

We several times discussed with Mark Berdichevsky and his team plans of the detailed comparison of two inversion strategies, namely the successive partial and the joint multi-component. And these discussions were very stimulating for our developments. First common results in this direction may be concluded basing on recent studies at NARYN transect (Berdichevsky et al., 2010; Sokolova, NARYN WG, 2010).
Finally, I would like to add few personal remarks on the importance of my relations with Mark Berdichevsky. I started my scientific career in mid-70’s during university years under supervision of Michael Zhdanov. He in turn was that time under strong influence of Mark Berdichevsky. Thus Mark’s name and papers where in the air all the time. But the first bright direct acquaintance with his personality I got in spring 1976 during the Soviet EM Workshop in Zvenigorod. The main event of this workshop was the discussion on the applicability and limitations of Tikhonov’s MT model. And Mark appeared in my eyes during this hot discussion as an epic hero, closely surrounded by two other warriors, Leonid Vanyan and Vladimir Dmitriev, leading our MT community to the clear understanding of Tikhonov’s paradigm with all possible extensions and limits. On this way Mark expressed a strong passion (of the Moses scale) and this emotional factor became very important for me in choosing of my further direction in the science. I learned many things from Mark later and we had many fruitful discussions, especially during the last decade of his life. At the last day of his life we, me and my colleagues Nikolay Palshin and Elena Sokolova, planned to visit him in the country side with our Polish guests, his good friends, Tomasz Ernst and Waldemar Jozwiak, to show very new results on the recalculation of tipper arrays into horizontal MV responses and their perfect comparison with the direct estimates of these data. Mark followed with a great interested our EM sounding studies in Polish-German Pomerania and several times participated in our workshops in Zvenigorod. The data we prepared to show him demonstrated the high accuracy achieved in the collecting of MV data and in further manipulations with them. We thought he would be glad to see such positive developments in MV studies, but we came few hours late…

References
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Sokolova E.Yu., Naryn WG. Mark Berdichevsky and EM studies of the Tien Shan deep structure and dynamics: recent approaches to joint interpretation of MT/MV data in high mountains // This volume. 2010.
Intensive studies of the Tien Shan region with the methods of deep electromagnetic sounding (MT, V, DMT) were started by the Research Station RAS in Bishkek in the early 80’s of the last century using field instruments of domestic production. Difficult geoelectrical settings of the high mountain Tien Shan area demanded for some correction in the regular scheme of the field MT observations and the conventional approach to the construction of the deep geoelectrical model. Totally, in 80-90’s, about 400 soundings were carried out with efforts of the Research Station personnel along a number of regional and local profiles on the Tien Shan territory.

EM sounding materials obtained in this region were interpreted with Mark Berdichevsky immediate innovating assistance and deep supervision. As a result, the first geoelectrical model of the Chu basin with its mountain surroundings was constructed (Batalev et al., 1989) and further followed with regional models along a series of MT profiles crossing the Tien Shan orogen in submeridional directions (Trapeznikov et al., 1997). Thus, the possibility of quasi-2D data interpretation of MT profiles was proved with regional change of the geoelectric strike from the strict latitudinal direction in the central part to the sublatitudinal (80–100ºE) in the east. In the specific settings of the mountain region an original and effective interpretation approach was formulated in the form of a three-level inversion algorithm, primarily considering only tipper information (which is a free from the influence of near-surface inhomogeneities (Berdichevsky et al., 1998)) and further taking into account the impedance (mainly phase) data (Trapeznikov et al., 1997). The main features of the deep electrical conductivity structure of the Tien Shan region were determined this way, namely, subvertical conductive zones linked with deep faults and highly conductive lower crustal layer presented practically everywhere at the depth ~30–50 km with the conductance increasing southwards (Fig. 1). We found spatial correlation of the crustal conductors with zones of low seismic velocities determined by the seismic tomography experiments, and made an assumption of their fluid nature (Rybin et al., 2001).

References
Introduction

The Central (Kyrgyz) Tien Shan, with its extended network of EM soundings implemented by the Research Station RAS in Bishkek, attracted a peculiar interest of M.N. Berdichevsky during two last decades. It was his “firing ground” for the development and tuning of the interpretation methods to construct conductivity models of this and other similar regions with complicated geoelectric structure.

The general features of the Tien Shan deep conductivity have been firstly revealed from the prospecting sounding data of 80-90’s due to the original MT/MV inversion approach, based on the priority of geomagnetic observations and built under Mark’s careful supervision.
[Tapeznikov et al., 1997]. The main results of this pioneering work are reviewed by Anatoly Rybin at this Workshop.

Later, in 2000’s, a variety of data in a broader period range were collected over the region (Fig.1). The soundings were mostly done with the modern equipment (LIMS, Phoenix) in synchronous observation schemes. The possibilities of the present-day magnetotellurics to give a stable resolution of complex conductivity section of an elongated orogen became the main interest of Mark at this stage of the Tien Shan investigations. Several years ago he has initiated the collaboration with researchers from GEMRC and jointed their efforts together with those of RS RAS and MSU groups to study this problem on MT/MV materials at the longest regional Tien Shan NARYN transect. It was a happy time of our common work with M.N. Berdichevsky, especially for those, who was deprived of so close collaboration since the University years. In this paper we present the actual status of these investigations, which NARYN Working Group, inspired by Mark, continues at present, extending the experience from this transect to other Tien Shan profiles as well as to the other areas of active mountain building.

**Methods**

By now NARYN WG has elaborated a complex of robust methods for MT/MV data analysis and interpretation, aimed at overcoming of main difficulties of the deep geoelectrics in the active mountain areas: the influence of the topography, strong near surface heterogeneity of conductivity distribution; multi-level anomalous structure of the crust and upper mantle, inhomogeneous observation grids (often both in space and in period band).

We put the following principles as the basis of our complex:

– priority of synchronous observations;
– integration of MT/MV data sets with “synchronization” of data of different field campaigns;
– multi-site processing with attention to accuracy of all components and long period estimates of transfer function (TFs);
– new schemes of invariant analysis, robust to galvanic distortions;
– robust inversion procedure with detailed model parameterization and adequate reconstruction of both smooth and sharp conductivity boundaries; accounting both for geoelectric structure and topography;
– inversion of all the variety of TFs according to the principle of complimentary information, but with the priority of less distorted by galvanic effects phase tensor and geomagnetic (especially horizontal magnetic) data;
– resolution study with a help of imitation data inversions.

In the case of pragmatic profile interpretation (for elongated orogens) this list is extended by:

– construction of quasi-2D ensembles of data for profile inversion with accounting for 3D near surface and off-profile distortions;
– specific inversion strategy based on successive partial and joint multi-component profile inversions considering different sensitivity to targets and “immunity” to 3D distortions of different data ensembles;
– study of the 3D effects of sedimentary valleys.

Our data processing tools rely upon multi-remote reference estimates with the control of horizontal magnetic field homogeneity, mRRMC technique [Varentsov et. al, 2003; Varentsov, Sokolova, 2005; Varentsov, 2007a].

We come to the reliable strike and dimensionality parameters with a help of widely recognized phase tensor technique (PT) [Caldwell et .al., 2004] as well as original developments, estimating tipper ($W_z$) and horizontal magnetic tensor (HMT) skews and strike directions [Berdichevsky, Dmitriev, 2008; Varentsov, 2007a].
Finally, we apply the regularized robust 2D inversion code [Varentsov, 2007b], using adaptive block and piece-wise continuous approximation of conductivity distributions and a variety of resources for the solution stabilization.

**Results**

We present the results of complex MT/MV analysis and interpretation at NARYN profile, which were accomplished in several steps.

1. The data of long-period LIMS observations along the NARYN profile were reprocessed with the new tools and summarized with revised prospecting sounding data and new estimates from sounings done with Phoenix equipment.

2. The effects of 3D near surface and upper crustal inhomogeneities were revealed by the invariant analysis of Z and MV estimates, with PT and HMT responses found to be less affected. However the regional 2D behavior of the data set was generally approved (with only exceptions of long period tippers because of the source effect). Quasi-2D ensembles of TF data for the inversion in broadband (MT, 0.1–1500s, 65 sites) and long-period (LMT, 16–20000s, 19 sites) ranges were compiled from the impedance, PT, Wz and HMT estimates. Each component of the data was rotated according to the regional strike and supplied with a specific mask of weights, reflecting data accuracy and a quantitative measure of local 3D distortions estimated via correspondent skew and strike invariants. These weights served as penalties to 3D distorted data, suppressing their influence in the inversion and concentrating the procedure on target 2D structures.

3. The elaborated strategy of the inversion at NARYN profile implied well grounded choice of starting models with impedance phase and geomagnetic data prevalence, provided by a priori weighting. The inversions run in two complimentary courses. The first, suggested by M.N. Berdichevsky, supplied a coarse-grid stable and conservative reference and implemented the successive partial inversions of LMT data, starting from geomagnetic components with step by step fixation of the parameters for reliably determined model blocks. The second GEMRC approach considered the initial study of partial data sets followed by joint properly weighted multi-component bi-modal inversions of LMT and MT data sets. In this latter case we use all the advantages of the extended broad-band data ensemble in the model with the dense grid (up to inversion 2000 cells) and fine topography approximation, concentrating parameterization resources in the scanning windows with main conductivity anomalies.

4. The detailed model, resulted from inversion runs in the frame of the second approach is shown in Fig.2 (top panel, S - left, N - right). It was constructed as a robust average (in the space of model parameters) of the inversion results for different subsets of MT and LMT data ensembles in a manner resembling the “bootstrap” technique. The important features of geoelectric structure are the low crustal conductive layer, sporadically revealed upper crustal one, the sub-vertical conductive zone in upper and middle crust of “Nikolaev Line” tectonic zone and asthenospheric structure [Sokolova et al., 2008]. The most prominent model elements are in a good correlation with modern seismic tomography data.

5. A round of 2D imitation inversions on the base of schematic and realistic models of NARYN conductivity section has been done. It was demonstrated, that in 2D environment with accurate incorporation of the topography into the model geometry and the availability of a dense multi-component and wide period-band MT/MV data ensure modern procedures of profile inversion to achieve a high resolution of a complex geoelectric structure of an active orogen (Fig. 2, two lower panels). At this step it was also shown, how a poor account for topography can introduce false structures in the recovering crustal conductive layer.

6. The examination of the 3D effects of the near surface sediments, being the last stage of the inversion analysis up today, has been done with a help of 2D inversion study of 3D synthetic data. It was shown that in spite of the perfect data fit the insufficient account for 3D data distortions in the inversion course can also strongly change the structure of crustal conductor, underlying sedimentary valleys of limited strike.
Fig. 1. MT/MV sounding sites in the Central Tien Shan made by RS RAS:
small grey circles – CES-2 (80-90’s);
big grey circles – LIMS (with S. Park, 1999-2001);
white diamonds – one-three day long Phoenix (2005-9);
700 km long NARYN profile passes along 76°E meridian.

Fig. 2. Inversion 2D resistivity models
(Om m, lg-scale, different vertical scale in horizontal strips) along NARYN profile,
from top to bottom:
resulting average model for a series of weighted multi-component bi-modal inversions;
simplified approximation of this resulting model in the imitation study;
2D inversion model for the imitated data set starting from a homogeneous half space with topography.
The maps of spatial distributions as well as pseudo sections of MT/MV parameters are analyzed in correlation with other geophysical images of the Central Tien Shan, in particular, with the regional seismic stress diagrams and seismicity distributions.

Conclusions

The effectiveness of elaborated interpretation approaches was demonstrated also for new broad-band MT/MV data at KOKEKEREN profile (74°E). Stable inversion results, obtained here with the suppression of 3D effects, revealed a distinct similarity of conductivity sections for both profiles being under consideration.

Namely, it is the lower-crustal conductive layer, being one of the main targets in our Tien Shan studies and the common feature in many other active orogens. The reliable resolution of its structure could be a significant contribution of MT method to the regional geodynamic synthesis. To this extent, our methods seem to be useful not only for the particular Tien Shan experiment, but also for other EM studies in active regions with high mountains. We already apply our experience in the analysis of the data along recent sounding profiles in Tibet (EHS3D project area).

Continuing our Tien Shan investigation we collect new modern quality data on other transects for their interpretation in the described way and do first steps toward the synthesis of the profile results into the volume prognostic conductivity model of the region, which will serve for geodynamic studies of this unique area of intra-continental building. On this way we miss M.N. Berdichevsky very much.

References

NEURONET BASED TECHNIQUE FOR CONSTRUCTION OF 3D GEOELECTRICAL MODELS FROM THE PROFILE AND ARRAY ARCHIVE MT DATA

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Despite of the presence of well developed tools for 2-D MT data interpretation the resulting models may be quite far from the reality by a number of reasons. The geological medium is three-dimensional and, hence, its approximation by two-dimensional models based on the profile data may result in unpredictable errors in target localization (both vertical and horizontal), considerably overestimated or underestimated resistivity values and to the appearance of false anomalies associated with, e.g., the proximity of the MT profile to the parallel deep fault. The situation could be improved to some extent by 3-D inversion of the profile MT data, especially if diagonal components of the impedance tensor are used or special inversion techniques are applied.

Meanwhile, if some archive scalar MT data are available in the vicinity of 2-D profiles (even limited in volume and poor in quality), one can try to construct a 3-D resistivity model of the region using both the profile and array MT data, thus increasing the volume of MT information involved in the inversion. The aim of the present work is to apply the neural network based algorithm to the construction of such a model in the vicinity of the SB-1 profile in the Eastern Siberia based on 2-D tensor MT data and archive scalar MT data. The resulting model is free of the depth resistivity distortions that are typical of 3-D models based on scalar MT data only, as well as of 2-D models obtained by inversion of profile tensor MT data. The proposed approach can be used for re-interpretation of archive scalar MT data and for reasonable planning of MT surveys as well.
Session 2: Basic theory

THE MAGNETOTELLURIC PHASE TENSOR: THEORY AND PRACTICE

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It is well known that the interpretation of magnetotelluric (MT) transfer functions can be affected by static shift due to galvanic distortion of telluric currents. The distortion alters the magnitude of the transfer functions by a frequency independent factor and thus leads to biased depth and resistivity estimates. Furthermore, the transfer functions generally depend on the orientation of the measuring devices. Frequently the interpretation of MT data is based on the assumption that the unknown resistivity structure is two dimensional at all sites. The impedance tensors are then rotated into the strike direction gained either by geological reasoning or mathematical concepts. In many cases the 2D assumption is not valid for all sites and the entire frequency range and thus leads to questionable resistivity models.

The phase tensor concept developed by Caldwell et al. (2004) produces distortion-free estimates of the impedance tensor which are rotationally invariant and display the frequency dependent dimensionality of the transfer functions. Consequently the phase tensor is the ideal data base for selecting the adequate dimensionality and for modelling the resistivity structure.

The spatial display of the phase tensor ellipses is often used for imaging the subsurface, however it might lead to misinterpretation, as the tensor reflects different depth ranges of the diffusion process of the electromagnetic waves into the subsurface depending on their orientation. Thus the phase tensor concept has been developed further to improve the imaging of the underlying structure.

The technique is explained by simple 3D numerical models and practical examples from data obtained at the Rwenzori Mountains situated at the most Western Part of the East African Rift system in Uganda, and from a large data set covering most parts of Iceland.

THE MAGNETOTELLURIC PHASE TENSOR REVISITED

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Mark Berdichevsky was deeply interested in how to extract conductivity structure from MT data in the presence of near surface effects that distort the deep information. Berdichevsky, et al. (1989) is a review of his pioneering work. I never got the chance to discuss with him what he thought of the Phase Tensor, but I like to think that he would have seen or perhaps did see clever ways to use it to extract quantitative structural information. While the phase tensor is now widely used to gain insight into regional structural dimensionality, I have seen no attempts to get more information from this very simple data invariant. In fact applications in the literature are entirely qualitative and often simply ignore phase tensor evidence that invalidates the interpretation method used in the paper.

The purpose of this paper is to re-formulate the original presentation of the phase tensor of Caldwell, et al. (2004) in a way that is more intuitive and makes it easier to visualize what the phase tensor implies about regional current flow. It addresses a shortcoming of the original paper in not recognizing that phase tensor phases can be “out-of-quadrant”, i.e. exceed 90° or be less than 0°. I will then address uses of the phase tensor in determining regional structure.

The magnetotelluric (MT) impedance tensor \( \mathbf{Z} \) is the complex frequency-domain transfer function between the horizontal magnetic (\( \mathbf{H} \)) and electric (\( \mathbf{E} \)) field vectors at an MT site: \( \mathbf{E} = \mathbf{Z} \mathbf{H} \).
Major issues in inverting $Z$ for sub-surface electrical conductivity are distortion by un-resolvably small-scale structure near the site and the dimensionality of the underlying regional structure. When the distortion is by deflection of the electric current by electric charges in-phase with the electric field, the measured impedance is related to the "regional" impedance that would be measured in the absence of the distortion by $Z_{\text{measured}} = DZ_{\text{regional}}$, where $D$ is a two by two matrix whose elements are real. This distortion is termed “Galvanic”. This relation is not immediately useful because it has four more unknowns on the right than there are measurements on the left. About 20 years ago, considerable progress was made by assuming that the regional structure was 2D (Bahr, 1988, Groom & Bailey, 1989). This reduces the unknowns on the right by four, and the data then allow determination of a strike and the phases of the 2D impedance elements. The regional impedance magnitudes are multiplied by “static shifts” or “gains” that are indeterminate without additional constraints. This is commonly called “impedance tensor decomposition” or simply decomposition. The calculation is unstable for data with noise, but can be stabilized by assuming that $D$ is independent of period (a necessary condition for Galvanic distortion) and/or the regional strike is the same at multiple sites (McNiece & Jones, 2001). Testing the validity of the assumptions underlying impedance tensor decomposition has been limited to the question of whether the decomposition is a statistically acceptable fit to the measured impedance within data uncertainty. Unaddressed is whether the decomposition model is applicable at all.

Caldwell, et al. (2004) introduced the MT phase tensor: $\Phi = X^\dagger Y$, where $X = \text{real}(Z)$ and $Y = \text{imag}(Z)$. This real two by two matrix is unaffected by galvanic distortion and if $Z_{\text{rotated}} = RZR^{-1}$, then $\Phi_{\text{rotated}} = R\Phi R^{-1}$.

The action of any 2 by 2 real matrix such as $\Phi$ on a vector is to rotate it and change its length. Applying the phase tensor to a family of radial vectors $c(\omega)$ whose tip circulates around the unit circle as $\omega$ increases produces another family of radial vectors:

$$ p(\omega) = \Phi c(\omega) $$

The phase tensor and radial vectors of a 2D impedance in strike-aligned coordinates are

$$ \Phi_{2D} = \begin{bmatrix} \tan(\phi_{yx}) & 0 \\ 0 & \tan(\phi_{xy}) \end{bmatrix} \quad p_{2D}(\omega) = \begin{bmatrix} \tan(\phi_{yx}) \cos(\omega) \\ \tan(\phi_{xy}) \sin(\omega) \end{bmatrix} $$

The relation on the right is a parametric equation of an ellipse whose semi-axes are aligned with the x and y coordinate axes (see Fig 1(a)). The semi-axis in the x direction has length $\tan(\phi_{yx})$ and the semi-axis in the y direction has length $\tan(\phi_{xy})$. Since $Z_{xy}$ and $\phi_{xy}$ are associated with electric field and current in the x direction and $Z_{yx}$ and $\phi_{yx}$ are associated with electric field and current in the y direction, each phase tensor axis is perpendicular to the polarization of its associated electric field. Note that I am using the coordinate system typical in geomagnetism with positive rotation clockwise.

Any non-singular two by two real matrix produces an ellipse when applied to the unit circle. In the 2D case, the point circulating around the unit circle crosses each axis of the ellipse exactly when the point circulating around the ellipse crosses the same axis. In general, however, the family of vectors $c$ is rotated relative to the family of vectors $p$. Additionally, the direction of circulation around the ellipse can be opposite to that around the circle. The geometry of this is shown in Fig. 1(b) and (c). The fact that any non-singular matrix results in an ellipse means that when rotated to a coordinate system aligned with the ellipse axes, the matrix must be equal to a diagonal matrix (i.e. an ellipse) times a matrix which rotates the unit circle vectors by an angle $\psi$. If $\theta$ is the angle (in the right-hand sense) between the x axis of $Z_{\text{measured}}$ (and hence $\Phi_{\text{measured}}$) and the semi-major axis of the phase tensor ellipse, this geometrical argument can be stated

$$ \Phi_{\text{regional}} = R(\theta) \Phi_{\text{measured}} R^{-1}(\theta) = \begin{bmatrix} \Phi_1 & 0 \\ 0 & \Phi_2 \end{bmatrix} R(\psi) $$

38
The right side of this equation can be expanded as

\[
\begin{bmatrix}
\Phi_1 & 0 \\
0 & \Phi_2
\end{bmatrix} R(\psi) =
\begin{bmatrix}
\cos(\psi) & \sin(\psi) \\
-\sin(\psi) & \cos(\psi)
\end{bmatrix} =
\begin{bmatrix}
\Phi_1 \cos(\psi) & \Phi_1 \sin(\psi) \\
-\Phi_2 \sin(\psi) & \Phi_2 \cos(\psi)
\end{bmatrix}
\]

Skew and trace are matrix invariants that can be computed in any Cartesian coordinate system. The ratio of the skew to the trace of the last matrix on the right gives

\[
\psi = \tan^{-1} \left( \frac{\Phi_1 - \Phi_2}{\Phi_1 + \Phi_2} \right) = \tan^{-1} \left( \frac{\Phi_{xy} - \Phi_{yx}}{\Phi_{xx} + \Phi_{yy}} \right)_{measured}
\]

A natural name for \( \psi \) is the “normalized skew angle” because it is derived from the skew normalized by the trace. It is equal to twice the angle “\( \beta \)” used by Caldwell, et al. (2004). Note that it is critical that a “4-quadrant” inverse tangent (atan2 in most languages) be used to compute \( \psi \).

Finally, the phase tensor computed from the measured impedance can be expressed

\[
\Phi_{measured} = R^{-1}(\theta) \begin{bmatrix}
\tan(\phi_1) & 0 \\
0 & \tan(\phi_2)
\end{bmatrix} R(\psi) R(\theta)
\]

where the lengths of the ellipse semi-axes have been written in terms of “principle” phase angles \( \phi_1 \) and \( \phi_2 \). This is a “singular value decomposition” (SVD) which differs in important ways from SVD’s computed by standard matrix routines: (1) the largest principle phase need not be \( \phi_1 \) and is not for all cases in Fig. 1; (2) principle phases are not restricted to the 1st quadrant. The regional phase tensor for Fig. 1 (c) can be written in two completely equivalent ways:

\[
\Phi_{regional} = \begin{bmatrix}
\tan(30°) & 0 \\
0 & \tan(60°)
\end{bmatrix} R(-160°) = \begin{bmatrix}
\tan(30°) & 0 \\
0 & -\tan(60°)
\end{bmatrix} R(20°)
\]

In the second form, the skew rotation is the same as for (b), but since \(-\tan(60°) = \tan(120°)\), the principle phase is now in the same quadrant as the phase of \( Z_{xy} \). \( \psi \) greater than 90° or less than -90° is diagnostic of out-of-quadrant principle phases but is not sufficient to sort out the quadrants. This can, however, be done with the addition of the details of the circulation about the ellipse.

A practical way to find \( \phi_1 \), \( \phi_2 \) and \( \theta \) follows directly from the geometrical development: generate points around a unit circle, apply the phase tensor in measurement coordinates and find...
the position of the resultant points farthest (and closest) to the origin. Calculation of $\psi$ using the skew and trace is easy. To identify whether $\phi_1$ is the long or short ellipse axis, test which alternative satisfies the last equation above. To estimate errors, I generate 1000 realizations of the measured impedance using normally-distributed random numbers, compute $\phi_1$, $\phi_2$, $\theta$ and $\psi$ for each realization and compute their variance. While not elegant, this works better than linear propagation of errors when the impedance elements errors are not very small and requires no complicated algebra.

A 2D regional impedance is only compatible with the measured data if $\psi=0$ within its error estimate. Groom-Bailey and related decompositions applied to data with non-zero $\psi$ are equivalent to forcing $\psi=0$, i.e. making an assumption about the data that is demonstrably untrue. Thus arguments about the applicability of the decomposition based on its statistical fit to the data are highly suspect. In fact, if $\psi$ is small enough that one is willing to concede it might be zero, the principle phases give the TE and TM phases directly. If the normalized skew is non-zero, the principle phases are the best approximations you are going to get to the TE and TM phases. Decomposition also gives 2D impedance magnitudes (apparent resistivity) within an unknown multiplier. If $\psi$ is forced to zero when it is not, the relationship between TM phase and apparent resistivity given in the very important paper of Weidelt and Kaikkonen (1994) can fail and the decomposition will result in incompatible phase and apparent resistivity data. If the TM mode is approximated with one of the principle phases, consistent apparent resistivity values can be calculated with the Rhoplus algorithm of Parker and Booker (1996). This requires constraining the resistivity at one period – precisely equivalent to the indeterminacy in decomposition magnitudes. I once asked Peter whether TE data should also have the 1D relationship between phase and apparent resistivity. His reply was essentially: “not rigorously” – one can invent 2D structures whose TE response violates the 1D relationship. He never told me what these models looked like, but said they are not very likely in the real world and I have never seen the phenomenon in field data.

References

THREE-DIMENSIONAL EM FORWARD MODELING USING VECTOR FINITE ELEMENTS ON UNSTRUCTURED GRIDS

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The finite element (FE) method is a very powerful tool to solve partial differential equations. Whereas the finite difference method is restricted to structured and orthogonal tensor product grids the FE method allows for unstructured grids using tetrahedra in 3D and triangles in 2D. These grids are suitable to mesh arbitrary geometric features, like topography, bathymetry or subsurface voids, and to adapt the grid size to the character of the solution. If the mesh is suited to a particular problem the number of degrees of freedom that is required to obtain a solution of desired accuracy can be reduced substantially.
We have pursued different strategies to implement finite element solutions in the frequency and time domain and have developed explicit time stepping schemes, frequency domain solutions using model reduction techniques, time-stepping via Krylov subspace methods including matrix exponential functions, and frequency domain solutions discretizing the curl-curl equation in a stabilized way to perform calculations of the electromagnetic field in a broad range from the wave domain to the diffusion domain.

We focus on two examples which illustrate the advantages of finite element solutions for an electric dipole transmitter over a rugged sea bottom and magnetotellurics over the realistic topography of Stromboli volcano in Italy incorporating digital terrain models.

3D-INTERPRETATION OF ELECTROMAGNETIC SOUNDING DATA BASED ON NUMERICAL 3D-MODELLING: THEORY AND PRACTICE

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At present the exploration of the earth geology at middle and deep depths is one of the important directions of electrical prospecting. In the first place it is an oil exploration connected with research of collectors at a depth from 1500 meters, an investigation of structure of earth in ore deposit areas and etc.

Profile survey with further 1D interpretation based on horizontally layered earth parameter recovery at each point of the profile is the main method for execution of electrical exploration. This technology demonstrated good results during near-surface section research. However, its application to deep investigations can lead to great mistakes in medium recovery when responses from deep bodies are significantly smaller than signal distortion from near-surface heterogeneities. Firstly it is connected with the considerable distinction between the influence of local variations in near-surface and of layers with analogous parameters directly under the researched point at late time. Secondly mistakes can be the result of the considerable distinction between the influence of deep target bodies and of layers with analogous characteristics. And thirdly mistakes can occur because of the influence of lateral heterogeneities in near-surface section.

The usage of area survey technologies and precise methods of 3D modeling for interpretation of experimental data is the real way for solution the problem of the deep geoelectric medium structure recovery.

The opportunity of electromagnetic field calculation in complex mediums, containing tens of three-dimensional heterogeneities, is the basic requirement for mathematical tool of 3D modeling. Only in this case there is an opportunity to recover and to take into account the influence of near-surface medium with high accuracy and “to see” the influences of deep target bodies against the near-surface medium.

The authors developed the software GeoEM, based on finite element modeling with usage of special mathematical statements, with field selection and automatic construction of finite element irregular grids. Three-dimensional electromagnetic fields are described by mathematical models of two types: the first type – for electromagnetic vector-potential with continuous components and scalar electric potential; the second type – for vector-potential with discontinuous normal components. The model of first type is used for approximations based on finite element method with nodal scalar basis functions (scalar FEM), and the second type model is used for approximations, based on finite element method with edge basis functions (vector FEM). Model of the second type makes it possible to calculate electromagnetic fields in mediums with magnetic conductivity, that differs from permeability of vacuum.

The software GeoEM consists of several subsystems: ESIAS (loop source), ES-HED (horizontal current line source), ES-VED (vertical current line source), ES-CED (circular electric
dipole source), ES-MTS (magnetotelluric problems). It allows to calculate stationary, non stationary, harmonic electromagnetic fields for controlled sources of any type, fields of induced polarization and three-dimensional magnetotelluric fields. Calculation time of the one problem for the model with several three-dimensional bodies is about some minutes for nonstationary process and about some seconds for stationary field. Construction of the one geoelectrical model with several three-dimensional bodies takes about some minutes, including and elimination of three-dimensional body from the model needs less than one minute and correction of its parameters needs some seconds.

Currently the row of theoretical and practical results, concerning the conductivity recovery of the medium deep structure was achieved for TEM sounding data by means of software GeoEM. Technology of 3D interpretation was applied to obtain these results. According to this technology geoelectrical 3D model is constructed on basis of high accurate 3D modeling. This model is common for all source positions. The common geoelectric model is constructed in such way that differences between calculated and experimental data are in the limits of measurement error. The main steps of this technology can be formalized as follow.

1. Definition of areas corresponding to normal field (the field of background medium).
2. Background medium fitting.
3. The construction of anomalous fields relative to selected normal field, conforming to loops
4. The fitting of the most considerable near-surface bodies by cyclic sequential fitting for all positions of the source:
   a. the influence estimation of the bodies, fitting to previous loops and included into the model is made when moving to the next source position;
   b. fitting of 3D bodies, corresponding to the remaining anomalies for considered position of the source;
   c. correction of “old” 3D bodies in consideration of new bodies influence.
5. Construction of anomalous fields and localization of weaker anomalies at later times. Fitting of deep bodies.
6. The influence estimation of inaccurate near-surface bodies fitting, when they are located outside the measuring zone, on accuracy of deep bodies fitting in the presence of “holes” in area survey or because of insufficient square of made measurements.
7. The final model correction (including the background medium) by sequential fitting weaker deviation in all time domain.

This technology in cooperation with software GeoEM was used to construct a volume model of a complex environment in the area of Karamken ore deposit as well as to construct a volume geoelectric models in a number of areas in the Eastern Siberia for oil and gas collector mapping.

In this paper we would like to pay particular attention to the fact that 3D interpretation itself does not allow resolving reasonably a problem of a depth structure reconstruction in case of considerably heterogeneous near-surface section if survey is undertaken along profiles or over limited area, as effect of heterogeneities located on the side of a profile or limited area in this case may be recognized and interpreted as effects of deep bodies located below the profile or limited area.

We will illustrate it by reconstructing environment of some conductivity based on data of TEM soundings acquired at one of East Siberia arias. The aim is to recognize heterogeneities of specific resistance in a layer at a depth on the order of 2500 m. The survey was carried out using loop source of 500x500 m², the value recorded is time derivative of vertical component of magnetic field induction \[ \left( -\frac{\partial B_z}{\partial t} \right) \]. Based on the data acquired we built a geoelectric model of upper layers, it consisted of about 50 3D bodies representing heterogeneities of specific resistivity in these layers. The layout of this geoelectric model and an observation system are shown in the Fig.1. After accounting the influences of all recovered near-surface heterogeneities a low resistive body was
outlined in the central part of the area at a depth of 2500 m. Its contour is represented by dotted line in the Fig.1. After it was inserted into the geoelectric model difference between acquired and calculated data for every measuring point of the central part of the investigated area (constrained by heavy line in the Fig.1) was below 4% for the entire time range of field recording.

It may seem that measurements taken over a smaller area that includes projection of the target body would be enough to recognize the recovered at a 2500 m depth target body. But in a case of a inhomogeneous upper part reducing the area of observation will result in ambiguity during reconstruction of deep structure of the environment and appearance of false deep heterogeneities of specific resistivity that would considerably distort geophysical result. Let us show this on the example discussed above.

Let us reduce the area of observation up to the region outlined by a heavy line in the Fig.1 (obviously, the target body is located within this outline) and make calculation for this model. Signal values in receivers for full and reduced models differ only at very late times, but they differ considerably, for measuring points located in the south-east of the reduced area differences reach 60% while response from the target body was below 25%. Thus the reduced model did not satisfy true (in this case playing part of experimental) data and a correction was required. As theoretical (for reduced model) and experimental (for full model) data differed at very late times, it was natural to insert a respective deep heterogeneous body into the model we calculated. We found that this heterogeneity was located the target layer and was of the same resistivity as the target body in the central part of the area. After we inserted it into the reduced model the difference between experimental and (new) theoretical data sharply decreased, the maximum difference over all measuring points in central and south-eastern parts of the limited area were below 5% at late times as well.

A layout of false heterogeneous body we found is shown in the Fig. 2. As a result a model with large false heterogeneous body in the target layer quit reliably and with low residual corresponds to measurements over the reduced area, dimensions (and responses) of this false heterogeneity are considerably greater than those of true heterogeneity.

Obviously in this situation it is impossible to avoid serious mistakes in reconstruction of deep horizon conductivity even using 3D modeling. However it will be enough to add some more measuring points to the observation system southward or south-eastward the edge of the discussed outlined area and the equivalence of the effect produced by deep heterogeneity and peripheral heterogeneities in the upper part the strata will be distorted, using these additional measuring points 3D modeling allows practically unambiguously interpret a reason of high anomalies at late times in points inside the outline as influence of thick outside heterogeneities in the upper part of the environment.

In summery we will represent a volume of calculation costs required for 3D interpretation of experimental data over the total area of investigation. The reconstruction of environment structure required solving about 3000 3D tasks, running time for one task ( at one core of computer with 2.4 GHz) ranged from 1 minute for an environment with some 3D bodies to some hours for full model of the environment including 50 3D heterogeneities. Interpretation was carried out by three operators during 2 months. Differences between calculated data, obtained from full model of the environment from experimental data at measuring points, located inside the outline shown in the Fig. 1, as it was told earlier is below 4% over the entire time range of the signal recording by receivers.

Thereby when responses from deep objects are considerably smaller than signal distortions from the near-surface heterogeneities, the reliable recovery of deep geoelectrical medium structure can be provided due to the usage of 3D-interpretation, based on high accurate 3D modeling. However it is should be considered that even in this case reducing of the electromagnetic field registration area can lead to serious mistakes in deep structure recovering of investigated zone if there are heterogeneities in near-surface section.
Fig. 1. Layout of the full geoelectric model

Fig. 2. Layout of the reduced geoelectric model with found false deep heterogeneity in the target layer
MAGNETOVARIATIONAL STUDIES IN POLAND AND THEIR TECTONIC IMPLICATIONS

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“We believe that magnetovariational sounding with its rather high sensitivity to horizontal and vertical conductivity variations and rather high immunity to near-surface galvanic distortion should be considered as an efficient tool of the modern geoelectrics.” (Berdichevsky and Dmitriev, 2008).

Magnetovariational soundings (MV) have been carried out in Poland since the sixties. They led to the discovery of two large conductivity anomalies connected with the Polish Basin (a part of the Southern Permian basin system) and with the Carpathians. Both are believed to be caused by mineralized water filling the rock’s pore space.

MV sounding results are usually presented in a form of induction arrows. However, many examples show that the horizontal magnetic tensor (HMT) is more informative and effective. Distribution of some HMT invariants directly traces the location of well-conducting structures in the crust and upper mantle. Furthermore, the inversion of the HMT is more effective and stable than the inversion of induction arrows. The only drawback of the HMT so far was the requirement of simultaneous observations at some normal reference, whereas conventional tipper data sets may be estimated from single station records. We could overcome this disadvantage by applying techniques capable to restore all magnetic field components necessary for HMT estimation from tipper data arrays alone. These techniques exploit the potential field representation of the magnetic field in a non-conducting atmosphere, and they apply spline approximation and Hilbert transform routines (Jozwiak, Nowozynski, Kovacikova, Varentsov; 2009).

For Central Europe, a large data set of induction arrows has been collected by the effort of many groups during the last fifty years. Recently we calculated the HMT on this base, and the results are very impressive. The spatial behavior of certain HMT invariants perfectly coincides with the main tectonic boundaries as a comparison with tectonic maps shows. We could identify the Carpathians, the Variscan Deformation Front, the Caledonian Deformation Front, and other smaller tectonic structures in an excellent way. These results confirm that MV soundings can be very useful to map and identify tectonic structures.

QUASI-3D INVERSION OF HORIZONTAL MAGNETOVARIATIONAL RESPONSES

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In this study we present the results of the quasi 3D inversion of the horizontal magnetovariational responses for the crustal conductance estimation within the EMTESZ-Pomerania and the KIROVOGRAD deep sounding arrays. The quasi 3D modelling is based on the approximation of the Earth’s anomalous structures by a thin horizontally inhomogeneous sheet buried at a specified depth in a generally layered Earth. The integrated conductivity (conductance) within the sheet is calculated from geomagnetic transfer functions estimated at the Earth’s surface. The unimodal case with only the account for the horizontal current components within the sheet is considered. The inversion problem is solved by minimizing the Tikhonov’s parametric functional with the weighted norm of misfit between
the observed and the model data. The minimization of the parametric functional is held by an iterative procedure using the re-weighted conjugate gradient method.

The inversion procedure was applied within two areas of interest: the EM TESZ-Pomerania array across the Trans-European Suture Zone in NW Poland and NE Germany and the northern continuation of the Kirovograd conductivity anomaly in SW Russia. Large amount of long period horizontal inter-station transfer functions (M-responses) was collected within both regions. The inversion models obtained for M-responses seem to be more noise-protected and informative than models resulting from the inversion of induction arrows.

To consider the complicated superposition of anomalies related to the surface sediments and the crustal conductors within the studied areas a unimodal thin sheet technique was extended to account for a second thin sheet with a fixed inhomogeneous conductance resulted from the short period MT data as a priori knowledge and related to the conductance of the sedimentary layer.

LONGITUDINALLY INHOMOGENEOUS STRUCTURES:
MAGNETOVARIATION AND MAGNETOTELLURIC PARAMETERS

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Over the last decades a huge number of studies are appeared in different regions of the planet. As the area experiments are laborious and expensive, so, the great numbers of the works are conducted along selected profiles which can cover a large area, crossing the different geological structures and, possibly, anomalies of electrical conductivity, which are connected with them. These observed data are often processed and interpreted in the framework of one-dimensional or two-dimensional representations, which become the basis of area construction. And a range of difficulties and problems is appeared.

Let us analyze the magnetotelluric and magnetic variation fields in highly elongated structures where the electrical resistivity varies on extending, and consider the question if it is possible to build three-dimensional models using only two-dimensional representations of profiles, which cross such a complicated structure. For calculations we use the software package of three-dimensional simulation of low-frequency electromagnetic fields, which are used in the methods of MTZ and MVP.

Let us imagine that there is an extended electrical anomaly, where the distribution of the electrical resistivity along extending of the structure is inhomogeneous. Thus, this two-dimensional structure is actually a complex three-dimensional domain in fact.

We calculated the anomalous magnetic fields and impedances in a wide range of periods for two types of structures: longitudinally-homogeneous – two-dimensional conducting ($\rho = 1, 10$ or $100$ Ohm m) and longitudinally inhomogeneous – quasi-two dimensional, with the electrical conductivity, which is varied along the extending and which is presented by alternate parallelepipeds with different resistivity ($\rho = 0.1, 1, 10, 100$ или $1000$ Ohm m). We have already looked through five types of longitudinally inhomogeneous models, which are differed according to the character of the sites distribution with high and low resistance, the upper edge of which lies in deep of 10 km.

Let us analyze the calculation of components of magnetic fields according to profiles of the cross stretch model for two polarizations: $y \times$ when the electric field is directed along the elongation of the body, and $x \times y$ when the electric field is perpendicular to the elongation of the body. Comparison of calculations carried out for $100 – 400$ periods in the maximum of the frequency characteristics area of anomalous magnetic fields.

For $|H_x|$ components in $y \times$ polarization there is a significant difference (more than 2-times in the center) between the longitudinally homogeneous and longitudinally inhomogeneous structures for all sites with $\rho = 1$ Ohm m. The maximum value corresponds to the profile, which is located near the gap structure with $\rho_n = 1000$ Ohm m.
It is interesting to note that in an area where there are no anomalies in the electrical conductivity, but which is lying between two conductors, however, there is an anomaly of the magnetic field of considerable magnitude. On the profile, which passes through the area with $\rho \approx 100$ Ohm m, magnetic field for 2D and 3D models is differed almost 10 times. If we analyze the magnitude of the anomalous field $|H_x|$ on the central profile along the elongation of the anomaly, then clearly seen sharp contrast two-dimensional and three-dimensional model.

In accordance with horizontal components of the magnetic field the similar phenomena’s are in vertical component, as follows, values $|H_z|$ along selected profiles are greatly differed for horizontally–inhomogeneous body from two-dimensional.

For polarization $E_x H_y$ (in case of longitudinal-inhomogeneous structure) the anomalies from 2 before 14% in all component of the magnetic field are appeared in a difference of 2D model.

There is manifested a significant difference between two-dimensional and quasi-two dimensional structures on the curves of MTZ. Over 25 s curves are naturally separated in directions for longitudinally homogeneous conductor in the central point of the model. For a longitudinally inhomogeneous structure, all the curves MTZ are also diverged or dispersed in directions depending on the location profile, however, the nature of a discrepancy. The curves in the xy direction for both types of structures are identically, while in the direction yx curves MTZ are differ significantly from two-dimensional.

In such longitudinally inhomogeneous structure, even the most extended, appear the effects, which do not give the possibility to use terminology, and idea of division of crooked MTZ on longitudes and transverse. The Values and nature of the connecting function and specific electric resistance sharing within the framework of 2D presentations do not correspond to reality absolutely, while geometric parameters are defined realistically.

It is possible to select the equivalent two-dimensional model, curves MTZ from which will well comply with curves for longitudes-inhomogeneous model, however, its specific electric resistance will in this case will differ from real importance for 3D 50 times.
Magnetovariation and magnetotelluric parameters.

Sectional charts \( |H_x| \) at \( x \) polarization: a – for all sites with \( \rho_a = 1 \) Ohm·m; b – in an area where there are no anomalies in electrical conductivity; c – on the central profile along the elongation of the anomaly; d – MTZ curves along the conducting structure in the central point of the profile.

In practice, we often meet the other type of extended structures, the resistance of which varies, but there is no gap conductivity. You can imagine the structure, in which the resistance increases (or decreases) across, or distributed symmetrically or randomly.

In these cases it is also fixed, but differently, essential difference of magnetic forming \( \|H_x\| \) of the anomalous field for three-dimensional of corresponding meaning of 2D models. The Anomalous magnetic fields of the two-dimensional models were calculated for resistance of each separate element of longitudes-inhomogeneous structures.

For different models and in different parts these differences are various. Such picture is explained by difference in concentrations of longitudes current depending on location of elements with different resistance, in other words, in fact it is difficult to estimate even on the qualitative level the size of anomalous resistance on basis of the two-dimensional estimation.

Let us turn to the analysis of induction parameters \( |W_{zx}| \) and \( |W_{zy}| \), which were got for models, with different levels of resistances as heterogeneous, so in the homogeneous areas of the models. In the field of inhomogeneous sharing of resistance the intensity of component anomaly \( |W_{zx}| \) decreases in contrast with two-dimensional distribution. However on the areas with \( \rho_a = \rho_n = 1000 \) Ohm·m and with \( \rho_a = 1 \) Ohm·m we can see nearly alike picture \( |W_{zx}| \) and its values is greatly lower, than in 2D variant with \( \rho_a = 1 \) Ohm·m. Anomalous values \( |W_{zx}| \) are defined by extending of inhomogeneous conductor.

Existence of component of induction parameter \( |W_{zy}| \) is connected with the borders of conducting and not conducting parts of longitudes-inhomogeneous structure. Values \( |W_{zy}| \) are
small in contrast with \(|Wzx|\) in spite of the fact that swings \(\rho_a\) are great from 1 till 1000 Ohm m. Values differentiation of the anomalous field \(|Wzx|\) depends basically on contrast of the resistances in marginal parts of the models. At the same time the appreciable values \(|Wzy|\) are appeared, which basically define the local inhomogeneous elements in the general extended structure.

So, exactly for polarization of the electric field across structure there are some effects in induction parameter, directed along longitudes-inhomogeneous model, with the help of which it is possible on the qualitative level to value existence of inhomogeneous sharing of resistance and location of areas with miscellaneous conductivity. At two-dimensional approach the construction of cuts along such longitudes-inhomogeneous structure this possibility is absent.

**Conclusions**

At the profiling variant of studies it is desirable to use 3D models or inversions for the estimation of the sharing the resistance inside longitudes-inhomogeneous conductor.

The longitude component of induction parameter of magnetovariation profiling, directed along longitudes-inhomogeneous structure, clearly in change from transverse component, points to three-dimensional distribution anomalous parts.

The MTZ curves, directed across greatly extended structures, are identical for 2D and 3D events in change from longitudes curves.

The frequency features of anomalous flap in the field of great periods are proportional to impedance of containing one-dimensional flaky ambience. It testifies about galvanic type of excitation of the anomalous field.

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**ABOUT GEOPHYSICAL CRUSTAL ANOMALIES DUE TO HYPOTHETICAL MAGNETICAL PHASE TRANSITION**

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In our earlier papers [1] we already suggested a possible additional source of geomagnetic and crustal conductivity anomalies: the so-called second-order magnetic phase transition in the Earth’s crust, namely a significant enhancement of the magnetic susceptibility near the Curie (Néel) depth. Some geomagnetic anomalies of unknown origin can be easily explained by this phenomenon. In this paper, on basis of [2], we summarize the one- and multi-dimensional magnetotelluric signatures due to a thin but very high-permeability body at mid-crustal depth. The magnitude of the anomaly due to a high-permeability layer is comparable to that due to a high-conductivity layer, with opposite sign. Wherever the classical magnetotelluric interpretation produces an unrealistic high-resistivity and extremely thick layer, and the nearby geomagnetic anomalies have a suitable spatial wavelength, the second-order magnetic phase transition might be also considered as possible explanation. Although it has been still questionable whether this phenomenon exists in the Earth’s crust, some recent solid state physics laboratory results make it more and more probable that the magnetic phase transition might be a potential source of various geophysical crustal anomalies. We think that the rock-physics laboratory experimental results (in terms sampling rate in the temperature scale, heating rate, external magnetic field, etc.) have not been yet sufficient for a full detection of this phenomenon. Acknowledgements: OTKA (Hungarian Scientific Research Fund) project number 68475.

**References**


**POSSIBILITIES OF INTERPRETATION OF MAGNETOTELLURIC DATA OBTAINED ON A SINGLE PROFILE OVER 3D STRUCTURES**

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The paper is based on idea, suggested by M.N. Berdichevsky and V.I. Dmitriev

Magnetotelluric soundings are often performed along single profile or remote profiles. In presence of 3D structures the interpretation of such data becomes complicated. We study its possibilities using synthetic data set, obtained for resistivity model, consisting of three background layers and three right-angle prisms, whose centers are situated at different distances from the observation profile.

Applying simple methods of magnetotelluric data analysis, we manage to localize positions of all three inhomogeneities with respect to the profile. Considering the results of quick smoothed-structure 1D and 2D inversions of different data components, we reveal background model, estimate depths of the anomalies and their approximate resistivities. On this basis, and also using prior geological and geophysical information, it is possible to construct 3D model in a more or less wide area around the profile, and then correct it using 3D inversion software.

**THE DEVELOPMENT OF PETER WEIDELT’S IDEAS IN THE THEORY OF INTERPRETATION OF EM DATA**

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All known approaches to the interpretation of electromagnetic anomalies include the assumption of the known geoelectrical parameters of the normal (1-D) section. From the other side the formal interpretation in the frame of 1-D model of the alternating electromagnetic data, which contain the influence of many unknown local heterogeneities leads to non forecasting results.

In the paper [1] P.Weidelt had shown that the operator of the 1-D inverse problem solution of magnetotellurics (MT) soundings is a self-adjointed operator [2], by that as input data it had be used the complex values of the impedance as a function of frequency. For the other side in the papers for example [3-4] it had been shown that in the common case the diffraction problems of 2-d or 3-d alternating electromagnetic field on the local heterogeneities is described by non self-adjointed operators. Nevertheless there are exist some 2-D and 3-D problems, which can be executed to a self-adjoned operator by using special functions, which describe the medium features and formulate the boundary conditions of the problem [addition to 4]. The spectral features of the differential operators are searched sufficiently detailed in the mathematical literature, for instance [2, 5-7]. As it leads from the theory, the spectral features of self-adjointed and non self-adjointed operators are different. Thanks of that mathematical result and the result of P.Weidelt [1] it had been achieved the regularization of the solution of the 1-D inverse problem of magnetotellurics [8-9] with use of the idea of V.N. Strachov [10], about filtration of the observed data in the area of defining of the inverse problem operator.

More over in the paper [9] it had been extended the method of P. Weidelt [1], devoted to reduction of the problem of electromagnetic soundings of 1-D medium with arbitrary source located out of the Earth to the problem with homogeneous excitation, to a case of artificial controlled dipole.
sources, located on the surface of the Earth. That was the base for a unique method of defining parameters of the normal section for data of the most types of sources used in the practice: horizontal electric dipole, vertical magnetic dipole and plane homogeneous wave.

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SOURCE-WISE APPROXIMATION IN 3D PROBLEMS OF ELECTRICAL PROSPECTING

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The difficulties of solving inverse electric prospecting problems necessitate the use of various representations of field observation results. One of the possible representations is sourcewise approximation. This approach was previously tested on one-dimensional magnetotelluric sounding and seismic prospecting problems [1], where Greene’s function of the respective equation, to which the physical field is subject, was used as the approximating function. The extension of this approach to the three-dimensional case resulted in a different set of the sourcewise approximation problem, which we shall consider on the example of a constant electrical field.

Sourcewise approximation for three-dimensional media consists in correlating the field observed with the solution of the direct task for the model of conductive half-space, with an elementary volume of excessive conductivity included in it. The volume of inclusion is defined from minimal separation of the survey system used. To take account of media anisotrophy, excessive conductivity is set using a tensor, whose elements alternately equal a unity with the rest equalling zero. This can result in a 3x3 matrix of correlation factors and a same size matrix of mean-square deviation. Based on these two quantities, we can estimate the location of heterogeneities in the lower half-space as the elementary volume moves inside the geological media volume under scrutiny, minimising the functional:
\[ \sum_{k=1}^{N} (\Delta \phi^k - k_i \frac{\Delta \phi^k}{\sum_{k=1}^{N} (\Delta \phi^k)^2})^2 = \delta^2_{ij} \]

where \( \Delta \phi^k \) – abnormal difference of potentials in experimental data, \( \Delta \phi^k \) – abnormal difference of potentials in the solution of the direct task, \( N \)– number of measurements, \( i, j = 1,3 \). Therefore, the \( k_{ij} \) correlation factor matrix and the \( \delta_{ij} \) mean-square deviation matrix are functions of the spatial coordinates of the elementary volume location. The criterion of the presence of a heterogeneity is the correlation factor being non-zero or different from some small value.

This approach is similar to the wavelet analysis of electric prospecting data [2].

Thus, sourcewise approximation makes it possible to define the initial approach to the solution of an ill-posed inverse problem for direct current electric prospecting and to reduce the dimension of solving the direct problem.

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NUMERICAL-ANALYTICAL APPROACH TO SOLVE 3D GEOELECTRIC INVERSE PROBLEMS

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The approach to solving 3D inverse problem when values of EM field transformed on frequency range are known on some set of points of the terrestrial surface is considered. The inverse problem consists in construction of conductivity distribution model in some 3D domain for which the part of its surface coincides with a site of known field values. The domain is divided on homogeneous elements – rectangular parallelepipeds. Thus, 3D medium is approximated by the plainly-layered model in which all layers are divided into elements with different parameters. The numerical solution of Maxwell’s equations system at harmonic dependence on time is reduced to solving Helmholtz’s homogeneous equation. By Trefftz’s method, the solution in each element is represented in the form of a linear combination of partial solutions of Helmholtz’s equation, and corresponding coefficients are calculated from conjunction conditions on adjacent elements boundaries. The numerical-analytical form of representation of the solution allows finding both the direct problem solution and inverse one. For this purpose, the functional as difference estimation (on the top side of each element and for some set of frequencies) between the corresponding function defined by parameters of underlying layers and one defined by field values on the terrestrial surface is constructed. Solving inverse problem consists in minimization of this functional on set of model parameters for all elements. The method of Hook and Jeeves with the one-dimensional minimization is used.

The presented approach of solving the inverse problem allows reducing calculations to sequence of solutions of some 2D direct problems for layers and 1D optimizations. For solving the linear systems arising at realization of the given solution technique of the inverse problem, the modified iterative method of Kachmaz with the preliminary preconditioning procedure by means of cyclic balancing process is used. These researches were supported in frames of the joint Project 13 of Russian Academy of Sciences and the Academy of Finland and by RFBR grant 09-05-00466-.
INDUCTION IMPEDANCES:
NEW APPROACHES AND THEIR MODELING

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The problem of impedance description of electromagnetic fields on the boundary between dielectric and conductive media has a long history. This heuristic idea has a constructive character and its evolution continues for the deep soundings of our planet up to now. Mark Berdichevsky and Peter Weidelt, as well as Ulrich Schmucker, have taken part in this discussion. The difficulties of solving the problem consist in combination of the quite different media: the ionosphere and lithosphere are ohmic domains, while the direct relations between the electric fields and currents are absent in the magnetosphere. Besides the lithosphere and the Earth’s mantle, the objects of our investigations are usually inhomogeneous. No wonder that the results of the discussion are not always unambiguous: impedances in general can depend on particular sounding methods, the exciting fields, the properties of the conductive medium, as well as on the adopted model of the space: plane or spherical (the latter aspect is important while considering the way in which the induced currents lock).

To learn the features of impedances, for instance their combination, the authors considered several approaches including different kinds of impedances, a comparison of which is illustrated in accordance with recently published papers (e.g., Dmitriev & Berdichevsky, 2002; Shuman & Kulik, 2002; Schmucker, 2003, 2008; Semenov at al., 2007; Shuman, 2007; Guglielmi, 2009; Semenov & Shuman, 2010; Vozar & Semenov, 2010).

2D INVERSION OF THE IMPEDANCE TENSOR DETERMINANT WITH DAMPED LEAST SQUARES SOLUTION BY SINGULAR VALUE DECOMPOSITION

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Two-dimensional modelling and inversion is widely used and could provide a good approximation over 3D geometries. There are many algorithms to solve 2D MT inversion problem. All of them generally based on regularization method: some parametric functional have to be constructed and minimized, to find the most appropriate solution with the best fit to experimental data. In this work we consider damped least square solution obtained via singular value decomposition. We invert the determinant of the impedance tensor. One of the advantages of the determinant is that its phase is free of galvanic distortion. Also being invariant it does not require the impedance tensor decomposition.

Three synthetic data sets are presented: model 1 is a simple cube over conductive basement, model 2 and 3 – COPROD2S2S and COPROD2S1, respectively, obtained from Varenstsov I.M. In the damped least-squares solution (DLS) the selection of the regularization parameter is very important. The convergence of the algorithm is strongly dependent on the selection of regularization parameter, which is kept constant during iterations.

The DLS was also compared to the results obtained with REBOOC. Synthetic data for complex models (COPROD2S2S and COPROD2S1) show some advantages of DLS. For example, shallow part of the model 2S2S was better resolved compared to REBOOC including the first layer and the system of conductive blocks. However, deeper part and the top of basement was more distorted. The results of application of the algorithm to the real data are presented as well.
Session 3: Marine EM studies

DEVELOPMENT AND APPLICATION
OF MARINE ELECTROMAGNETICS AT IFM-GEOMAR, GERMANY

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Over the last 4 years, the newly established German marine EM group at IFM-GEOMAR has developed diverse marine magnetotelluric (MT) and controlled source electromagnetic (CSEM) instruments. We are now able to image resistivity variations on a variety of depth scale ranging from tens of meters to a 100 km. The instruments have been used to study a mixture of geoscientific problems which are associated with resistivity variations. On the shallow depth scale we will present an ongoing research project in imaging fluid and gas venting on mud volcanoes for which we developed a 3D CSEM tomography instrumentation based on stationary receivers and a moving source. Based on the CSEM measurements we are working on discriminating active fluid flow areas which are associated with low salinity pore fluids from inactive regions, which are usually associated with saline pore fluids. On the medium depth scale we will present a study on the use of magnetotellurics to image potentially oil bearing sediments underneath a basalt layer. The basalt layer is shielding seismic energy rendering conventional industry type seismic surveys ineffectual and thereby opening the door for the industrial application of MT in the hydro carbon industry. The key to success here is the integration of MT with other geophysical measurement such as seismic refraction and gravity data. We will furthermore present a deep scale study down to mantle depths based on an amphibious MT study on the Costa Rican subduction zone, which was done in cooperation with the H. Brasse of the FU Berlin. Based on a 350 km long profile, we were able to image the entire hydration and dehydration cycle in the subduction cycle. Next to presenting ongoing research we will also discuss future technological application and challenges in marine EM.

MARINE CSEM FOR SUBMARINE GAS HYDRATE EXPLORATION

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Marine controlled source electromagnetic (CSEM) has become a valuable tool for the detection of offshore hydrocarbon deposits. Natural occurring hydrocarbons, e.g. oil, free gas, and gas hydrate increase the sediment bulk resistivity as they replace otherwise conductive pore fluids, typically seawater, during formation.

Submarine gas hydrates are abundant along continental margin and are recognized as a possible future energy resource, as well as a geo hazard with the potential to contribute to global warming. Estimates of the global gas hydrate budget differ considerably, but are believed to be in the order of natural gas and coal worldwide. However, there is a need to improve the capacity to detect and accurately quantify areas where gas hydrate and free gas is present in seafloor sediments.

CSEM is a promising tool, but has been so far rarely used to identify submarine gas hydrate reservoirs. A towed inline electric dipole-dipole system is used to reveal the electrical resistivity structure of a gas hydrate deposit. The electrical resistivity of marine sediments is controlled by the porosity and the distribution of the pore fluid, i.e. conductive seawater. Where gas hydrate forms in sufficient quantities the conductive pore fluid is replaced by non-conductive hydrate. As a consequence, the electrical resistivity measured over a gas hydrate layer is elevated.

The system has been used to collect CSEM data at cold vents in Cascadia, offshore Vancouver Island, Canada, and over methane seeps on the Hikurangi Margin, off the east coast of
New Zealand’s, North Island. In both study areas, the vents correlate with highly anomalous resistivities which point at concentrated gas hydrate layers at depth below. Instrumentation, data analysis and interpretation of these two case studies will be discussed. Present work of the marine EM team at BGR is focussed on CSEM instrument developments and data analysis to integrate marine CSEM in multidisciplinary studies and international programs and provide relevant key parameters for more accurate gas hydrate quantification.

EXPLAINING EXOTIC TRANSFER FUNCTIONS
AT THE SOUTH AND CENTRAL AMERICAN MARGINS

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In the recent past, many unexpected magnetotelluric transfer functions have been determined at various locations along the South American (Chile/Bolivia) and Central American (Costa Rica/Nicaragua) continental margins. At first glance they show exotic characteristics and can’t be interpreted by two-dimensional conductivity models in a simple manner.

1) On the continental slope offshore Costa Rica, where ocean-bottom instruments were deployed by IFM-Geomar (Kiel), apparent resistivities, phases and tippers seem to violate the Kramers-Kronig causality relations. This effect is, however, easily explainable with simple 2-D models, employing a highly-anomalous current concentration in the ocean above the instruments.

2) On the Bolivian Altiplano, several sites display phases which vary smoothly from -135° to +45°, while apparent resistivities remain normal and obviously unaffected. Very simple 3-D models can explain this behavior, employing a resistive mountain range extending into a highly-conductive sedimentary basin.

3) At several locations along the Chilean margin, induction vectors are systematically deflected from the expected direction perpendicular to the trench – in the Central Andes they point even parallel to the coastline. Here we employ 2-D anisotropic models with electrical preference directions which fit well to an ensemble of large faults and the direction of the regional stress field.

Attempts will be presented to include these structures into already existing conductivity models at both subduction zones.

EFFECTS OF OCEAN MOVEMENT
ON MARINE ELECTROMAGNETIC DATA

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The noise level in controlled-source marine electromagnetic measurements is usually small compared to land measurements, because the conductive ocean efficiently attenuates any energy from sources above sea level. However, for the detection of hydrocarbons, extremely low noise levels are necessary, because the signal may be very weak, depending on depth and size of the reservoir. Therefore, sources of noise that can be neglected for the detection of large reservoirs, have to be considered when trying to detect smaller or deeper reservoirs. Here, we study the noise generated of ocean movement, such as surface waves or channel sterams.

Conducting water particles moving in earth’s magnetic field experience a Lorentz force, resulting in a current density which acts as a source of secondary electromagnetic fields. We
formulate the problem by decomposing Maxwell’s equations into two independent modes. The tangential magnetic (TM) mode is generated by purely horizontal water flow in one direction, characterised by a wavelength and a frequency. The magnetic field is parallel to the direction of flow. The tangential electric (TE) mode is generated by water flow in a vertical plane. This mode is used to describe oceanic surface waves, where frequency and wavelength are related by a dispersion relation. In this case, the electric field is purely horizontal. The Our simulations for typical settings indicate that for practical cases at greater transmitter-receiver (T-R) separations, the motionally induced electric and magnetic field contribution is relevant for reservoir detection.

We also analyse measured marine CSEM data from different locations with respect to the existence of motion-induced noise. In addition to the noise types described above, we were able to identify natural noise and frequencies typical of different phenomena called microseism and swell.

THE IMPEDANCE METHOD IN THE REMOTE SOUNDING PROBLEMS

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The use of powerful artificial sources of the electromagnetic waves is a new trend in the geophysics. Exploration of possibility of a sea-shelf sounding by powerful source located at the terrain is one of the problems within this trend.

The main challenge of modeling of such sounding is the calculation of background field at the sounding area, which reflects the coast effect and the complex pattern of currents spreading on the terrain near the source. Our research is devoted to the exploration of possibility of using the impedance method of data interpretation for such sounding. The guess of such possibility is based at the M.N. Berdichevsky and V.I. Dmitriev results about slowly varying waves and the asymptotic of the fields of the artificial source in normal section.

The base model is cylindrical island, with vertical magnetic dipole placed at the center of the ground as source. The main computational challenge for such model is computing of the double improper integrals, that includes the multiplications of Bessel functions of the large arguments. Special computational methods based on the reduction of this problem to Hankel transform of slowly varying function were developed. It is shown that impedance method of the interpretation can be applied at distances greater than 1.5 wavelengths in the sediments from the source for seabed measuring. The electromagnetic fields at such distances are large enough to be measured with modern equipment due to the island effect.

DEVELOPMENT OF DIRECT ELECTROMAGNETIC METHODS TO SEARCH FOR HYDROCARBONS IN THE SEA

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The method of deep electromagnetic sounding with a controlled ELF-source is a promising direction in modern geophysics. The purpose of this study is to find a low-frequency
electromagnetic method for the detection of hydrocarbons in the prospective anticline structures. Well-known Shtokman gas-condensate reservoir in the Barents Sea was taken as an example. The problem was solved using three-dimensional mathematical modeling employing the method of integral equations. All components of the electromagnetic field induced by an artificial source (electrical bipole) at different frequencies in the range of 0.01 – 10 Hz were calculated for various models of gas-bearing reservoir, including the lack of gas condensate at the points located at the bottom of the sea at the area of the anticline.

Shtokman reservoir consists of several deposits of varying gas-saturation, located at different depths.

The most effective source is the horizontal electrical bipole oriented to the deposit and placed at the sea-bed. The most effective measuring for such source is the measuring of the vertical electrical component. But each of the possible polarizations of the source (except vertical) and each of the measured components (except the vertical magnetic) produce particularly effective combinations. This allows creating systematic redundancy, which is necessary for the responsible withdrawal of productive structure. The radial polarization is preferable under constraints associated with carrying out the field measurements. The most informative component is the vertical one, which is the most exotic in the modern practice of the sounding.

Computer experiment showed that the combination of two deposits induces a field virtually indistinguishable from field induced only by the lower reservoir in case of large horizontal extent of the latter.

PERSPECTIVES OF THE MAGNETOTELLURIC SOUNING IN THE ARCTIC OCEAN

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The Arctic Ocean has a complex geological structure including formations of different genesis. The main purpose of this work was to study the possibilities of the magnetotelluric sounding (MTS) to identify the type of crust underneath these structures. To solve the problem three-dimensional mathematical modeling was carried out using the method of integral equations.

Apparent resistivities and impedance phases were calculated at different periods from 10 seconds to 24 hours for two variants: surface (on ice) and ocean bottom measurements. The following models were used: simple horst and trough located in a sedimental layer on typical oceanic or continental crust, and then of real large-scale structures of the ocean – the Gakkel ridge (mid-ocean ridge lying on typical oceanic crust) and the Alpha-Mendeleyev ridge (supposing it is lying on continental crust). The main difference between the types of crust for our purposes was the depth of the conductive base in the geoelectric model: 50 km for the crust of oceanic type and 400 km for the typical continental crust.

It is shown, that, despite of much lower resolution of the magnetotelluric sounding from the surface of ice in comparison with ocean bottom MTS, the type of crust is reliably defined. Resolution of the MTS from surface of ice is a little bit higher above oceanic crust, but for the problem of mapping the structures we shall fruitfully apply only the ocean bottom MTS. As it is shown by the results of modeling on the Gakkel and Alpha-Mendeleyev ridges, bottom amplitude and phase curves of MTS adequately reflect the geoelectric structure of crust and mantle in the range of depths 10 – 400 km.
EFFECTS OF SMALL SCALE FORMS OF OCEAN FLOOR ON EM RESPONSES IN APPLICATION TO MV STUDIES IN THE ARCTIC OCEAN

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We investigated induction interaction of various structures of ocean floor relief on the base of the two-dimensional electromagnetic modeling. We considered both the fault zone consisted of a single fault or a group of fault and symbiosis of positive structures of a small scale.

We found out that the anomalies of such structures were summarized so that the form of the result MT curve did not depend on the number of such structures. At the same time the total effect of small size structures is important and they must be considered for numerical modeling of large scale structures.

We performed the numerical modeling of coast effect taking into account the small scale structures of ocean floor in the neighboring zone of coast. We considered two types of such structures within the neighboring zone of sea coast 1) local heights; 2) faults. The results of numerical modeling demonstrated the considerable changes of the form of normal coastal MT curve.

Thus, the induction interaction between small scale and large scale structures of ocean floor relief may in practice play a significant role in large areas.

We made calculations using the two-dimensional electromagnetic forward modeling for periods within the limits of 1 to 24 ours. Our research was performed in application to the magnetovariation profiling in the Arctic Ocean.
Session 4: Deep EM studies

ELECTRICAL CONDUCTIVITY OF THE UPPER MANTLE
BENEATH FENNOSCANDIA

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Deep EM studies along with seismic tomography are effective methods for probing the structure of the upper mantle. Seismic and conductivity models considerably complement each other, because electrical conductivity and elastic properties are governed by different physical laws.

The main objective of our research is study of deep structure of Precambrian cratons by the example of northern part of east European Craton (EEC) aimed for better understanding of geological, geodynamic and geochemical processes taking place of the Ar-Pt boundary and following geological epochs. These studies were initiated more that 30 years ago by Mark Berdichevsky, Leonid Vanyan and Sven-Eric Hjelt. During last years in the north-western part of EEC mainly on the territory of Finland, Sweden, Norway and Poland a large amount of EM observations were carried out. The results of these studies enable significant progress in understanding the upper mantle structure of the region.

One of the main critical results was the confirmation of the hypothesis for heterogeneous structure not only the Earth’s crust but upper mantle as well, which was considered before rather homogeneous in the sense of electrical conductivity.

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ELECTROMAGNETIC DATA ON THE NATURE
OF SEISMIC WAVEGUIDES AND DESTRUCTION ZONES
IN THE CONTINENTAL LITHOSPHERE

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The deep seismic studies revealed several low velocity layers (waveguides) in the cratonic lithosphere. The nature of these waveguides is difficult to explain without additional independent information. The electromagnetic data proved such information. A combined analysis of seismic and electromagnetic data makes their physical and geological interpretation more reliable. The seismic wave velocity is mostly controlled by the rock composition and their mechanical properties (pores and fractures). The electrical conductivity of the fluid-bearing rocks is independent of the solid phase composition and is determined by the fluid content and its salinity. The most effective results of the combined seismic and electro-magnetic studies are obtained at the determination of origin of the low velocity layers (waveguides) in the lithosphere and at the investigation of the fracture zone nature.

The crustal waveguides. In many regions of the world: in the Baltic, Ukrainian and Canadian shields, in the Russian and American ancient platforms and in the young plates the low velocity layers were determined in the middle crust at a depth of 10-20 km [Grad and Luosto, 1987, Aichruth 1992, Pavlenkova, 1994 and others]. Very often these layers are characterised by the lower electrical resistivity [Berdichevsky et al., 1984; Hughes et al., 1992; Jones, 1992; Kovtun et al., 1994 and others]. The depth and the thickness of this crustal conductive layers correlate well with the parameters of the low P-velocity layers.
The most detailed studies of this crustal waveguide nature were made in the Baltic Shield where the combined seismic and electromagnetic data were compared with the supper deep Kola borehole data. In Fig. 1 the velocity and the resistivity cross-sections of the crust are shown for the profile POLAR in the northern part of Finland. They are the most detailed cross-sections of the crust near the Kola borehole. The seismic studies reveal the low velocity layer at a depth of 10-20 km and electromagnetic data show that this waveguide is a high conductivity layer at which two listric form faults flatted out. These data mean that the crustal low velocity layer is a zone of fluids concentration. This effect is supported by data from the Kola overdeep borehole. Here, a 0.2-0.3 km/s decrease in seismic velocities, discovered in a homogeneous sequence at a 4.5 km depth, correlates with decrease in the bound water concentration and an increase in the amount of free water. The local velocity-inversion zone at depth of 7 to 9 km is associated with increase in porosity and water inflow [Ganchin et al., 1998; Vannjan and Pavlenkova, 2002].

The geophysical studies in the other regions of the world, show that this crustal low velocity and high electrical conductivity layer has a global significance. Some specific structural features are typical of the layers. In the platform crust this seismo-electrical layers are characterised by the changes of the reflectivity pattern and of earthquake number. The change of velocity pattern where the block structure is transformed into a subhorizontal layering and the local isostatic equilibrium
are typical at the layers. These structural features suggest that these layers separate brittle and weak parts of the crust. Usually they play the role of detachment zones at crustal block moving.

Dehydration is one of the possible factors favouring the formation of lower velocity and higher electrical conductivity zones in the middle crust. It seems, however, the most reasonable to explain the properties of the seismo-electrical crustal layer in terms of the theory of dilatancy cracking of the crust described in the papers [Nikolaevsky, 1985]. The theory suggested the weak zones at the base of the upper crust to be develop due to rock fracture and dilatancy effect. In the upper crust the normal vertical faults are formed as a result of horizontal displacement stresses; tilted shear faults are located below, and at a depth of 7-10 km they degenerate into completely sheared rocks. Development of extremely fine cracking at depth of more than 10 km results in the saturation of rocks by fluids, the appearance of low-velocity and high-conductivity layers and corresponding increase of their plasticity.

According to geological data, the weakened layers can be associated with zones of relative horizontal motions of the upper versus lower crust (detachment zones). These are zones of fractured rocks similar to subhorizontal faults.

*The waveguide in the cratonic upper mantle.* Several long-range seismic profiles with large chemical and Peaceful Nuclear Explosions (PNE) were carried out in Russia. They show that structural peculiarities of the upper mantle are difficult to describe in the classical lithosphere-asthenosphere system. The asthenosphere can not be traced as a low velocity layer, on the contrary such layers are revealed inside lithosphere [Pavlenkova G. and Pavlenkova N., 2006]. The regular change of horizontal inhomogeneity determine three layers of different plasticity which are divided by thin weak zones (seismic boundaries N and L) at a depth of about 100 and 200 km. The boundaries are not simple discontinuities, they are heterogeneous (thin layering) weak zones. Beneath the N boundary the block structure typical for the upper part of the lithosphere disappears and low velocity layers are often observed. Thus, the N boundary is considered to be the mechanical lithosphere bottom. At L boundary the Q factor decreases and upper mantle structure is changed showing the isostatic equilibrium at this bottom of the ‘thermal lithosphere’. The deep earthquakes and deep xenoliths are also concentrated around the depths of 100 and 200 km.

The deep seismic studies show, that this velocity inversion zone and the N boundary are observed in many other regions [Thybo, 2006] and in the oceans as well [Pavlenkova et al., 1993]. They are located inside the thermal lithosphere beneath old platforms (the East-European, Siberian, North-American) and at the bottom of the lithosphere in the active tectonic areas (West Europe) and in the oceans (the Angola-Brazil Geotraverse).

The nature of the lithosphere low velocity layers is well understood. In the cratonic area at depth of 100 km they cannot be a result of partly melting. The most realistic explanation of all these data is a concentration of mantle fluids at this critical depth. The fluids change mechanical properties of the matter; they initiate the partly melting at the low temperature. The matter flow along the weak zones results in the origin of the corresponding seismic boundaries. This interpretation is based on the electromagnetic data (Fig. 2). The velocity inversions at a depth of 100 km are often characterised by higher electrical conductivity [Kovtun, 1994; Jones, 1992; Zhamaletdinov, 2006] and may be they are the result of fluids concentration.

*The fracture zones.* The combined seismic and electromagnetic studies give also the important results at the studies of fracture zones. The reflection seismic data trace the vertical and inclined faults in the crust and determine their form and inneren structure. That is important information on the tectonic development of different regions. The crustal faults become also of grate interest in the prospecting geophysics: it was shown that large mineral deposits are located in the region where the deep faults reach the surface. It may be explained by deep fluids flows along the faults which bring mineral components into the crust. The electro-magnetic studies help to determine such active faults [Salnikov, 2007].

An example of fluids rich faults determined as high conductivity zone is shown in Fig. 1. It is Lapland-Cola orogenic belt where several mineral deposits are located. Major thrust belt raises possibility of foreland basin type deposits – topographically driven fluids thrust zone. A
broad correlation of mineralized domains and position of large scale features deformation events drive orogenic fluid flow. These shear zones may have conducted fluids from deeper levels to the shallow ones.

Fig. 2. Generalized geophysical models of the cratonic lithosphere: (a) seismic velocity model of the Siberian Craton [Pavlenkova N. and Pavlenkova G., 2006], (b) the electrical resistivity model of the North-western Canadian Shield (Jones at al., 1992) and (c) of the Fennoscandian Shield (Zhamaletdinov, 2006).

Thus, the low velocity and high conductivity layers should play an important role at any tectonic processes. Together with deep faults they form a channel system for the mantle fluids flow. The fluids provoke the matter melting in asthenolites and the plume tectonics. The weak zones and the plastic flows at their levels help the lithosphere blocks to move at the local plate tectonics.

References
LARGE-SCALE THREE-DIMENSIONAL INVERSION OF EARTHSCOPE MT DATA FROM THE NORTHWESTERN UNITED STATES

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We apply 3D inversion to magnetotelluric (MT) data collected in the northwestern United States as a part of the EarthScope project. By the end of 2009, MT data had been collected from 262 stations located throughout Oregon, Washington, Idaho, Montana and Wyoming. We used data from 139 MT stations in this analysis. We have developed a fully parallelized rigorous 3D MT inversion code based on the integral equation method. We also implemented a receiver footprint approach which considerably reduces the computational resources needed to invert large volumes of data covering vast areas. The inversion domain was divided into 2.7 million cells. The inverted electrical conductivity agrees reasonably well with known geological features of the region.

Introduction

_EarthScope_ is the United States’ National Science Foundation-funded Earth Science Program to explore the structure and evolution of the North American continent and understand processes controlling earthquakes and volcanoes. A major part of the _EarthScope_ project is the _USArray_ program which consists of seismic and MT stations being deployed across the entire continental United States over the next decade. _EMScope_, the MT component of _USArray_, comprises short-period investigations at hundreds of sites in the continental United States. By the end of 2009, MT data had been collected from 262 stations located throughout Oregon, Washington, Idaho, Montana and Wyoming; 139 of which were used in this analysis (Figure 1).

During recent years, significant improvements have been made in both MT data acquisition systems and the quality of processing and analysis of MT data. However, development of 3D inversion methods still represents a very challenging numerical and practical problem; the reasons for which are threefold. Firstly, continental-scale MT surveys contain large volumes of data that need to be processed to remove static shifts. Secondly, 3D modeling of these surveys requires extra attention and detail to model accuracy. Thirdly, the inversion of MT data is unstable and non-unique; one should use regularization methods and physical constraints to obtain stable and geologically meaningful solutions for the MT inverse problem. It follows that MT inversion is a computationally and memory intensive problem to solve.
We present the results of the 3D inversion of principal MT impedances from 139 MT stations collected at 28 frequencies ranging from 0.00006 to 0.3 Hz. As the forward modeling engine, we use the integral equation (IE) method. We use the quasi-Born (QB) approximation for Fréchet derivative calculations. To reduce memory requirements, we have introduced the concept of a receiver footprint for truncating the sensitivities that need to be computed and stored. As a result, our IE-based inversion method requires just one forward model at each iteration step, which results in a relatively fast, memory efficient though rigorous inversion method.

3D inversion of MT data

Electromagnetic fields can be separated into the sum of their background \( (b) \) and anomalous \( (a) \) parts (Berdichevsky and Zhdanov, 1984). The integral equation (IE) method is based on the reduction of Maxwell's equations to a system of integral equations with respect to the anomalous electric field within an inhomogeneous domain embedded in a conductive host (Weidelt, 1975; Hohmann, 1975):

\[
\begin{align*}
E(r') &= E^b(r') + \int G_e(r',r) \Delta \sigma(r) E(r) \, dv, \\
H(r') &= H^b(r') + \int G_H(r',r) \Delta \sigma(r) E(r) \, dv,
\end{align*}
\]

where \( G_e(r',r) \) and \( G_H(r',r) \) are electric and magnetic Green's tensors for the background resistivity model. We obtain fast and accurate solutions to equations (1) and (2) by using a contraction form of these integral equations which exploits the Toeplitz structure of the large, dense system matrices in order to solve multiple right-hand side source vectors using an iterative method with fast matrix-vector multiplications provided by a 2D FFT convolution (Hursán and Zhdanov, 2002).

The interpretation of MT data is based on the calculation of the transfer functions between the horizontal components of the electric and magnetic fields, which form the magnetotelluric impedance tensor (Berdichevsky and Dmitriev, 2002, 2008):

\[
Z = \begin{bmatrix}
Z_{xx} & Z_{xy} \\
Z_{yx} & Z_{yy}
\end{bmatrix}.
\]

MT inversion is ill-posed, i.e., the solution can be nonunique and unstable. Unique and stable solutions may be obtained by regularization (Tikhonov and Arsenin, 1977, Zhdanov, 2002); in particular by minimization of the Tikhonov parametric functional:

\[
P(m) = \phi(m) + \alpha s(m) \rightarrow \min,
\]
where $\mathbf{m}$ is the vector of model resistivities, $\phi(\mathbf{m})$ is the misfit functional between observed and predicted data, $s(\mathbf{m})$ is a stabilizing functional, and $\alpha$ is a regularization parameter. The minimization problem (4) can be solved using any gradient-type technique. We use the re-weighted regularized conjugate gradient method (Zhdanov, 2002, 2009). The distinguishing feature of our implementation is the inclusion of the special stabilization functionals which allow construction of models with both smooth and sharp 3D resistivity distributions. It has been shown that the use of focusing stabilizers recovers more geologically realistic resistivity distributions (Zhdanov et al., 2010). In order to apply a gradient-type minimization technique, one need to be able to compute the Fréchet derivative of the impedances relative to the anomalous conductivity. The partial derivatives of the impedances with respect to the field components are analytic. The Fréchet derivatives of the field components themselves are computed using the quasi-Born expressions:

$$
F_{E,H}(r',r) = \int_v G_{E,H}(r',r)E(r)dv,
$$

where $\mathbf{E}$ is the domain electric fields are computed using the IE method at each iteration for the current conductivity model. These fields need to be evaluated anyway so as to compute the predicted data. Therefore, no extra computation is required to find the background field for the Fréchet derivative calculation.

The Fréchet derivative is the most expensive item in the inversion not only in terms of the computation time, but also in computer memory required for its storage. The number of entries in the Fréchet derivative matrix is equal to the number of data points times the number of cells in the inversion domain. With large volumes of data and large inversion domains, the computer memory requirements may become prohibitive. To reduce the storage requirements, we introduce the footprint approach in our MT inversion. This means for a given receiver, we compute and store the Fréchet derivative of those inversion cells within a predetermined horizontal distance from the receiver. Figure 2 shows a plan view of the MT station locations with the receiver footprints. The footprint area for every receiver is shown by a semitransparent red circle. The radius of the footprint was selected based on the rate of the corresponding Green's tensor attenuation. The bright red color shows the area of the overlap of the footprints for several closely located MT stations. The computer memory requirements are reduced dramatically by using this approach. In effect, we are neglecting irrelevant sensitivities from the inversion. Note that the entire domain of inversion is accounted for in the predicted data computations, thus maintaining model accuracy.

Fig. 2. Plan view of MT station locations with examples of their corresponding receiver footprints. The stars show the positions of the stations. As an example, the footprint boundaries for several MT stations are shown by the black circles. The bright red color shows the area of overlap of the footprints for several closely located MT stations. One can see that in this case we have a complete continuous coverage of the entire area of observation with the overlapping footprints.
Inversion of the EarthScope MT data

After completing a static shift correction, we applied our 3D IE based inversion to the $Z_{xy}$ and $Z_{yx}$ data from all 139 receivers at 12 frequencies distributed logarithmically between 0.05 and 0.0002 Hz. The inversion domain is spanned in the X and Y directions from -150 to 1050 km, and from 4600 to 5500 km, respectively. The inversion domain extended to depths of 700 km. We used a model discretization of 5 km by 5 km horizontal size, and with vertical cell sizes ranging from 0.5 km near the surface and increasing logarithmically to 50 km at the bottom. The total number of cells in the inversion domain was around 2,764,800. The initial model was selected as an 80 Ohm m half-space. Inversion was run for 28 iterations, and the normalized misfit decreased from 27 to 8%.

Figure 3 shows a 3D geoelectrical model obtained by the inversion of the EarthScope MT data. The geoelectrical model of the northwestern U.S. deep interior produced by 3D inversion indicates several electrical conductivity anomalies in the lithosphere including a linear zone marked by low-to-high conductivity transition along the Klamath Blue Mountain Lineament associated with a linear trend of gravity minima. High electrical conductivity values occur in the upper crust under the accreted terrains in the Blue Mountains region. We attribute the most visible conductive anomaly at depths to the conductive asthenosphere. We note that our inverse model correlates well with the published Patro and Egbert (2008) results obtained for EarthScope data collected in the state of Oregon only.

![Fig. 3. 3D view of the resistivity model obtained from the inversion of EarthScope MT data with a conductive asthenosphere shown.](image)

Conclusions

We have applied a 3D MT inversion algorithm to the MT data from 139 northwestern U.S. MT stations available through the EarthScope project. The observed data were corrected for static shift. Our study demonstrates that inversion based on the integral equation method can be successfully applied to real data sets on a regional scale with large data volumes. The geoelectrical model obtained as a result of this inversion correlates reasonably well with the available seismic information.

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XENOLITH CONSTRAINTS ON CONDUCTIVITY OF THE TARIM – TIEN SHAN JUNCTION ZONE

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The present work deals with the petrological interpretation of the MT inversion data on the base of chemical analysis and laboratory measurements of electrical conductivity of xenoliths collected from the basaltic outcrops in the South Tien Shan. Tien Shan mountains have been formed due to the indentation of Indian subcontinent into the Eurasian plate which started for about 58–56 Ma ago. The knowledge of a xenolith geotherm of the region is essential for reconstructions of the former and present day temperature field and conductivity behaviour beneath the active orogenic belt of Tien Shan.

**Geology.** The Kyrgyz Tien Shan mountains are located between the structures of the Tarim Plate (on the South), and the Kazakh Platform (on the North). The geodynamic history of the Tien Shan formation may be divided in four main periods (Fig. 1). During the first period, corresponding C1-2 (350–320 Ma), there were closing of Turkestan basin and formation eclogite in subduction zones (Burtman, 2009). In C2-P1 (320–250 Ma) there was a collision of Alai-Tarim and Kyrgyz microcontinent. The next stage K-Pg (~70 Ma) is characterized by a plume activity and basalt volcanism (Simonov et al, 2008a, b). From 35 Ma to present the geologic structure and geodynamics of the Tien Shan Ranges were greatly influenced by the crustal shortening and underthrust faulting processes. The late Cenozoic tectonic activity was a result of the ongoing indentation of the Indian subcontinent into the Eurasian plate which has been started about 55-56 Ma ago (Molnar and Tapponnier, 1975). The lithosphere structure beneath Tien Shan has been addressed recently in the magnetotelluric study along 76°E profile 450 km long across Tien Shan. The results of the MT-sounding inversion are shown in Fig. 3, (Bielinski et al., 2003).

**Basalt outcrops.** Meso-Cenozoic basaltoids with xenoliths occur as dikes and necks among the Paleozoic Tien Shan complexes. In the southern Tien Shan, in Tuoyun basin, China and in Fergana
valley the basaltic flows and sills occur among Cretaceous-Paleogene marine deposits (Sobel and Arnaud, 2000). Recent 40Ar/39Ar dating (Simonov et al., 2008a, b) has shown that the Tien Shan basalts formed at about 60–76 Ma ago, before the intracontinental compression in the region. Meso-Cenozoic effusive bodies are mainly composed of olivine and plagioclase basalts. The trace – and rare-earth-element compositions of rocks show that the most of the studied basaltic series in the Tien Shan have been formed in within-plate magmatic systems related to mantle plume sources (Simonov et al., 2008a). Peridotite xenoliths were found in basalts from the Bailamlat, Kastek, Tuoyun, and Uchkuduk sites (Sobel and Arnaud, 2000). The Ortosuu basalt site with xenoliths is located on the right bank of the Ortosuu River, in the southern part of the Ak-Say area in Kyrgyzstan. Basalts intruded the early deposited carboniferous limestones and shales, and occur as a pipe with 30 m in diameter. The Ortosuu basalts are fine-grained rocks with olivine and clinopyroxene phenocrysts and plagioclase microcrystallite. Besides peridotite xenoliths clinopyroxene megacrysts, pyroxenite and granulite xenoliths are observed in Ortosuu basalts. The age of the Ortosuu basalts is estimated by comparison the age of with nearby Tuoyun, Terek, Tekelik sites which characterized by a similar type of basaltic volcanism. 40Ar/39Ar measurements provide the age about 71–76 Ma of these basalts. Thus, Ortosuu basalts age are probably about 70–75 Ma old.

Fig. 1. Scheme of magnetotelluric profile of 76° meridian across Tien Shan ridges with basalts outcrops and eclogite sampling points (left panel), and geodynamic history of investigated Tarim-Tien Shane junction zone, showed as dashed rectangular, (right panel). Modified after Burtman, 2009.

Geothermometry, geobarometry and heat flow data. The Ca-in and two pyroxene geothermometers (Wells, 1977, Brey and Köhler, 1990) were used to estimate equilibration temperatures of the Ortosuu xenoliths. The equilibration temperatures obtained from the spinel lherzolites range from 1015 to 1070°C for the type 1 and from 860 to 910 for the type 2 lherzolites. The equilibration pressures calculated from the Cpx geobarometer of Nimis (1999) are in the range from 1.4 to 1.7 GPa for the type 1 and within 0.9–1.2 GPa for the type 2 lherzolites. Based on the calculated P-T conditions, the conclusion has been drawn that the type 1 spinel lherzolite xenoliths were derived from the uppermost mantle and the type 2 spinel lherzolites are from the depth close to the crust-mantle boundary. The equilibration temperatures of garnet granulites are c. 790-900°C (judging from the Ca content in Opx) and are 860–950°C (according to two pyroxene geothermometer). The estimated pressure is from 1 GPa (Nimis, 1999) and to 1.1 GPa (Nickel and Green, 1985) for garnet granulites, and is about 0.6-0.7 GPa for garnet free granulites. Thus, the pressure estimates of mantle and crustal xenoliths indicate a crustal thickness about 35-40 km beneath the south Tien Shan in Meso-Cenozoic period. Based on these P-T conditions, the collected xenoliths match a stable continental geotherm corresponding to the heat flux ~ 80–85 mW/m² (Fig. 2).

The paleo-heat flux value is larger than the observed today heat flux in the region ~ 55-60 mW/m². The heat flow data along the magnetotelluric profile (76°E meridian, across Tien Shan) were taken from the heat flow map of Tien Shan and Pamir (Duchkov et al., 2001) and used for temperature-depth profile reconstruction by using COMSOL Multiphysics package (Femlab). The temperature distribution
in a box 320 x 140 km was calculated in order to fit the observed heat flow data on the surface. The intensity of radioactive heat sources in the crustal lithosphere and the thermal conductivity of rocks along the same profile were taken from Shvarcman (1984).

**Electrical conductivity measurements.** Electrical conductivity of Tien Shan rocks, samples of eclogite, mafic granulite and spinel lherzolite, have been measured in laboratory at high T und P by the use of electrical impedance method. In the present study the impedance spectroscopy (IS) measurements have been realized in a high pressure cell consisting of CaF2 (pressure transmitting medium), graphite sleeve heater and BN-sleeve (insulator between the heater and the outer electrode). In the present measurements the Mo-foil electrodes have been used. The frequency range of IS measurements was from 0.02 Hz to 200 kHz. The complex impedance data collected with the help of Phase-Gain Analyser Solartron 1260. The conditions of electrical conductivity measurements were chosen as follows: for eclogite samples $P = 2$ GPa and $600 < T < 1300^\circ\text{C}$, for spinel lherzolite $P = 1.5$ and 1.0 GPa and $500 < T < 1100^\circ\text{C}$, for mafic granulite samples $P = 1$ GPa and at $400 < T < 850^\circ\text{C}$. Prior to the repeated cooling-heating cycles, the samples were annealed at the highest temperature for about 80–90 h. The results of electrical conductivity measurements presented in Arrhenius plots are compared with the literature data in Fig. 3b, c, d.

**Discussion.** The direct comparison of the specific resistance of rocks and the resistance derived from MT-inversion indicate a good agreement for the layer of eclogites beneath Atbashi ridge. The laboratory estimated conductivity at temperatures 700–1000°C corresponds exactly to the conductivity of a layer at the depth 70–100 km from MT-inversion. Thus, the present geotherm beneath Atbashi ridge is very close to the calculated model.

The agreement between the laboratory conductivity of spinel lherzolites at temperatures corresponding to paleogeotherm and the conductivity of layers at similar temperatures obtained from MT-inversion demonstrate a difference, which can be only explained by a vertical down shift of the geotherm (lithosphere cooling) for about 25 km (Fig. 2). The laboratory conductivity of mafic granulites is compared with the conductivity of layers near the Moho boundary in MT-inversion model. During the time of xenolith transport to the surface, the geodynamic situation in the region corresponded to a hot spot type volcanism with a generation of basaltic magmas close to OIB type. A speculative idea may be that this was caused by a mantle plume (Simonov et al., 2008b). In this case, the lithosphere beneath Tien Shan was hotter than in the surrounding blocks, for example beneath Tarim Basin. This temperature anomaly estimated from the shift of electrical conductivity according to paleogeotherm temperatures and the electrical conductivity calculated from MT-inversion could be about 100°C. Cooling of the crustal lithosphere beneath Tien Shan since 60-50 Ma ago could be due to stopping of a mantle plume which caused the Cenozoic volcanism.
Fig. 3. Geoelectrical model (a) for studying profile from Bielinski et al., 2003. Profile is shown in colors and combined with thermal model, which is shown as contour lines. Temperature is in Celsius degree. Solid blue diamonds are vertical profiles of determination temperature and conductivity magnitudes for comparison with laboratory measurements conductivity. Conductivity Arrhenius diagram for laboratory measurements of Granulite (b), Spinel Lherzolite (c), Eclogite (d).

Conclusion

1. Comparison of the specific resistance of rocks and the resistance derived from MT-inversion indicate a good agreement for the layer of eclogites beneath Atbashi ridge. The laboratory estimated conductivity at temperatures 700–1000°C corresponds exactly to the conductivity of a layer at the depth 70–100 km from MT-inversion.
2. 70–60 Ma ago the heat flux value was significantly larger (~ 80–85 mW/m²) than the observed today heat flux in the region ~ 50–60 mW/m². This geologic time corresponds to a hot spot type volcanic activity in the region. The crustal thickness of south Tien Shan was about 35–40 km with a hotter crustal lithosphere basement. The temperature on the Moho discontinuity was c. 750–800°C, i.e. 100°C higher than today.
3. Modern thickness of the crust beneath Tien Shan is 55 km (Roeker, 2001). The collision event of India with Eurasia caused a propagation of crustal shortenings and resulted in a crustal thickening of the south Tien Shan for about 20–30 km. The temperature at Moho discontinuity is now c. 650–700°C.
4. Comparison of the specific resistance of mafic granulite, spinel lherzolites and the resistance derived from MT-inversion indicate a good agreement for the layers of granulites and lherzolites beneath Ak-Say valley and Kok-Shaal ridge in compliance with present temperature distribution. The laboratory estimated conductivity at temperatures 700–1000°C corresponds to the conductivity of a spinel lherzolites layer at the depth 60–80 km from MT-inversion.

References


MAGNETOTELLURIC DATA FROM THE TIEN SHAN AND PAMIR CONTINENTAL COLLISION ZONES, CENTRAL ASIA

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We present magnetotelluric (MT) data obtained within the framework of the multi-disciplinary Tien Shan – Pamir Geodynamic program (TIPAGE). The dynamics of the Tien Shan and Pamir orogenic belts are dominated by the collision of the Indian and Eurasian continental plates. With the geophysical components, we intend to image the deepest active intra-continental subduction zones on Earth (the N-dipping Hindu Kush and the S-dipping Pamir zones) and to establish how the highest strain over the shortest distance that is manifested in the India–Asia collision zone is accommodated structurally.

The MT data were recorded in summer 2008 at 80 stations in the Pamir mountain ranges in Tajikistan and in summer 2009 at 98 stations the southern Tien Shan in Kyrgyzstan. A typical spacing was approximately 2 km between BB-only sites and 14 km for the combined BB+LMT sites. The stations form an approximately 340 km long profile from Osh in Kyrgyzstan via Sarytash, the Kyrgyz-Tajik border, Karakul and Murgab to Zorkul in southern Tajikistan. We present
examples of the MT data, which are of exceptionally high quality in this very remote area, and show preliminary 2D inversion results.

This project can be seen as a modern continuation of EM-surveys which Mark Berdichevsky and Leonid Vanyan began together with colleagues from the Russian Academy of Sciences in Bishkek in the mountainous areas of Central Asia.

DEEP GEOFLECTRIC MODEL OF THE EASTERN TIBET DERIVED FROM JOINT INVERSION OF LONG PERIOD MT/MV DATA WITH IMPLICATIONS TO RECENT YUSHU EARTHQUAKE

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The ongoing collision of the Indian and Asian continents has created the Himalaya and Tibetan plateau through a range of deformation processes. These include crustal thickening, detachment of the lower lithosphere from the plate and flow in a weakened lower crust. The area of Eastern Himalayan Syntaxis (EHS) and surroundings (Fig. 1) is a key place for the study of dynamic mechanism of the uplift and post collisional deformation in Himalaya-Tibetan region. This area is one of the most earthquake-active regions in China. Active fault studies and GPS data indicate that the surface of the crust rotates clockwise around EHS. Previous MT studies point out at a very conductive lower crust and upper mantle beneath the plateau (Bai et al., 2003; etc.). To understand why and how the rotation occurred around EHS, the long-term EHS3D project (3D study of deep structures and dynamics of EHS) was launched by the Institute of Geology and Geophysics, Chinese Academy of Sciences in 2004 (Bai et al., 2006). However, the deep electric structure of the lithosphere was poorly probed with the use of conventional prospecting magnetotelluric (MT) instruments. Therefore, a cooperative Chinese-Russian-Ukrainian program in long-period sounding of the area was launched in 2007. Bi-lateral Chinese-Russian cooperation ran in 2007-9 in the frames of RFBR-NNSF joint grant 07-05-92124 (Xiao et al., 2008; Varentsov et al., 2008).

More than 45 long period sites were worked out in the EHS3D area during two field seasons, in 2007 and 2009, using Ukrainian instruments LEMI-417. These sites were located at two profiles, EHS-2 and 3 (Fig. 2), each about 1200-km long. The simultaneous observation scheme was employed and the magnetovariational (MV) reference at Langzhou (LZH) geomagnetic observatory also used. A complete system of long period transfer functions (TF) including the impedance, tipper and horizontal MV responses was estimated from these observations using Russian simultaneous multi-site data processing system (Varentsov et al., 2003; Varentsov, 2007b). The impedance data were reliably estimated for periods 30-10800s, the tipper data for periods 100-7200 s and the horizontal magnetic inter-station responses (relative to LZH) for periods 250-16000 s.

The spatial structure of several important MT and MV TF invariants is shown in Fig. 2. The dominant orientation of real induction arrows in Wiese convention in the SW array part is close to SWW-SWW (exceeding 0.5 in length), in the array centre arrows are very small and further to NW they start to look NNE. Horizontal magnetic maximal amplitudes (Varentsov, EMTESZ-Pomerania WG, 2005; Varentsov, 2007b) show positive anomalies at central profile parts with the maximum up to 1.5-1.7 (depending on the base site selection) reached at periods 1000-2000 s. These positive anomalies follow quite well the location of predicted crustal flow outlined in Fig. 1. The effective apparent resistivity is below 30 Om·m at periods longer than 1000 s in the most part of Tibetan region and locally decreases below 10 Om·m in the area NW from large induction arrows.
Still there are some gaps in long period soundings at both profiles, which will be filled with new sites in 20010-11. Nevertheless, we already present a geoelectric model along submeridional EHS-3 profile (Fig. 3) resulted from the joint 2D inversion of 8-component data set including bimodal phase tensor phases, downweighted apparent resistivities, tippers and horizontal MV responses selected from initial TF functions rotated 25°NE. The excess of data components is compensating to some extent the lack of observation sites in this analysis. The robust inversion scheme with the correlated cell resistivity parameterization (Varentsov, 2002, 2007) was applied in the mode providing the account for the topography and for data 3D effects. The importance of accurate topography account is proved by imitation 2D inversion studies (Sokolova, Varentsov, 2009). The true data error estimates from data processing routines are used in the inversion procedure. The account of 3D effects is held by the data error increase (error bars extension) at distorted sites proportionally to correspondent skew estimates.

The constructed geoelectrical model gives a number of conductive structures associated with the subducting Indian Plate. The depth of these structures generally decreases in NNE direction. The brightest crustal anomalies are located at depth 10-40 km within the Lhasa block and the Qiangtang terrain (between YZS and XSF lineaments, see Fig. 3). The similar, but less developed anomalous zone is traced in NE Tibet, south from the Altyn fault. The central Tibetan part is characterized with deeper upper mantle conductive anomalies at depth 50-250 km. The anomalous upper mantle also extends to north at depth 50-100 km till the Altyn fault.

The presented model contains important information serving for understanding of the geodynamic processes in the study area. We hope to increase the resolution of deep structures in this model adding more long period soundings and involving into joint inversion the impedance and tipper data from denser prospecting range soundings. We plan to apply the same inversion approach also at EHS-2 profile and to correlate both geoelectrical sections. The correlation of geoelectric sections constructed in the EHS3D area basing only on prospecting soundings (Bai et al., 2010) with all the lack of deep resolution brought important observations on the regional geoelectrical structure and possible position of crustal flow channels. Now we are getting possibilities to trace the
changes in upper mantle conductivity distribution controlling the regional thermal state and fluid saturation regime.

Fig. 2. Maps of the effective apparent resistivity (left) and the maximal amplitude of horizontal MV response (right) at period 1024 s for EHS-2 (SW-NE) and EHS-3 (S-N) profiles; both maps are overlapped by real induction arrows for the same period and most important lineaments; horizontal MV data are given relative to site 307 at the southern edge of EHS-3 profile.

Fig. 3. Geoelectric section (Ohm·m, lg-scale) along profile EHS-3 resulting from joint 8-component 2D inversion of the impedance, tipper and horizontal MV responses at 32 long period sites; vertical scales differ in 3 horizontal strips; positions of main lineaments (Fig. 2) are shown in the top line; the projection of recent closely located Yushu earthquake is marked by an asterisk.
Finally, we would like to mention that MT/MV soundings at both EHS-2,3 profiles are very important for understanding the mechanisms of two recent catastrophic earthquakes (Fig. 2), the Wenchuan 2009 located close to EHS-2 profile and the Yushu 2010 situated just at profile EHS-3. The projection of Yushu earthquake epicenter onto the geoelectric model along EHS-3 profile appears (Fig. 3) just at the XSF lineament at the edge of upper crustal conducting zone and northern highly resistive crustal block. This zone needs further detailed investigation.

References

MT ARRAY DATA PROCESSING IN THE EMMA PROJECT

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In magnetotelluric (MT) method reliable estimation of transfer functions is an important step towards the final interpretational model. Several important aspects of magnetotelluric data processing are considered. Application of robust estimators proved to be very efficient in improving the accuracy of MT transfer functions estimations. Multivariate analysis (Egbert 1987) opens another perspective to further facilitate data processing. It allows to fully explore the simultaneous nature of magnetotelluric array observations and provides some hints on source field structure as well as noise behavior.

Two electromagnetic arrays were measured in EMMA project to study conductivity structure of the Archaean lithosphere in the Fennoscandian Shield. The first array was operated during almost one year, while the second one was running only during the summer time. Twelve 5-components magnetotelluric instruments with fluxgate magnetometers recorded simultaneously time variations of Earth's natural electromagnetic field at the sites separated by c. 30 km. The quality and duration of the first EMMA array provides an excellent possibility to test different approaches to data analysis. The results of EMMA array data processing are presented.
EM IMAGING IN GEOPHYSICS WITH TENSORIAL INVARIANTS:
FROM THE NEAR-SURFACE TO TRANSDANUBIAN DEEP STRUCTURES

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Besides the traditional electromagnetic data processing, nowadays one can see more and more transformation solutions, especially for very large data systems, which provide direct images about deep geological structures and their dimensions are free of the orientation of the measuring system. The key parameters of these transformations are the tensorial invariants.

In this paper it is demonstrated (as it has been discussed in details in the PhD Thesis of Attila Novák at University of West-Hungary, Sopron, 2010) that the basic (1D) invariants provide a robust and realistic picture about the subsurface bodies. The shape-, side- and corner-dependent (1D, 2D and 3D, accordingly) features of invariants are summarized by using dimensionality analysis. As it has been found by noise studies, the most noise-sensitive invariants are the multidimensional (2D and 3D) ones, especially the 3D invariants.

Comparing various invariant results (completed with dimensionality analysis) with results of classical magnetotelluric interpretations (inversions) to the large datasets in two research areas in West-Transdanubia (Hungary) the main tectonic lines could be easily identified.

The main characteristic tectonic line along the CEL-07 MT profile is the Balaton line (Ádám et al. 2007), which manifests itself with the highest conductivity anomaly. The “Nagyatád” data base could be unambiguously interpreted due to the invariant images, where the long-period homogeneity of the phase invariant map refers to the depth-limited extension of the geological heterogeneity.

Perspectives of tensor invariant imaging in geoelectrics were investigated in details through a case history, based on database of aprx. 50 thousand DC resistivity tensors measured in the Piliszentkereszt archaeological area (Varga et al., 2008). The constancy of invariant images has also been demonstrated in a special field test.

The ensemble of theoretical, modelling and field results means a significant step toward recognising magnetotelluric invariant maps as standardized geophysical presentation forms, similarly to other geophysical (gravity, magnetic and telluric) maps.

APPLICATION OF IMPEDANCE TENSOR INVARIANTS
IN AT STUDYING THE EARTH’S CRUST AND UPPER MANTLE

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Determination of the parameters of the lower part of geoelectric cross-section was carried out in accordance with the following scheme:

– determination of the geoelectric dimensionality of the medium skew, phase-sensitive skew ($\eta$), inhomogeneity N and orientation of the strike-along and strike-perpendicular directions of 2D upper $\theta_l$ and lower $\theta_r$ geoelectric floors;

– in case of 1D upper part of the section, schemes employing the electric and magnetic vectors orthogonalization [Eggers,1982] or only magnetic/only electric field orthogonalization [Counil, le Mouel, Menvielle, 1986] are applied and SVD procedure is used [Latoraka, 1983]. In case of 2D upper part of the section, the analysis should be carried out together with the Zhang-Bahr scheme [Zhang et al., 1987; Bahr, 1991] or phase tensor diagram phase ellipse of the phase tensor [Caldwell, Bibby, Brown, 2003]. If the upper part is three-dimensional and the lower substratum is 1D-3D, the scheme involving phase tensor should be used.
– to estimate the parameters of the lower substratum in case of 1D upper floor, the Council scheme was used at low frequencies and the phase difference between $argZ_{max}^H(\arg Z_{min}^H)$ and the phases of the phase tensor or Zhang-Bahr tensor $argZ(\theta_r) (argZ(90^0+\theta_r))$, was controlled;
– if the upper stratum includes 3D inclusions and the lower floor is one- or two-dimensional, it is expedient to apply schemes of equal phases diagonalization along the columns of the impedance tensor and phase ellipse of the phase tensor. Here the phase difference between $argZ_{max}^H(\arg Z_{min}^H)$ and the phase tensor, or between these quantities and $argZ(\theta_r) (argZ(90^0+\theta_r))$ should be controlled.
– in case of 3D structures presence in the upper and lower floors, determination of the parameters of the deep parts of geoelectric cross-section should be carried out using the phase tensor method together with 3D modeling tools.

The use of the phase curves of the phase tensor makes it possible to construct, employing full complete dispersion relations, the amplitude curves $\rho_{fac2}^{\max} (\rho_{fac2}^m x)$ and $\rho_{fac1}^{\min} (\rho_{fac1}^m x)$ free of the distorting effect of local inclusions contained in the upper substratum if the reference impedance value $Z_{k}^e$ free of near-surface local geoelectric inhomogeneities is available even at only one frequency. 1D inversion of these curves yields geoelectric structure of the lower part of the cross-section whereas its upper part is reconstructed using 1D inversion of $\rho_{max}^e$ and $\rho_{min}^e$.

In 3D regional media the invariant curves allow for additional impedances (that is, the effect of current concentration at the edge of the structure the effect of current flow to the edge of the structure is taken into account). In this respect, these curves are more sensitive to deep inhomogeneities than $\rho$ curves oriented along the axes of the expected regional structures. Therefore, when constructing the geoelectric cross-section, one should estimate the resolving power of each of the curve types in determination of the geoelectric parameters.

2D inversion of the phase curves $argZ_{max}^H (arg Z_{min}^H)$ is possible if they are equal to $argZ(\theta_r)$, $argZ(90^0+\theta_r)$ phases or to the phase tensor phases. Here, the background distribution of conductivity in the lower part of geoelectric cross-section or the background distribution of $\rho$ in the upper part of the geoelectric cross-section should be known. The choice of the polarization type depends on the orientation of these phases with respect to the supposed regional strike-along and strike-perpendicular directions.

3D fitting of the electrical conductivity distribution should be started from the comparison between the model and the observed phase frequency dependencies and $\rho_{k}$-curves. As an initial model approximation, the 1D inversion of the invariant curves least distorted by near-surface inhomogeneities is used.

This scheme was tested on experimental data obtained at North Caucasus, Tien Shan and in Koryakia. A good agreement between the obtained geoelectric results and seismic reconstructions speaks for a workability of the scheme developed.

GEOELECTRIC STRUCTURE OVER THE ARAKAN-YOMA FOLD BELT, SURMA BASIN

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The westerly convex sinuous structural ridges and valleys with sub meridional trend subjacent to the Arakan Yoma suture zone generated during neogene are demarcated as Surma basin. The Surma basin filled with continental sedimentary rocks has evolved under E–W compressive stress field, initially responded by a folding episode having broadly N-S axial planes and later by conjugate set of strike slip faulting episode.

The E-W profile between Rajiv Nagar (Tuipuibari) and Champhai, around 120km long that cut across the compressed Arakan Yoma fold belt was chosen for the MT field work. The crustal geometry
of the Surma basin is inferred from an electrical resistivity model obtained from broadband magnetotelluric (MT) data. The MT time series data obtained using the MTU 5A is transformed, processed, interfaced, decomposed, constrained and inverted to get the 2D model or geoelectric structure along the profile. The profile over the Arakan Yoma fold belt, Surma basin has delineated the geoelectric crustal configuration up to 40 km depth. The model highlights an undulating resistive layer of 100–200 Ωm at a depth of 6–30 km beneath a relatively conductive 10–15 Ωm layer running almost parallel all along the profile that reflects the compressive nature of the deeper crust. The 2D inversion of the tensor decomposed response functions (Groom Bailey) shows three narrow anticlines intervened by two broad synclines filled with the sediments. The main conductivity features having resistivity of 1–5 Ωm with a thickness of 4–7 km are the sediments that underwent transpressional deformation during convergence and transportation in conjunction with the eastward drift of the Indian plate leading to the formation of the Arakan Yoma suture. The thickness and the conductance of the sedimentary layer show a general increase towards the east, up to 20 km east of Champhai.

Two highly resistive blocks, as compared to the surrounding sedimentary rocks of the region, in the range of 1–5 kΩm, one below the undulating pattern and the other at shallow depth beneath the station 02, 03, 12 and 13 are inferred, and may be due to the presence of low conductive bodies, such as massive quartzites, granites, transposed massive dewatered metasedimentary rocks, buried beneath the sedimentary cover. The geoelectric structure along the profile reveals a sub-vertical strike slip fault at the western periphery may be the Kaladan fault (Churachandpur Mao fault) whereas towards the eastern margin a parallel fault dipping around 75º towards west due to wedging is interpreted which may be the Kabaw fault and both these are the deeper crustal structures, probably marking the boundaries of the pull apart Surma basin.

Further studies are being carried out along Agartala–Silchar–Imphal profile to bring out the comprehensive crustal model.

Fig. 1. Profile location over tectonic setting
Spatial relationships between gravity anomalies and features of conductivity structure of the Earth crust was revealed as a result of multi-year studies. Thus it makes possible to develop an unconventional approach to construction of electro-gravitational model with use of EM studies.

Conductivity structure of the upper part of the Earth crust along a 260 km profile crossing Middle Trans-Ural region was constructed to a depth of 20 km. The model was constructed using EM data obtained along the Sverdlovsk Geotraverse crossing all major structural zones in the middle part of Urals. 2D interpretation of Bouguer anomaly along with EM data allows constructing of electro-gravitational model of the upper part of Earth crust.

The main results are as follows:
– there is structural-tectonic relationship between the main geological structures and features of electro-gravitational model;
– the boundary between the Urals and the West Siberian Platform is clearly defined as a sequence of normal and subvertical faults, on the southern and northern extension of which the Triassic grabens of the Ural eastern slope are located;
– deep faults with appearance of flood volcanism on boundary of the East Ural trough and the Trans-Ural rise are allocated;
– the boundary of the Trans-Ural rise and the Tyumen-Kustanai trough is accompanied by a chain of the ultrabasic rocks (serpentines) that testifies to presence of deep-fault zones.

The thickness and peculiarities in the structure of sedimentary cover, electrical resistivity and density of rocks along cross-section are established; peculiarities of basement stratification are revealed; positions of the basic boundaries between structural-material complexes are specified.

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THE RESEARCH OF MAGNETOTELLURIC FIELD IN THE BAIKAL REGION

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The magnetotelluric methods used for the study of the earth conductivity are based on the hypothesis of original electromagnetic plane wave that is favored by M.N. Berdichevskii and his followers. There is also the opinion that the original wave contains the vertical component. The recent experimental observations made on the frozen surface of Lake Baikal have been cited as evidence contributing to the validity of using the plane wave model in magnetotellurics. The electrotelluric field has been recorded with 500-m long horizontal and vertical dipoles whose contact with water has been provided by lead electrodes. The experimental results have shown that the ratio of vertical to horizontal component variation ranging from the first seconds to the first minutes is hundred-thousandth, i.e. at the noise level. This is because the water layer and its underlying sediments are almost homogeneous. The obtained results say for the plane wave model that does not imply vertical electric currents in a homogeneous medium. The variation in the vertical component of electric field with a period of the first tens of minutes and longer may be attributed to the effect of geoelectric inhomogeneity caused by the Baikal basin sides.

Besides, MTS curves along and across Lake Baikal have been obtained from the experiment data. MTS curves have been recorded in the periods ranging from hundredths of a second to 10000 seconds and more. These curves have provided an idea of the electrical conductivity structure of the earth crust and upper mantle beneath Lake Baikal, thus supplementing geoelectric model of the Baikal rift zone constructed by M.N Berdichevsky and L.L. Vanyan. It is pertinent to note that MTS curves recorded on the frozen lake surface are not affected by local near-surface geoelectric inhomogeneities then assuming almost homogeneous electrical properties for the water layer. Longitudinal MTS curves agree well with the standard curve of apparent resistivity in the low-frequency region. These curves contain information on the sedimentary cover beneath the water layer and on the lithospheric conducting layer. In accordance with formal interpretation of longitudinal MTS curves, the sedimentary cover is 1.5–2.5 km thick and has a resistivity of the first ohm-m units. The lithospheric conducting layer is at depths of 30–50 km that correlates with the DSS data. It is worthy of note that transverse MTS curves are represented by descending asymptotic branch whose resistivity is as high as hundredths of an ohm-m in the low-frequency region. This distortion of transverse curves is typical for the Baikal rift on the lakeshore. In accordance with bimodal interpretation of MTS curves, the eastern boundary of the middle rift is not confined to the water area of the lake and extends inland.

STUDIES OF STRUCTURE AND RECENT GEODYNAMICS OF THE ANTARCTIC PENINSULA BY ELECTROMAGNETIC METHODS

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Since 1998 the magnetotelluric, magnetovariational and tectonomagnetic methods were applied to study a deep structure and recent geodynamics of the Earth's crust and upper mantle in a location of the Ukrainian Antarctic station “Academic Vernadsky”. Field works were carried out during a local summer season only because of specific location of the region under study.

Magnetotelluric soundings were carried out at the geomagnetic observatory “Argentina Islands” (AIA), which is located on the Galindez Isl. As results the magnetotelluric impedance tensor and magnetovariational transfer functions (tippers) were obtained for period band 30–10000 sec. During summer seasons 2005–2008 geomagnetic variations data were computed on 9 points along the west
margin of the Antarctic Peninsula. On the base of this data magnetovariation parameters (tippers) were estimated in the period band 30–10000 sec. Pseudo cross-sections of these parameters along and across the coast line were measured.

The method of the scale analog physical modeling was applied to study of a conductivity of the Antarctic Peninsula and adjusting regions. The magnetotelluric and geomagnetic transfer functions were obtained for model. The numeric inversion of obtained response functions were compared with geoelectric cross section which is known for scale model. This comparison allowed to estimate the influence of real 3D effects on geoelectric inversion in this region.

Tectono-magnetic investigations in the region were done for appreciation and mapping of active faults and seismic-active processes monitoring in the crust. To solve this problem in the location of “Academic Vernadsky” station in 1998 was founded the Antarctic tectonic-magnetic polygon. The network of tectonic-magnetic points was based on the islands of the Antarctic Archipelago and West slope of the Antarctic Peninsula. It is placed on the square 60X15 km. During 1998 – 2008 yrs. Here were done 8 estimation cycles for geomagnetic module T. On the base of repetitive observations in the region the zones of intensive local field (T) dynamics (2–2.5 nT/year) were defined. In the most active zone – Three Little Pigs Island – during 1998–2008 yrs. continuous falling of T-field equals 21 nT.

Definition of active blocks and faults of the crust and estimation of tectonic tensions intensity in the region were made on the base of tectonic-physical interpretation.

THE ROLE OF DEEP GEOELECTRICITY FOR DEFINING THE MECHANISMS AND STRUCTURE OF CONVECTION IN THE EARTH’S MANTLE

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The problem of mechanisms and structure of convection is central by the research of Earth’s mantle dynamics [1, 2]. The mantle convection events consist on the main part of geodynamical activity, the relative shifts of tectonic plates, formations of faulting structures. The convective heat and mass transfer defines the thermal mantle structure. The relative thin thermal boundary layers with high temperature gradients surround the almost adiabatic cores of convective cells.

Owing to large viscosity of the medium the Prandtl number by mantle convection achieves very large values and that allows to neglect the inertial terms in the impulse balance equation what simplifies the mathematical problem. But the rock mantle rheology is significantly more complicated, than it is regarded in technical applications. The dependence of viscosity from temperature can ensure its change in the inner of the area on several orders. At last the mantle matter it is needed to consider as polyphase and multicomponent liquid. On the depth 420 km and 670 km strongly-firm phase transitions are observed, which influence on the system dynamics.

The main part of mantle for subsurface geodynamics is obtained with use of simple models of a plain liquid homogeneous layer, which is heated from the bottom (convection Reley-Benar). The model of Reley-Benar allows us sufficiently accuracy estimate some integral parameters: average velocity of plate movements, the value heat density flow, gravitational and thermal anomalies. In spite of the achieved for last years a progress in mathematical modeling of mantle convection, a set of unresolved problems exists. The main is the question what is the structure of mantle convection. Is it layered or it is homogeneous on the whole mantle thickness. Does its structure change in time? What is the mechanism of convection is it of thermal or concentration origin? The additional question is linked with mantle plumes and their interaction with convective flows. To that problems are devoted many researchers [2, 4-10, 32-33].
The progress in research of mantle convection depends not only from the development of the mathematical description methods but more over from the opportunity of use new experimental observations on the Earth’s surface for gathering geophysical and geochemical data.

It is known [11, 2], that the conductivity $\sigma$ in the mantle depends strongly from $\sigma\text{-conditions.}$ In the papers [12,13] are cited some results linked with the reconstruction of mantle temperature distribution, which had been developed by use global, averaged by the existing set data of conductivity. There are also results of mantle conductivity research using global geomagnetic soundings [14-20].

In the paper [21] it had been shown, that by use the relation of the conductivity from the temperature and pressure and additionally yet point magnetotelluric (MT) sounding data we can obtain the information about the existence, structure and relative intensity of mantle convection. If for defining of the matter conductivity we shall use the relation, offered in the paper [11], then taking into account the results of temperature distribution, obtained from the solution of the developed convection solution [4] for variants, when the convection covers the whole mantle or exists only in a local structure of the upper mantle as well if the temperature distribution reflects the “cold” mantle without convection we had calculated [21] the theoretical curves of 1-D magnetotelluric sounding data using the recurrent formula for the apparent resistivity and impedance phase [23]. We had obtained qualitative different curves of MT soundings. The key for estimation of obtained results was the testing, are there registered in practice such types of curves $p_k$ and to what tectonic regions they satisfy. The comparison of theoretical and experimental distributions $p_k$ shows, that the data for the deep part of the Pacific Ocean [24] corresponds to the theoretical variant with convection of the whole mantle or with very intense convection in the upper mantle. The curves $p_k$, which had been in Zauralje [25] are conformed to theoretical curves, which correspond to the variant with convection of average intensity, and on the Russian Platform [26]–to the variant with “cold” mantle. That results show, that MT soundings can include the information about the existence and structure of contemporary Earth’s mantle convection. For that it is necessary to have full curves of $p_k$ and impedance phase, by the way the most attention must be devoted to the time domain ($4 \times 10^2 - 3 \times 10^5$) sec. More over, it is evident that the MT sounding data, which correspond to the 1-D medium, can not practically be obtained; therefore we must arrange area synchronous systems of observation. From the other side the relations $\sigma=\sigma(T,P)$ after the results [11] give the principal opportunity for experimental refining that relation for any probable mantle content.

The obtained results show the expediency of the mathematical formulation of the inverse problem for defining the driving mechanisms of convection and the distribution of physical parameters, which control them. The formulation includes additionally to the Maxwell system of equations the system of convection equations in different formulations of the boundary problems. That problem is divided on some stages: on the first stage we make the interpretation of area deep MT soundings data, using the approaches, published in the papers [27-29]. As a result we obtain a model of conductivity distribution: $\sigma=\sigma(x,y,z)$ and with the use of the relation $\sigma=\sigma(T,P)$ we restore the temperature distribution $T=T(x,y,z)$. The defined temperature distribution we shall use as the input data for inverse problem solution for identification of the convection mechanism. It must be paid the attention to a very significant feature of using of the results of deep MT soundings for temperature distribution estimation in the mantle. Because of the low thermal conductivity of the mantle matter, $k=10^{-6}$ m$^2$/sec [21], the response on the temperature changing on the depth $h\sim10^5$ m will come to the surface only after the time about $\tau=h^3/k$, that corresponds about to $(10^7-10^9)$ years. Therefore the observing now contemporary heat flow may not reflect the structure of the contemporary non stationary heat field in the convective mantle.

In the papers [30-31] there are represented the equations of the inverse problem for mantle convection in a frame of the model: one component viscous compressed gravitating liquid, which is between the free horizontal isothermal plane boundaries in the form [4, 5]. During the time domain of providing deep MT soundings we can neglect the change of the velocities and temperatures fields.
in the mantle. That allows us to use for our problem a stationary approximation. For obtaining data of conductivity distribution on the whole mantle we need to arrange electromagnetic survey with periods of one year. That can be arranged in a frame of observatory in one point. Mathematically the defining of the convection mechanisms means to evaluate the values of the Reley number Ra and its analogues.

The obtained equations allow us to do a conclusion about the degree of comparison of used models of the physical mechanisms, which arrange convection, to the real physical conditions and also to answer on the question: to what distribution of the physical features of the medium coincides the instantaneous distribution of the temperature field, which is obtained from the deep MT soundings data.

On theoretical examples it had been tested the method’s opportunity and the equations of the inverse problem, offered in the paper [31] Earth’s mantle convection driving mechanisms. It had been shown that for variants when the model, which is tested in the inverse problem and the model for which are given the input data coincides it is a good agreement between the input and reconstructed values of the local number of Reley. By solving the inverse problem with a testing model which does not correspond to the input distributions of the physical parameters, the difference between the input and reconstructed values of the Reley number is more then one and half order of the value. That difference has a geophysical meaning and allows us to hope for success by using that method for interpretation of natural data.

The references show the integration significance of the scientific school works, which was leaded by M.N. Berdichevsky.

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ON DYNAMICS OF MAGNETIC TIPPER AND HORIZONTAL TENSOR FROM THE MAGADAN AND PETROPAVLovSK-KAMCHATSKII OBSERVATORY DATA

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The geomagnetic field variations contain information on conductivity of the geological medium that can be obtained with transmission magnetovariational parameters such as magnetic...
tensor and magnetic tipper. In the last few years, M.N. Berdichevsky emphasized the necessity of studying these magnetotelluric parameters because they are not affected by local near-surface geoelectric inhomogeneities. In this connection, the magnetovariational parameters have been used for the study of specific features in the dynamics of lithospheric conductivity from the simultaneous observations of the magnetic field variations at one-second intervals made in the Magadan and Petropavlovsk-Kamchatskii observatories in 2006–2009. Below are the identified properties of transmission magnetovariational functions.

In Paratunka (Kamchatka) and Magadan observatories, the magnetic tipper showed the coast effect that is most pronounced in real induction arrows for respective periods of 6000 and 7000 s. The maximum coast effects are determined by active current concentration in the Kuril-Kamchatka Trench (Paratunka observatory) and deepwater part of the Deryugin basin in the Sea of Okhotsk (Magadan observatory). The imagery induction arrow response to reactive currents is maximum for 300–400 s periods (Magadan observatory) and for a 1000–2000 s periods (Paratunka observatory), which results from electric induction in crustal conducting layers.

The magnetic tipper and magnetic tensor monitoring data have shown annual variation for 300–3000 s periods. They are most pronounced in the imagery induction arrow response for a 300-s period (Magadan observatory) and for a 1000-s period (Paratunka observatory). The MTS relates these periods primarily to the conductive layer. There is reason to think that the annual variations of magnetic tipper and magnetic tensor area are associated with electrical conductivity of the lithosphere containing the crustal conducting layer. The annual variations of electrical conductivity of the lithosphere may be caused by the Earth rotation around the Sun that gives rise to annual cycle variations in the lithosphere fracturing, degree of saturation with hydrothermal solutions and their mineralization degree.

The anomalous time series behavior of magnetic tipper and magnetic tensor in 2006–2009 might arise from large earthquakes with $K \geq 6.3$. For the magnetic tipper, these are stepwise variations of the real induction arrow parameters 10–15 days prior to earthquake. This variation is rated at 30 percent before the M=7.7 earthquake. The magnetic tensor behavior exhibits a notable increase of dispersion in component $m_{yy}$ for a 300-s period that might be associated with an earthquake. The nature of anomalies in the magnetic tipper and magnetic tensor may be attributed to the variation in geoelectric inhomogeneity of the medium that is due to variable occurrence of fractures in the rocks and the degree of their saturation with mineralized waters through the geodynamical processes preceding large earthquakes.

USE OF MAGNETOVARIATIONAL RESULTS TO IMPROVE THE DISTORTION DIAGNOSTIC IN DEEP MAGNETOTELLURIC SOUNDINGS

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An interpretative experience from nine deep magnetotelluric soundings was carried out in the central region of Argentina (Fig. 1). As shown in this figure, the soundings are away each other so much as 50–100 km along 500 km from the Andean region in the West to the cratonic zone in the East. Soundings were done from 1985 to 1993. The main interest was focused on the determination of deep conductive layers in the crust and upper mantle. These soundings do not have interpenetrated their effective volumes; therefore, each one of them have to be interpreted isolate within a particular geological context. After field data processing, the first step in interpretation process – as it is known (Berdichevsky et al 1989) – is to make a distortion diagnostic from the principal curves at each sounding location, using the distortion theory and the available tectonic knowledge. The target is to build in mind the most reliable tectonic structure causing distortions in each site, and its subsequent removing or attenuation to estimate a normal curve; i.e. a curve
without distortion, previous 1D modelling. A correct estimate of each normal curve – especially its position – is crucial to obtain correct depth estimates of deep layers. To perform this operation, the distortion theory (Berdichevsky & Dmitriev 1976, Berdichevsky et al 1989) was used, but it is very important to have a priori information to arrive to satisfactory results.

In this experience, the magnetotelluric soundings are isolated each others, which sometimes makes it more difficult to obtain good diagnostics. Therefore, a magnetovariational study was carried out using the horizontal geomagnetic variation field. Taking into account the near presence of the Pilar Geomagnetic Observatory (PGO) (Fig. 1), giving synchronous magnetograms to those in the field, comparisons between horizontal magnetic events in field and PGO were conducted and hodographs were built for all MT sites. This study was of great importance to reveal large conductive structures causing distortions in some soundings; and thus, to obtain better normalizations of soundings, detecting unsuspected structures and mistakes in diagnostics. As a first step, using the distortion theory and rather scarce available tectonic information from the surrounding of each MT location, an approximate normal curve was estimated at each site. Then, from the ρN curves, the integrate conductivity at T=1000 s of period were also estimated at all locations. As these conductivities were then compared with magnetic transfer functions (MV study), the period of 1000 s was selected because it is approximately the central period between 10’ and 30’ where the majority of magnetic events are present.

Fig.1: Map of studied region in South America; squared areas indicate orogenic zones, dashed areas are sedimentary basins; black points mean MT sounding sites; PGO means Pilar Geomagnetic Observatory, used as a reference site in MV study.

The integrate conductivities were estimated from each MT sounding, considering the estimate normal curve at 1000 s, using the tetra-logarithmic abacus proposed by Fournier (Fournier 1965). These values were normalized (Sr) using the integrate conductivity at 1000 s of period at PGO (730 Siemens); the PGO is seated on a cratonic region (Fig.1). On the other hands, using the hodographs from the horizontal magnetic field, the transfer functions (amplitude ratios) corresponding to H and D between 10’ to 30’ of periods was also estimated at each location, using PGO as a reference site. Then, the average transfer functions between 10’ to 30’ of period were estimated at each location. To do this estimate, H and D transfer functions, for a given period, were averaged only in the case they had similar values; otherwise, when H and D transfer functions differ, the lower value was used (H or D), considering that the higher value is suggesting a conductive structure. All values thus obtained for all magnetic events between 10’and 30’ of period were then averaged. Now, the graphic expression of Sr = f(Ar) on a bi-logarithmic space clearly suggests a linear law (Fig.2). Therefore, if this were correct, a procedure to check and correct estimated normal curves would be available.
In the present study, points on figure 2 – corresponding to field sites - located outside the estimate linear law (Fig.2) were shifted up or down in order to re-locate them on the line. As a consequence, new more accurate integrate conductivities at T=1000 s are now available for those locations, thus indicating that the position of ρN curves, first estimated, in such locations were not correct. Observing figure 2 it becomes clear that, according to this methodology, the initial normalization were only correct for LP and BUL sites (Fig.1). In the other sites, diverse mistakes were produced in the first estimates of ρN, due to the scarce geological information used. Let us briefly see the arguments taken into account in the first estimates of ρN at some sites and the tectonic consequences arise later from the correct ρN (ρNc). USPA sounding was carried out in a tectonic valley into de Andean Cordillera. Both principal curves (~ NS and WE) seem to be shifted down by edge effects (Rokityansky 1982), suggesting a 3D structure. The NS curve (presumably ρ∥, parallel to Andean Cordillera) has a strong deformation probably produced by the coast effect from Pacific Ocean (230 km westward). The WE curve does not seem to present deformation, but according to suppose 3D context, this sounding is no interpretable because the correct position of ρ┴ is unknown. However using information from MV study it is possible to shift up ρ┴ at its correct position as ρN curve, becoming the interpretation now possible and also confirming the 3D character of the structure in this region.

TUPU sounding was carried out next to Frontal Cordillera, with the mountain region to the West and the plain to the East (Figs. 1, 3). Principal directions are roughly NS and WE. To estimate ρN, the NS curve – parallel to Cordillera – was considered as ρ∥. Therefore, as ρ┴ seems to have less deformation, this one was shifted down in order to its high period branch agree to the high period branch of ρ∥. However, this ρN thus estimated, without enough tectonic information, revealed to be no correct. In fact, according to MV results, the integrate conductivity in the site at 1000 s of period would be a lot smaller (Fig. 2). So, to obtain the correct ρN curve (ρNc), the ρ┴ had to be shifted up (Fig. 3). If were correct, the ρNc would be giving evidence of a probable 3D

Fig. 2. Graphic expression of Sr =f(Ar), where: Sr is the integrate conductivity corresponding to the normal curve, at each site, at T= 1000 s, normalized to PGO at the same period. Ar is the average horizontal magnetic transfer function between 10’ and 30’ of period. Black points indicate results obtained from the first estimates of normal curves. Only at two sites the estimates were correct according to this methodology; in the other locations, according to the Ar values, the Sr values are not correct (points are outside the line). Then new values of Sr are estimated shifting the points outside the line on it, and therefore new conductivities and correct positions of normal curves were obtained.
conductive effect on $\rho_\parallel$ (Berdichevsky et al 1998). As a consequence, $\rho_\parallel$ is descended, revealing a no suspected 3D structure.

BEAZ sounding was carried out into a very saline basin (Fig. 1). However, the correct normal curve ($\rho_{Nc}$) (obtained from MV results and using the procedure explained) is suggesting that both principal curves have excessive resistivity values, which is an unexpected result. Therefore, some resistive structures should be present into the basin, no visible in surface.

The procedure used in this interpretative experience present however a feeble aspect. As visible on Fig. 4 the horizontal magnetic field has small sensibility to detect large conductive structures compare to the electric field, which is a lot more sensible. Therefore, a small variation in the magnetic transfer functions implies large variation in the integrate conductivities. As a consequence, we should use many magnetic events in order to estimate correctly as the transfer functions, due to the natural dispersion of magnetic events, especially at large periods.

Fig. 3. Heavy lines correspond to the MT $\rho_a$ principal directions obtained at TUPU sounding. At a first approximation the site was considered as 2D, according to the available tectonic information. The lower curve, approximately parallel to Andean Cordillera was considered as $\rho_\parallel$. To obtain the normal curve ($\rho_N$), the upper curve (apparently less deformed) was shifted down in order to its large period branch agree with the large period branch of longitudinal curve. However, the MV study (Ar) indicates as wrong this normalization. The correct position of $\rho_N$ would be the $\rho_{Nc}$ with less conductivity. If true, the sounding would have 3D tectonic with a probable 3D conductive effect on the longitudinal curve.

Fig. 4. Amplitude transfer functions corresponding to TUPU site, referred to PGO. Only events between 10’ to 30’ of period were used to estimate Ar.
On the other hand, this experience gives evidence that a more acceptable distortion diagnostic – closer to the true – can be obtained if we have:

a) a good skill in distortion theory,
b) a MV study, including horizontal magnetic field, and the vertical one if possible (induction vectors), conducted previously to MT study;
c) good knowledge of tectonic and geological context, with \textit{a priori} information.

\textbf{References}


\textbf{THE RESULTS OF WIÈSE VECTORS CONTINUOUS OBSERVATIONS IN THE TRANSCARPATHIAN REGION}

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Permanent analog magnetic-variation observations are performed in the Transcarpathians seismic-active zone more than 20 years. Simultaneously, digital magnetic-variation observations are done since September, 1999. On the base of these data Wiese vectors for every day were calculated, for short-period variations – every two hours. This permits to investigate thin effects in the temporal variations of Wiese vectors, and to correlate their anomalous behavior with the seismicity of the Transcarpathian deep.

The methods, algorithm and software for processing of large arrays of digital data from magnetic-variation observations were developed. This permits to accelerate the calculation process of Wiese vectors and to increase the quality of monitoring. Correlation of anomalous temporal variations of Wiese vectors let us study the peculiarities of time-spatial correlations of its anomalous changes in correspondence with local earthquakes: for earthquakes, with epicenters near Transcarpathian deep fault anomalous values of Wiese vectors are manifested before earthquakes and for earthquakes with epicenters in the central part of the Transcarpathian deep – after earthquakes.

Increasing of Wiese vectors density, obtained from digital data, gave an opportunity to define their season and diurnal variations. These variations consist in changes of shape and orientation of vectors tips on the plane of their components. During the night time the figure is of an ellipse shape of inconsiderable extend (ratio of diameters of ellipse ratio of diameters of ellipse is less then 2). Accordingly with sun rise the ellipse shape lengthen, and at the meridian ratio of diameters of ellipse ratio of diameters of ellipse exceeds 10. It is also from sunrise till meridian occurs changes of angle of a large axe of a figure. Temporal variations of Wiese vectors are in evident correspondence with a season cycle: the maximum elongation and the minimum declining from meridian direction for the figure of Wiese vectors tips are observed in summer period.

On the base of yearly averages of Wise vectors absolute values analysis there was obtained dependencies of theirs long-period changes that correlate with 11-year cycle of the Solar activity.
Application of neural network time series data prediction for forecast of seismic events
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The geodynamics process preceded to an earthquake may lead to change of the specific layer's resistance of a geological section which has an effect on magnetotelluric (MT) fields. We investigated the possibility of the seismic event forecast based on MT data observed at the Aksu station in the Bishkek geodynamical testing area, Northern Tien Shan. As a result of the three-year-long field experiment on seismic and MT monitoring, a representative database has been collected which included both the MT data measured during the monitoring and the seismicity parameters of the region (the class of a seismic event and the distance to the hypocenter of an earthquake).

In this work we determined the opportunity of correlation between the dynamics of geological section layer's resistance received as a result of 1D inversion of MT data and dynamics of seismic activity in the target region in a definite time. We formulated the task as the prediction of time series. To predict the class of seismic event we used a neural network based on the error back propagation technique. We searched for a relationship between the layer resistances of geological section during some days and the level of seismic activity on the next day after them. The temporary window determined the structure of the neural network. It should not be less than three days. The number of the teaching data was defined from the time domain that should not be less than 40 days. After the corresponding teaching of the neural network we detected the correlation between the dynamics of geological section layer's resistance and dynamics of the seismic activity.

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MT AND MV OBSERVATIONS IN THE REGION OF HIGH SEISMIC ACTIVITY (DNESTROVSKII WATER BASIN, UKRAINE)

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The work is dedicated to analysis of magnetotelluric (MT) and magnetovariation (MV) data, their processing and interpretation, as well as the identification of links between anomalous conducting structure and area of high seismic activity in southern part Volyno-Podoliskoy plate, namely in the area of the Dnestrovskiy basin. The configuration of observations includes the locations for observational at specific sites, which gives possibility to obtain optimal data across the strike the zone of seismic activity, and to avoid the effects of various man-made interference.

An analysis of the MT sounding curves together with tipper showed a local minimum at the period range 3–7 seconds. We can assume that this minimum corresponds to conducting body at depth of about 4÷8 km. We should pay particular attention to the fact that in this area in 2005–2007 a local earthquake occurred with the same focal depth.

It is shown that a close spatial correlation of earthquake sources and the anomalous conducting body may be indicative of their general nature and origin. It is important to note that when analyzing the results of MV and MT data one must take into account a wide range of noises and distortions, which may be caused by various sources, such as man-made noise, inhomogeneities of the sedimentary cover, as well as dynamic change of the stress-strain state of the basin. All these factors have an influence on the experimental data and the quality of their processing and interpretation.
Session 5: Prospecting EM studies

CHARACTERISING PORE SIZE DISTRIBUTIONS IN SANDSTONES: A COMPARISON OF APPROACHES

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Characterizing the movement of water and contaminants in groundwater systems is challenging because of the limited ability to determine a high spatial density of measurements in a non-invasive manner. Geophysical methods provide a potential means of overcoming this challenge by mapping the variation of subsurface properties over relatively large scales. Unfortunately, most geophysical properties are poorly linked to key hydrogeological characteristics. However, since induced polarization (IP) measures the electrical conduction and charge storage associated with the ion movement within the pore space of a rock, the technique provides a direct measure of the internal surface area of a porous medium and, we believe, a means of determining the pore size distribution (PSD) in a non-invasive manner. The challenge is to develop mechanistic models that link pore size characteristics with IP response. We have begun to address this by examining the IP behaviour of a number of well characterised sandstones. We aim to build on this work by formulating a unified model of IP mechanisms, thus allowing indirect estimation of PSD in groundwater systems. Since the PSD controls permeability and the retardation of reactive contaminants and also strongly influence migration of colloid transport, we believe that our future work will provide immense value to the hydrogeological community.

We have selected a number of well characterized sandstone samples for study, although we focus here on measurements of Island Rust and Berea sandstone. Island Rust sandstone is composed mainly of subrounded to angular quartz. The minor sandstone constituents are potassium feldspar, quartzite lithic fragments, chlorite and epidote. The main grain size is 0.2 mm; the porosity of the Island Rust sandstone sample used here is 14%. Berea sandstone is a Mississippian age, quarried in Berea, Ohio. The major components of this sandstone are subrounded quartz, quartzite lithic fragments and feldspar. This sandstone is widely used in rock characterization studies because of its homogeneity. The mean grain size of 0.3 mm; the porosity of the Berea sandstone sample is 19%.

A suite of the sandstones was IP measurements and nuclear scanning. Mercury injection capillary pressure (MICP) data were previously recorded (Baker, 2001) on samples obtained from the same block used for characterization here. The electrical measurements were performed in the petrophysical laboratory in the Council for Geoscience CGS. Following this the samples were sent to The South African Nuclear Energy Corporation (NECSA) for a X-ray and neutron tomography measurements.

Neutrons are sourced from the SAFARI-1 nuclear research reactor operated by NECSA through controlled fission of enriched 235U nuclear fuel. From the reactor core, a beam tube directs the neutron beam through a collimation (beam shaping) system to the radiography experimental facility on the beam port floor of the reactor. A 100 kV X-ray tube can be installed at the exit of the collimator to replace the neutron beam delivery with X-rays.

In the initial stage, the samples were totally saturated with water and 2D neutron radiographs were obtained. The next stage was to dry all the samples until no change in weight could be observed and to take another 2D neutron radiograph in the dry state. From these radiographs (after applying neutron scattering corrections to the neutron data) and weight measurements from the samples in the dry and wet states, the porosity of the samples was calculated. Porosity estimates based on neutron measurements were similar to those obtained through gravimetric analysis. With the samples in the dry state, high resolution X-ray tomography scans were conducted (spatial resolution of 0.05 mm) to determine the porosity of the samples through 3D reconstructed imaging.
For better spatial resolution and visualization of the small pores within the samples, micro-focus X-ray tomography on one of the samples with a spatial resolution of 0.005 mm was conducted. Analysis of these tomographic data is currently in progress.

Fig. 1. Mathematical modeling of the electrical response of two sandstone samples, Island Rust (left column) and Berea (right column): a - measured and modeled electrical responses, b - measured and modeled cumulative pore size distributions, c - modeled pore size distributions.
The laboratory measuring of electrical properties of the rocks have been performed at the CGS for several years using the instrument RIP built by M.Hauger. The instrument contains a holder with two silicon electrodes (for current injection and potential measurement). The sample of rock is located between the electrodes. At time on both electrodes serve as transmitter electrodes, at time off – as receiver electrodes. The analysis of the electrical response is described by Zadorozhnaya and Hauger (2009), which is based on the original membrane polarization concepts of Marshall and Madden (1959).

A comparison of results of the mathematical modeling of the electrical response and the measured pore size distribution from MICP are shown in Fig. 1. Our initial results indicate close agreement between MICP and IP derived pore size distributions. We are currently examining the electrical responses of other sandstone samples and analyzing X-ray tomographic data in order to provide some further comparison of the different methodologies.

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2D JOINT INVERSION OF DC AND RMT DATA:
A CASE STUDY ABOUT GROUNDWATER CONTAMINATION

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The impact of untreated sewage disposal and sewage irrigation practice around Roorkee/India, on groundwater contamination is studied using surface geoelectrical techniques. Electrical resistivity tomography (ERT) and radiomagnetotelluric (RMT) data were recorded in a sewage-irrigated area close to Roorkee and in a remote site where groundwater contamination due to sewage was not expected. The sewage is mainly composed of domestic and municipal waste. Lithology data were used for correlating the resistivity values, which were derived from the 2D inversion of DC and RMT data, with the subsurface formation.

DC and RMT methods were used jointly to increase the reliability of the results in mapping of groundwater contamination. In addition to the individual 2D inversion of DC and RMT data sets, a 2D joint inversion algorithm was applied on the data which was newly developed (Candansayar and Tezkan, 2008). This algorithm can be used for the 2D inversion of apparent resistivity data sets collected by multi-electrode direct current resistivity systems for various classical electrode arrays (Wenner, Schlumberger, dipole-dipole, pole-dipole) and radiomagnetotelluric measurements jointly. We use a finite difference technique to solve the Helmholtz and Poisson equations for radiomagnetotelluric and direct current resistivity methods respectively. A regularized inversion with a smoothness constrained stabilizer was employed to invert both datasets.

The RMT method is not particularly sensitive when attempting to resolve near-surface resistivity blocks because it uses a limited range of frequencies. On the other hand, the direct current resistivity method can resolve these near-surface blocks with relatively greater accuracy. Initially, individual and joint inversions of synthetic RMT and direct current resistivity data were compared and we demonstrated that the joint inversion result based on this synthetic data simulates the real model more accurately than the inversion results of each individual method.
The comparison of the 2D individual and joint inversion results from the contaminated area close to Roorkee/India with the reference profile indicated that the resistivity of the water bearing layer of the upper unconfined aquifer decreases in the vicinity of contaminated zones.

It was thus observed that the sewage pollutants, infiltrated through the soil, reach the shallow unconfined aquifer in and around the polluted area, up to a limited distance from the existent waste disposal sites. The present study suggests that the groundwater present in the shallow unconfined aquifer (<10 m depth) close to waste disposal sites is contaminated.

**2D INVERSION OF MT/MV DATA IN MINING APPLICATION: A CASE STUDY ON DRILLED DEPOSIT**

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**Introduction**

The modern concept of magnetotelluric (MT) and magnetovariational (MV) methods is based on the estimation of the geoelectric structure from different transfer functions between electromagnetic (EM) field components simultaneously observed at one or at a number of sites (Berdichevsky, Dmitriev, 2008). High energy of the natural EM field and its wide period range give a possibility to use the same methodical basis and software instrumentarium to study the Earth at different scales from the tectonosphere in the whole to regional and prospecting surveys for upper crustal and sedimentary targets. The frequency sounding principle makes possible the resolution of a series of overlapping conducting objects at different depth levels. The simplicity of EM field excitation stimulates the development of modeling and inversion techniques for inhomogeneous media. Currently, joint MT/MV techniques become a powerful practical tool to study geoelectric media in full volume representation.

A new, intensified development of these techniques lies in the field of mining prospecting. The recent progress in this field was mainly caused by the development of audio-MT (AMT) technology which made possible the search of near surface targets in highly resistive media with the increased labor productivity (Andreeva et al., 2006). In many cases the MT method became a tool for the direct search for massive ore deposits, in other applications it gives the geoelectric image of the whole mining zone for the complex study together with other geophysical methods of structures (intrusions, faults, etc.) controlling the location of mining targets.

During the last five years, the Nord-West Ltd. in cooperation with the Geological Faculty, Moscow State University and the Geoelectromagnetic Research Centre IPE RAS accumulated a valuable experience in numerous mining applications of modern MT technologies. Prof. Mark Berdichevsky provided an important consulting for this work. Both broad band and audio MT soundings were done by hundreds to thousands per year in different mining regions at various stages of prospecting. The following targets were explored: the intrusions with sulphide copper-nickel ores (Norilsk and Cola Peninsula regions), the explosion tubes and gold deposits (Yakutia), the poly-metal deposits of various natures (Trans-Baikal and Altai regions, Kazakhstan), etc. On this way the simultaneous MT/MV observation schemes were extensively used, providing for the sufficient EM noise reduction in the areas close to industrial objects, and the approaches for the effective joint 2D interpretation of such data with the account for 3D data distortions were worked out (Alexanova et al., 2006; Varentsov, 2006; Yakovlev, 2007; Varentsov et al., 2010). The small observation time (less than an hour) of AMT soundings forced the transition from profile surveys to dense sounding arrays. Such observation patterns with up to 1000 sites were already worked out.
(Norilsk and Trans-Baikal regions), stimulating first experiments in the construction of volume geoelectric models and 3D inversion solutions.

Below we discuss a case study of mining AMT survey over a known deposit comparing the resolution of a number of MT data inversion techniques with the drilling results.

**Case study at Chernogorskaya area (Norilsk region)**

In many cases conductivity anomalies associated with the sulphide mining bodies are seriously masked by nearly located conductors of other nature. In the Norilsk mining region such masking factor is often represented by graphitized terrigen rocks of the Tungusskaya series. A special AMT sounding experiment was carried out in summer 2005 by Nord-West Ltd. on the request from “Norilsky Nickel” within the Chernogorskaya area over the well drilled copper-nickel sulphide deposit. Its aim was the implementation of joint MT/MV sounding scheme and the estimation of possible target resolution within different interpretation approaches. This AMT experiment was supported with the induced polarization (IP) survey over the whole Chernogorskaya ultra-basic intrusion hosting the mining body (Andreeva et al., 2006).

The considered AMT soundings were held along two 1.5-2-km long SSW-NNE profiles crossing the intrusion in the centre (P15) and within its eastern edge (P06). Observations were done with Phoenix AMT instruments simultaneously with a remote reference site located outside the intrusion. The total number of soundings exceeded 30. Resistivity models constructed for these profiles using different inversion techniques are shown in Fig. 1 (P15) and 2 (P06). These models are overlapped with intrusion and mining deposit contours in correspondent sections basing on the drilling results and their geological interpretation. The mining target was in the intrusion bottom at absolute heights of 100-200 m and its integrated thickness was below 100 m.

The first model at profile P15 was constructed by 1D inversion technique for the effective (square determinant) impedance data in the mode with the spatial smoothing (Fig. 1, top panel). This result was followed by 2D bi-modal impedance inversion solution (Fig. 1, second from top panel) using Mackie’s code [Rodi, Mackie, 2001]). These two sections quite definitely outline the resistive intrusion and peripheral conductive structures of the Tungusskaya series, while the conductors in the intrusion bottom are looking strictly oversmoothed and not separated from peripheral ones.

The joint 2D inversion of the impedance and tipper data using Varentsov’s code (Varentsov, 2002, 2006, 2007a) took into account 3D data distortions by means of error bars extension proportionally to transfer function skew parameters. The tipper data were inverted in (Re,Im) representation. We compared two approaches to invert the impedance data. In the first only effective impedance data were considered (Fig. 1, third from top panel). This approach reduces requirements to the strike analysis and is less sensitive to 3D data distortions (Pedersen, Engels, 2005), but oversmoothes resulting conductive structures. In the second approach bi-modal data were inverted (Fig. 1, lower panel) with phases taken from the impedance phase tensor (Caldwell et al., 2004). In both cases apparent resistivities were strictly (10 times) downweighted to overcome static shifts. The starting models had resistivity of 1000 Ohm m. The important initial inversion parameter defining the stabilizing functional structure (Varentsov, 2002, 2007a) was a priori size of structures being studied. It was changed between 50-200 m vertically and 100-300 m horizontally with optimal values providing for the best compromise between inversion solution stability and resolution selected as 100x200 m. Note that this vertical size is just the vertical bound for the mining target thickness.

Both models constructed with Varentsov’s code give higher intrusion resistivity (about 10000 Ohm m) and more contrast conductors aside it and in its bottom (3-30 Ohm m). The solution for the effective impedance still looks oversmoothed, but the bi-modal result fits quite well with the target’s image taken from the drilling. The conductive anomaly in the intrusion bottom is located at the absolute heights of 100-200 m, has the width up to 700 m and thickness up to 100 m. Absolute data misfits in the latter inversion are small enough, their medians are below 2° for phases and below 0.06 and 0.03 for tipper components, respectively.
Fig. 1. Resistivity sections (Ohm m, lg-scale) derived from AMT data at profile P15 in the central section of the Chernogorskaya intrusion, from top to bottom:
- spatially smoothed 1D inversion,
- bi-modal impedance 2D inversion (Mackie’s code),
- joint 2D inversion of effective impedance and tipper (Varentsov’s code),
- joint inversion of bi-modal impedance and tipper (Varentsov’s code);
horizontal axis – profile coordinates (m), from SSW (left) to NNE (right), vertical axis – absolute heights (m); 1 – highly resistive intrusion (external black contour based on drilling results), 2 – conducting intrusion bottom part (mining deposit shown by internal black contour), 3 – graphite-bearing sediments of the Tungusskaya series.
Fig. 2. Resistivity sections (Ohm m, lg-scale) derived from AMT data at profile P06 in the eastern peripheral section of the Chernogorskaya intrusion, from top to bottom:
- spatially smoothed 1D inversion,
- bi-modal impedance 2D inversion (Mackie’s code),
- joint 2D inversion of effective impedance and tipper (Varentsov’s code),
- joint inversion of bi-modal impedance and tipper (Varentsov’s code);
see the legend in Fig. 1.
The inversion results at profile P06 are compared in the same way (Fig. 2) and are looking quite similar with those at profile P15. However, the intrusion thickness here in its peripheral part is reduced and the bottom conductor looks more segmented, with smaller width (below 500 m) and higher position (150-250 m). Nevertheless, in the bi-modal joint inversion solution (Fig. 2, lower panel) this conductor lies 50 m below the mining target, most probably due to systematic side 3D effects in the data. In Mackie’s bi-modal inversion (Fig. 2, second from top panel) both the resistive intrusion and the bottom conductor are downshifted to greater extent and the resolution contrast is very small. In the inversion based on the effective impedance (Fig. 2, third from top panel) these 3D effects are smaller and the target depth is resolved quite well.

At both profiles we see a strong need for the accurate account in the inversion procedures for the observation surface topography. Its variations within few tens of meters visibly disturb (in the cases of full neglecting or too rough approximation) the target structures at the depth of 100-200 m.

It should be noted that the best AMT inversion results corresponds quite well with the IP and electrotomography survey anomalies (Andreeva et al., 2006). In particular, at profile P15 the body with 5% polarization appears at absolute heights of 150-200 m with a width about 700 m, almost overlapping the AMT conductive structure.

The complex electroprospecting study performed at the Gernogorskaya intrusion proved the effectiveness of the joint MT/MV simultaneous soundings in the audio period range in the search of medium to rich copper-nickel deposits of the Norilsk type at depths below 500 m. For greater depths longer AMT observation times and joint AMT – broad band sounding schemes are required. The resolution of these studies may be high enough when sophisticated joint 2D inversion schemes accounting for 3D data distortions and a priori dimensions of studied structures are used.

References


THREE DIMENSIONAL GEOELECTRICAL MODEL
OF MUTNOVSKY GEOTHERMAL FIELD

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The results of interpretation of MT-data collected at Mutnovsky geothermal field (Kamchatka region, Russia) during 2004-2008 are presented. The approaches to MT-data interpretation in the presence of severe 3D distortions and coast-effect are considered. The efficiency of 1D– and 2D-inversion codes applied for inversion of observed data is estimated. The procedure of 3D conductivity model construction is illustrated and the results of 3D MT-response modeling are described. The final 3D geoelectrical model up to 8 km in depth is presented.

Major imaged geoelectrical horizons and structures are analyzed and described in terms of conductance and morphology. The zones of high conductivity values are revealed along with the areas of high lateral contrasts off conductivity. The latter are related to the geotherm's outcrops. The results if MT imaging are approved by drilling.

THE EXPERIENCE OF MT/AMT SURVEY FOR GEOTHERMAL EXPLORATION ON THE KAMCHATKA PENINSULA

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High-temperature geothermal deposits are concentrated in areas of modern volcanic activity. Existence of sources of thermal water is connected with the presence of the high-temperature deep center and tectonic faults in which exists circulation of thermal water. In Russia geothermal deposits have been found on the Kamchatka peninsula and Kuril islands. Now there is a quit big world experience of MT-AMT method application in geothermal areas. The problem of heat supply has great importance for the town Palana in the Koryak autonomous area (north-western part of the Kamchatka peninsula), and MT-AMT investigations were carried out to search new geothermal deposits in this region.

The application of MT-AMT soundings can detect geothermal deposits usually as zones of low resistivity at several hundred meters – some kilometers below the surface. Works by the MT-AMT method were carried out in the area near the town Palana. The purposes of the works were study of geologic structure of the territory, allocation of deep conductive zones, potentially connected with deposits of thermal water, and also determination and contouring of local conductive anomalies for choice of sites for prospecting drilling.

The territory is located within limits of the West-Kamchatka structural zone. A synclinal structure of the N-NE direction is allocated here and there are a number of faults with the vertical shift up to 500-1000 m. Rocks of various ages from Carbon up to modern are exposed in the geologic structure of the area. They are represented by volcanic (basalts, agglomerate lava, andesites, dacites), sedimentary (sandstones, conglomerates, siltstones and argillites) and volcano-siliceous (siliceous slates, jaspers diabases) formations.
MT-AMT investigations were carried out using ACF-4M tensor equipment with the frequency range of 0.1–800 Hz. The recorder has four synchronous channels and 24 bit ADC in each channel. For reduction of the noise influence the remote reference technology was applied.

At the first stage of investigation the area with the square about 36 km² was studied. Geoelectric sections up to 1500 m depth were derived according to 2D inversion results. Three anomalies zones of low resistivity values were delineated. Based on these results and economical reasons an area in the vicinity of the town Palana was selected, and detail MT-AMT investigations in the area with the square about 9 km² were fulfilled. Total number of station was more then 130, separation between profiles was 250 m and between stations 125–250 m. The high efficiency of investigations with the ACF-4M equipment allowed us to implement works during one month (4–6 soundings per day for one field crew). The quite detail survey allowed us to fulfill the reliable data interpretation.

Geoelectric sections were studied up to 2000 m depth. Two layers geoelectric structure was obtained as a result of this work. The first (upper) layer (500 m thickness) of high resistivity (the first thousands ohm-m) is connected with the volcanic and volcano-siliceous rocks. The second layer of low resistivity (30–50 Ohm m) is connected with sedimentary rocks. A broad conductive anomaly was delineated at the south-eastern part of the area. It is located between two faults of north-eastern direction. The most conductive part of the anomaly zone is localized at the depth of 500 m. The allocated anomaly is the most promising for the detection of geothermal source.

RESULTS OF MT STRUCTURAL INVESTIGATIONS IN POLISH EASTERN CARPATHIANS

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The analysis and reinterpretation of magnetotelluric (MT) data was made for area located in the marginal overthrust zone of the eastern Polish Carpathians. The interpretation of surface geophysical data including reflection seismic data in particular, is rather difficult for a complex geological medium developed in a specific tectonic loop that was formed as a result of interaction of the Carpathian overthrust and basement structures.

The objective of MT data reinterpretation was to verify the earlier made interpretations of MT soundings with the use of new geological and geophysical data and new methods and algorithms and software applied. A geological task was to evaluate a depth and morphology of the top of the sub-Tertiary basement. The Precambrian top is related with a distinct geoelectric boundary at which there is a sharp resistivity rise by 1-2 orders of magnitude. The reinterpretation included MT data of so-called second generation surveys that were acquired with the use of the MT-1 system in the years 1998-2002 at three regional MT lines. To synchronize records from measurement sites and the reference site and evaluate effects of EM noise on MT soundings, the actual interpretation was preceded by a review of MT data processing results. In doubtful cases, check reprocessing of measurement data was made with the use of state-of-art robust processing methods. To assess the accuracy of reproducing a depth to the main high-resistivity horizon, a series of least-squares (LSQ) and Very Fast Simulated Annealing (VFSA) interpretations were made for different starting models. Furthermore, the statistics of the obtained results was made.

Sounding curves were interpreted with use of 1D and 2D forward and inverse modeling procedures. Starting models for 1D inversion were prepared as results of integrated interpretation of soundings made close to deep boreholes with application of well-logging and borehole geological data. Starting models for 2D inversion were constructed based on results of 1D interpretation and other geophysical and geological information. As a result of MT data interpretation resistivity cross-sections were constructed. Structural geological models were made based on resistivity cross-
sections and results of studies that employed gravity, seismic and borehole investigations. Forward modeling was applied for verifying interpreted models.

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RECOGNITION OF HYDROCARBON DEPOSITS IN POLISH CARPATHIANS BASED ON ELECTROMAGNETIC METHODS

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Saturation of geological medium with hydrocarbons causes specific changes of its physical properties. The saturated zones generate anomalies in physical parameters of environment distribution and measured geophysical fields allowing, in some step, discovering of deposit presence and even recognizing of its range, structure and changeability of deposit parameters. From point of view of electromagnetic methods deposit complexes are characterized by increasing of resistivity of geological medium of 1-4 ranges of magnitude. Particularly distinct contrast appear on lower boundary of deposit, between reservoir rock saturated with highly mineralized water and saturated with oil or natural gas as well as on upper deposit boundary covered by low-resistivity, sealing clayey rocks. Moreover at the boundary between hydrocarbons and stratal waters a contrast of ability to electric polarization of environment induced by electric current flow appear. As a result of the contrast, anomalous distribution of polarization parameters appear, particularly anomaly of so called phase parameter of polarization marking itself at deposit contour zone.

Direct reflecting of deposit in surface anomalies depends on its size and depth of depression so as effects from objects of small size buried to significant depth disappear among anomalies generated by petrophysical differentiation of overburden. The indirect gauge of hydrocarbon deposit presence is near-surface zone of mineralogical changes connected with diffusion of hydrocarbons from deposit zone to Earth surface. As a result of the changes a zone of scattered sulfide mineralization appear inside diffusion chimney, modifying mainly magnetic properties of geological medium and its electric polarization ability.

EM investigations were made in zones of oil fields “Grabownica” and “Łodyna” located inside Carpathian flysch structures and in the zone of gas field “Rudka” in Carpathian Foredeep. These deposits are relatively shallow so that they mark at interpreted geophysical parameters despite of its small sizes. Particularly, zones saturated with hydrocarbons mark as relatively high-resistivity and specific anomalies of phase parameter of polarization appear on deposit contours.

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RESISTIVITY AND ELECTROMAGNETIC METHODS IN NONDESTRUCTIVE TESTING

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Resistivity and electromagnetic methods are frequently applied in non-destructive testing of metal, polymers, wood, concrete and masonry in various ways. Many of them are quite similar to or even identical with geophysical methods. The frequency range spans from 0 Hz to several Hz. Our focus is application in civil engineering.

Resistivity methods and its extensions “Spectral Induced Polarization (SIP)” or complex resistivity (frequency range 0–40 kHz) are used at BAM to do research on material properties. We apply mainly SIP to investigate structure, material and moisture content on dams and dikes, for the low frequency electrical properties of masonry and the characterization of salt- and water associated damages. A new field is the non-destructive tomographic condition analysis of wood. Other group are using the high frequency variant of SIP, impedance spectroscopy for measurements on polymers and other material.

The primary purpose of eddy current testing (frequency 10–100 kHz), based on the principles of electromagnetic induction, is to detect or investigate metallic objects. In civil engineering the main purpose is to detect rebars in concrete and to measure their diameter. Another important application in railway engineering is to determine the depth of crack-like damage in the gauge corner of rails. This type of flaws has led to serious accidents.

With the radar method, which uses electromagnetic waves in the high MHz and low GHz range, the internal structure and the moisture distribution in concrete and masonry can be investigated. Especially the influence of reinforcement and interfaces in concrete structures is under research. Another group is working on the detection of non-retrievable landmarks. The development of high frequency antennas for detection of ducts and cables in the subsurface is also done at BAM.

On the high frequency edge (several GHz) are microwave sensors. For example BAM has developed a microwave borehole method for depth resolved moisture determination in brickwork. It is possible to observe the moisture condition for longer periods, e.g. for monitoring the dry up process of walls. The moisture determination is based on the measurement of the absorption of the microwave energy in the material between. It is planned to optimize the technique also for applications in concrete structures.

REASON OF THE TEMPERATURE DEPENDENCE OF THE HF EM FIELD DAMPING IMPULSES OF THE GEORADAR PROBE

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There are experimental results that show the relationship between changes in temperature of the sounding environment and the attenuation of high frequency (HF) electromagnetic (EM) field in the permafrost (PF). When temperature $t_z$ of PF soil rise, the amplitude of attenuation of EM pulses of georadar increases (so-called “damping rate” k). The delivered material indeed allowed the author of [1, 2] to build a compelling dependence graphics of the parameters $t_z$ and k. Attenuation of amplitude of EM waves in the medium depends not only on the depth, but also on the electrical conductivity $\sigma$ of the medium. A clear example of this is the “skin effect”, when the depth of HF EMF penetration is directly proportional to the wavelength and inversely proportional to the medium $\sigma$. If to note in this case that the $\sigma$ itself may depends on the temperature, it obviously
follows that the attenuation of the HF EM field indirectly related to the tz of the medium. This is particularly true of this type of medium as PF.

There are few reasons of $\sigma$ the of Earth's upper layer. In porous moisture rich mediums the $\sigma$ is generated by ionic conductivity. The $\sigma$ of the PF soils is related to their temperature, but it also depends on a number of other factors (mineralization, clay soil, etc.). Therefore, it is fair to consider other than the temperature above-mentioned influencing factors. Moreover, if we consider all these factors we should bear in mind that the relations are multifactorional: $\sigma = \sum_{i} \sigma_i$, where $i$ indicates the variety of a factor. The scheme of this relations are as follows: $\Delta tz \uparrow \sum \sigma_i \uparrow \Delta k$ (i.e., due to the increase of temperature - the $\sigma$ increases (or decreases depending on $i$), and with the increase (or decrease) the $\sigma$ the attenuation of HF EM field should increase (or decrease). Complexity of $\sigma$ can also in some cases explain the significant scatters of points on the graphs. Examining the role of temperature we should emphasize that at shallow depths near zero or above zero temperatures in the zones of LTF the amount of non-freezing water is increased in them, so that the electrical conductivity increases. And with an increase of $\sigma$ of the medium the attenuation amplitudes of the HF EMF increases. So this “temperature dependence” is not simple direct but indirect (through conductivity) “dependence” of damping HF EM field on the medium. So the method permit us to estimate not only temperature dependences, but to determine electric conductivity of the medium.

References

MAGNETOTELLURIC STUDIES IN SALT-DOME TECTONIC SETTINGS IN THE PRE-CASPIAN DEPRESSION

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The results of several MT-surveys carried out by “Nord-West” Ltd. in Pre-Caspian depression, well known as a salt-dome tectonics area, are presented. High efficiency of MT method for subsalt strata and salt inhomogeneities imaging is shown with implementation of 2D and 3D numerical modeling. The scale of considered MT-investigations is varying from regional (southern edge of the 1-EV line, Astrakhan region, Russia) to semi-local (Altatino-Nikolskaya area, Saratov region, Russia) and local (investigations of a single salt-dome structure, Western Kazakhstan).

APPLICATION OF DC RESISTIVITY AND TDEM TO WATER INGRESS INVESTIGATION

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The objectives of this project are:
– Directly, indirectly identify and prove areas where ingress is taking place by geophysical mapping of suspected ingress areas lying above shallow undermining.
Where possible identify the location of buried shafts and evaluate their water bearing probability based on their geophysical signature and occurrence.

Map groundwater bearing structures and other geological structures possibly having a control on the flow of groundwater.

**Methodology:** Two dimensional surface resistivity data was collected using a Syscal Pro Switch 72 multi electrode system utilizing 35 electrodes at 10m spacing allowing a depth of investigation of up to 73m with the dipole-dipole array. A computer program Res2DINV was used to generate model blocks and to determine the resistivity of the blocks so that the calculated apparent resistivity values agree with the measured values from the field survey. Time domain electromagnetic sounding method (TDEM) was used for collecting data along several profiles. Two instruments have been used: TEM-FAST48 and Tskl-5, surface area of the receiver loop was 625 m². In this area TEM-FAST48 allows to investigate the depth 120-150 m, Tskl-5 more than 300 m. 95% of the signals collected by both instruments were distorted by electro osmosis IP effect. A computer program TDEM-COV and TDEM_INLOOP were used to determine the resistivity, thicknesses of layers, polarizability η and constant decay τ of each layer in the cross-section

**Results:** The northern half of the ingress area is underlain by quartzite, conglomerate and shale of the Johannesburg and Turffontein subgroups in a complex relation to each other due to the faults occurring in the area. The southern half is underlain by younger basaltic lava of the Klipriviersberg Group of the Venterdorp Supergroup thus the resistivity of rocks of all subgroups is very high. Interpretation of the DC measurements show what appears to be conductive to moderately conductive layers between the varying depths of 20m and 70m overlain by very resistive outcropping quartzite sandstones interpreted to be water bearing structures probably associated with mine out areas or shafts. However high resistive quartzite and lava do not allow investigating deeper sections: electrical current does not flow through high resistive materials. Time domain soundings carried out across the profiles confirm the conductive layers observed with the DC resistivity technique with more resolution and at greater depths. It was shown that the water ingress source could be located in the rural area of Johannesburg.

**MECHANOLECTRIC EFFECTS IN ROCKS**

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Mechanolectric effects occurring at elastic mechanical loading of rock samples in neutral medium and at weak electric polarization of the samples have been studied. It has been found that application of weak electric fields to the samples intensifies or weakens the mehcanoelectric effects, depending on the direction of the applied field.

**Introduction**

Besides being of purely scientific interest, the mehcanoelectric phenomena in naturally occurring dielectrics are of great practical importance because of the problem of interpreting electromagnetic precursors of dynamic manifestations of earthquakes [1–3]. In addition, they facilitate understanding the physical nature of powerful responses to weak causes (including electromagnetic responses to seismic events [4]) and a special state of solids [5, 6]. It has been demonstrated that the phenomenon of an electric field arising in dielectric solids under load has a lot in common with the polarization of materials in a weak electric field [7]. Pilot studies of this subject have been published in the 70ties [8, 9]. Comprehensive review of the data on the mehcanoelectric phenomena in rocks can be found elsewhere [10]. In the present work we investigate the effect of mechanical stress on the polarization of dielectric solids in weak electric fields.
Experimental studies

In the present paper we report experimental results obtained for quartz and marble samples. Marble is widely used in laboratory studies since it has all the main properties of dielectric solids but does not exhibit the piezoelectric effect, a property important for understanding the nature of mechanoelectric effects. In what follows, we will call the electric potential arising under mechanical stress the mechanoelectric potential (MEP) to be distinguished from the electric potential (EP) arising due to usual polarization by an electric field. The experimental setup is presented in Fig. 1.

Fig. 1. Experimental setup including sample (1), electrodes (2), electrometer probe (3) and insulator protecting the probe from electric fields (4).

Marble sample, a 40x40x100 mm prism, was loaded by uniaxial compressive stress produced by hydraulic press through glass ceramic insulators. Two electrodes 2 made of a silver powder mixed with epoxy were attached to opposite surface sides of the sample. The electric voltage between the electrodes was supplied by a dc power source. The electrodes can be grounded, if need be. The distribution of electric potentials in the sample is measured with a specially designed electrometer (EM) in a contactless mode. Electrometer probe 3 was attached to a micrometer feed system permitting the scanning along the sample surface maintaining a 2-mm clearance between the probe and the surface. Under uniaxial compressive loading, an induced electric field (IEF) arises in a marble sample, with the side surface taking a positive potential. Without a mechanical load, the sample is polarized if a voltage is applied to the electrodes. In the latter case, the induced electric field is symmetric relative to the sample center and there are parts of the sample surface with positive and negative potentials.

A sequence of measurements of IEF performed with fixed probe position is presented in Fig. 2. At time $t_1$ the sample was subjected to a uniaxial compressive load $P$ equal to 0.3 of the failure load, and the load was immediately released. A positive induced potential $F_e$ was detected. Next, at time $t_2$, a positive voltage (of the same polarity as under a mechanical load) was applied to the electrodes. When the electric potential reached the steady state in the period $t_2-t_3$, the sample was subjected to the same mechanical load again and then was again released. This time, the IEF increased by $\Delta F$. Let us denote the total potential at this moment as $+\Psi$. The induced potential returned to $F_m$ when the mechanical load was removed. Then, at time $t_4$, the voltage on the electrodes was switched off and they were grounded for some period of time. After that, at the moment $t_5$, a voltage of the same magnitude but of opposite sign was applied to the electrodes again. The probe detected a negative potential, which soon reached a constant level $F_m$. Next, at time $t_6$, the sample was subjected to the same compressive uniaxial load. The detected potential decreased by $F$, and the total electric potential was equal to $-\Psi$. After the load was removed, the potential returned to $F_m$. Then, electrodes were grounded to ensure electric neutrality of the sample.
Fig. 2. The sequence of variations in the electric and mechanoelectric potentials under the action of mechanical and electric fields applied to the sample.

This procedure was repeated in one case with step like increasing mechanical load but with the voltage between the electrodes kept constant. In another case, the voltage was varied but the mechanical load was kept constant. The induced potential $F_m$ increased or decreased depending on the direction of electric polarization of the sample.

Figure 3 shows the induced electric potential $F_m$ as a function of the mechanical load. Line 1 corresponds to no electric polarization; line 2 corresponds to the case where the polarities of the induced electric field and electric polarization are the same, that is, where $F_m$ and $F_e$ have the same sign. Line 3 corresponds to the case where the polarities of the induced electric field and electric polarization are opposite. All the dependencies are linear in this range of loads, but they have different slopes.

Fig. 3. Mechanoelectric potential as a function of the compressive mechanical load $F$ measured without electric polarization (1); in the case where the polarities of the electric potentials coincide, that is, where $F_m$ and $F_e$ have the same sign (2); and where the polarities of the induced electric field and the electric polarization are opposite (3).
Formally, one can introduce the electromechanical modulus of a material by analogy with the piezoelectric modulus:

\[ E = F_m \pm \Delta F. \]

In our experiment, it would make no sense to measure the absolute value for the modulus, because it depends on the probe design, its size, the gap between the probe and the sample, etc. However, the relative variation in \( E \) is characteristic for the effect of mechanical stress on an IEF at simultaneous electric polarization. It was found that the electric modulus increases (decreases) when the polarities of the electric fields induced by the electric and mechanical polarizations are of the same sign (opposite in sign).

Figure 4 shows variations in the IEF potential when the mechanical load is constant and the potential of electric polarization is varied. Three sections can be separated in the line shown in Fig. 4. The point on the vertical axis corresponds to the IEF potential without any electric polarization, i.e., to \( F_c = 0 \). Section 1 corresponds to the case where the electric and mechanical polarizations are of the same sign. Here, for the same load, the sample’s response to the stress is stronger, so the modulus increases. Sections 2 and 3 correspond to the case when EF and IEF are opposite in sign. In this case, the electromechanical modulus decreases and, at a certain point, the sample does not react to the mechanical load \( F^* \) at all. It is interesting that a further increase (in magnitude) of the negative polarizing electric field (at the moment \( t_3 \)) causes the potential to appear again when the mechanical load is applied, but in this case the potential is negative. So, a rather complex interaction occurs between the fields of electric and mechanical polarization.

There is another parameter of great interest, especially for practical applications. Let us consider Fig. 2. When the IEF polarities induced by the electric and mechanical fields coincide, the total potential \( \Psi \) increases under load (upper part of Fig.2), and the total potential decreases under load if the polarities mentioned above are opposite (bottom part of Fig.2). Let us introduce the generalized parameter:

\[ \psi = (+ \Psi) + (-\Psi), \]

which is the sum of two electric potentials equal in magnitude that arise on the opposite-polarity electrodes when both the load and electric field are applied simultaneously. This parameter turns out to be the sum of the potentials measured under load.

![Fig. 4. Dependence of the electric potential \( F_e \) on \( F_m \).](image)

This dependence is linear because it is the sum of two linear functions, 2 and 3 in Fig. 3. Moreover, it is almost independent of the electric polarizing field. As the field increases, the slope of line 2 grows but the slope of line 3 decreases. For this reason, this parameter may be used for measurements of unknown mechanical stresses, e.g. in the bulk of rocks. In practice, estimation of mechanical stresses by this method is complicated by the relaxation of the IEF [4]. Therefore, this technique is more suitable for measurements of variations in mechanical stresses, which are equally important for forecasting dynamical manifestations of macroscopic breakage, in particular,
in an earthquake epicenter at the active stage.

Discussion

Thus, our data provide compelling evidence in favor of interaction of the electric fields induced by mechanical and electric polarizations. This interaction is not limited to simple addition of the field potentials but is more complex in nature. The phenomenological studies presented in this paper are insufficient for a complete understanding of this phenomenon. Theoretical development of a microscopic model, based on materials with a simpler structure, is necessary. However, some hints as to the direction of development for such a model can be obtained from an experiment by comparing the induced electric fields under compressive and tensile stress.

The simplest way to make such comparison would be to bend the sample. The corresponding experimental setup together with results obtained is presented in Fig. 5. One end of a beam-shaped quartz sample was fixed, and a bending moment was applied to the other end. The registering probe was rigidly fixed at some place, and compression or tension at this point was produced by the direction of the applied bending moment. Figure 5b shows that the induced electric fields are opposite in sign for compression and tension. Moreover, the magnitude of the electric field is strongly affected by the gradient of the mechanical stress field.

An attempt was made to relate the IEF to the orientation of dipoles by the gradient of the mechanical stress field [8]. It is noteworthy that the appearance of IEF under the action of a mechanical stress field is a rather universal phenomenon. Manifestations of this effect for quartz glass and marble are qualitatively similar despite the great difference in the physical properties of these materials. Because of this similarity electromagnetic phenomena occurring at deformation and destruction of dielectric solids (in particular, rocks) can be treated on common grounds.

In [9], the appearance of electromagnetic impulses at the formation of cracks was explained in terms of the separation of charges on the crack’s walls. Without denying this mechanism of generation of electromagnetic impulses, we can suppose that all dynamic processes, including the formation of cracks, must cause drastic changes in local mechanical fields and, therefore, in the induced electric fields accompanied by emission of electromagnetic impulses. This universal mechanism can explain the electromagnetic phenomena, both static and dynamic, that occur in epicenters of rock bumps and earthquakes.

![Fig. 5. Bending experiment: (a) – the field distribution and (b) – the induced electric potential $F_p$ as a function of deformation at the bending of the sample for the cases of compression (1) and tension (2).](image-url)
Finally, one can suggest a procedure for registering dynamic changes in a rock massif. Electrodes for the electric polarization of the massif’s section are fastened at some distance from each other. The applied electric field would be about a few V. The probes for registering the induced polarization of the segment are placed near the electrodes. When drastic changes in the stress state occur, the massif’s response is registered by the electrometers. The responses registered at the positive and negative electrodes are expected to be different, and thus one can determine the direction or gradient of the mechanical field involved.

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MAGNETOTELLURICS AND RADIO-WAVE INTERFERENCE SOUNDINGS

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Plane harmonic electromagnetic fields are considered in theory of magnetotelluric (MT) methods in the frequency range from 0.0001 Hz to 20 kHz. These natural fields provide information about depths from tens of meters to 100 km and more. Radio MT soundings extend frequency range until 1 MHz and allow to study depths from first meters. These plane wave methods are supplemented by method of radio-wave interference (RWI) sounding, using higher frequencies (up to 100 MHz). Conduction and displacement currents become comparable, which allows to reveal anomalies of both electric conductivity and dielectric permittivity. For two-layered model simple kinematic approaches to interpretation of RWI sounding curves were developed. In multi-layered and horizontally heterogeneous media it is required to solve forward problem of electrodynamics and inverse geophysical problem.

In the paper theoretical basics and peculiarities of RWI soundings, their role in geophysics and possibilities to solve geological tasks are considered.
MOBILE AND CONTROLLED SOURCE MODIFICATIONS
OF THE RADIOMAGNETOTELLURIC METHOD AND PROSPECTS
OF THEIR APPLICATION IN THE NEAR-SURFACE GEOPHYSICS

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Creation of new instruments and technologies of the near-surface geophysics for the fast investigations of extensive territories is a very important problem. Fast measurements described below allow us to cover 20–40 km of profiles per day and they are cheaper then standard methods like SEV and TEM. Data of shallow investigations are used for the solution of engineering, hydro geological and environmental problems as well as geological mapping and mineral exploration. The prospects of these technologies application are raised at the possibility of surveys at any surface type (dry sand, gravel, asphalt, concrete, frozen rocks, snow, ice).

The radiomagnetotelluric (RMT) method is the one of the most promising facilities for the solution of wide range of the near-surface geophysics problems. Rocks’ resistivity distribution studied by the RMT method can be used at the solution of different geophysical tasks.

In 2002-2005 investigations in the framework of the EU Copernicus project were carried out and the four-channel RMT equipment RMT-F for foot survey had been developed by the Saint Petersburg State University, MicroKOR Ltd. (Russia) and the University of Cologne (Germany). The equipment operates in the frequency band 10-1000 kHz. The apparent resistivity and impedance phase frequency dependencies in two orthogonal directions are determined. The depth of investigations is from first meters to first dozens of meters. Using of ungrounded (capacitive) electric antennae allows us to carry out measurements in case of adverse grounding conditions both in summer and winter time.

A mobile (car-borne) modification – the RMT-M instrument measures the horizontal electric field component by ungrounded electric antenna and two horizontal magnetic field components by induction coils allows us to fulfill fast surveys of wide areas. 5–7 km/h speed of a car provides the separation between sounding stations about 30–40 m. 2D inversion results of mobile survey data have good correlation with ones from foot survey.

A controlled source modification of RMT equipment consists of four-channel recorder with electric and magnetic antennae and portable electromagnetic field source (CS – generator). This modification operates in 1-1000 kHz frequency band making wider the investigation depth compare to standard RMT method. The CS-generator connects to the 200–700 m length grounded cable. Due to generator’s rectangular pulse we obtain up to 10–12 odd harmonics of main frequency, thus using 3-4 main frequencies from the frequency range 1–100 kHz one can cover all frequency range from 1 to 1000 kHz. CSRMT method allows us to investigate an area from 500 m to first kilometers from the source (satisfying the far-field zone conditions). The CSRMT system can be applied at remote territories, for example in northern part of Russia, where are no enough radio transmitters.

The work was fulfilled in frameworks of Federal Target Program NK 631P “Scientific and scientific-educational personnel of innovative Russia” (coordinated by Ministry of education and science of Russian Federation).
DETECTION OF ATMOSPHERIC ELECTRICITY
SIMULTANEOUS $E_z$ AND $j_z$ PULSATIONS

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2 – Pushkov Institute of Terrestrial Magnetism, Ionosphere and Radio Wave Propagation RAS, Troitsk, Russia

We present results obtained with original atmospheric electricity (AE) equipment on the basis of the Alibag (India) geophysical observatory during in situ monitoring studies of surface part of the global atmospheric electric circuit. The experiment consisted in synchronous continuous measurements of AE parameters ($E_z$ field and the electric current density $j_z$); D, H and Z geomagnetic field components and meteorological parameters (temperature $t^\circ$ C, air humidity $v$ and atmospheric pressure $P$). A set of meteorological and AE ($E_z$ and $j_z$) parameters reflects the well known dependence of the former from the latter. The mechanism of aeroelectric structures (AES) generation is determined by the aerodynamic turbulence and convection as explained in many papers. The AES as the volume charges (VC), driven by winds, must register as a variation. When "floating clouds" of VC pass the place of the $E_z$ sensor it detects $E_z$ time variation. But VC sets movements are not the unique source of $E_z$ pulsations. Quasi-harmonic $E_z$ and $j_z$ pulsations may reflect electromagnetic waves too. Quasi monochromatic variation of small amplitude, by analogy with geomagnetic pulsations, are named AE ($E_z$ - $j_z$)-pulsations.

During the experiment oscillation train events ("wave packets") were observed as with damping amplitudes so with the increase in the amplitudes of these $E_z$ and $j_z$ pulsations. The periods of $E_z$ and $j_z$ pulsations were 6 and 10 minutes, sometimes increasing to for 20 and even 110 minutes. An important feature of these quasi harmonic pulsations is that they were observed simultaneously both in $E_z$ and $j_z$. The $E_z$ pulsations were observed on the background of bay-like variations in $j_z$, but also in their absence. The phases of AE parameters of these pulsations coincided, whereas for most of bays were opposite. Not all events of pulsations, noises and bay type $E_z$ variations were observed during the $j_z$ event.

In the conclusion we discuss two possible mechanisms of the generation of the described AE pulsation trains of $E_z$ and $j_z$ with increasing or decreasing amplitudes (and, in some events, periods) One of them was mentioned above. But another explanation may be also considered. The observed manifestations of AE may be the result of atmospheric gravity waves generated by an earthquake with a rapid upward movement of lithospheric plates over its epicenter. Even if it occurs under the ocean floor, it may produce not only tsunami waves, but also infra low frequency acoustic, gravitational and magnetohydrodynamic waves.
Session 6: Organizers and Sponsors

GEOPHYSICAL EDUCATION AND RESEARCH
AT GEOLOGICAL FACULTY OF MOSCOW STATE UNIVERSITY

One of the oldest Russian institutions of higher education, Moscow State University (MSU) was established in 1755. Later it was named after Academician M.V. Lomonosov (1711 - 1765), an outstanding Russian scientist and educator, who greatly contributed to the establishment of the University in Moscow. It is interesting that Lomonosov, in particular, performed pioneer researches of the Earth’s gravity and electric fields and seismicity.

Old university campus is located in the center of Moscow, near Kremlin. In 1953 a new campus with its famous main building was opened on the high bank of the Moskva river. Currently MSU comprises 39 faculties, 15 research institutes, 4 museums and the Science Park. The total number of students exceeds 40000, number of teaching and research staff is over 10000.

As of November 2009, our university exploits world’s 12th supercomputer “Lomonosov”. In 2005 and 2009 MSU launched scientific satellites. There have been 11 Nobel Prize winners among MSU professors and alumni, out of 18 Russians who have received the prize so far.

Geological Faculty was founded in 1938, although teaching geology in MSU started in 1804. Situated in MSU main building, it is now one of the major divisions of the University. Number of students is over 1200 and the Faculty staff totals 400 people. The Faculty consists of 16 Chairs, dealing with different aspects of geology, geochemistry and geophysics. MSU Geological Faculty has a base for field studies, able to host 500 students and located in unique geological surroundings of mountainous Crimea.

Geophysical education in Moscow was organized by Professor A.I. Zaborovsky. In 1923 he started to teach geophysics in Moscow Mining Academy, in 1928 – in Physics and Mathematics Faculty of MSU. In 1930 he created Geophysical Faculty in Moscow Geological Prospecting Institute, and in 1944 – in Chair of Geophysical Methods of Geological Faculty, MSU. In 1975 a part of it formed Chair of Seismometry and Geoacoustics.

Together these two Chairs of MSU Geological Faculty form the Geophysical Department, headed by Professor V.K. Khmelevskoy. It is the leading center of geophysical education and research. In addition to regular staff, geophysicists from other universities and research institutes of Moscow region give lectures in MSU and participate in research projects.

About 40 students of MSU Geological Faculty obtain bachelor’s degree in geophysics each year. Most of them go directly to a master’s degree program, specializing in some geophysical method or area of application. Several Ph.D. students participate in fundamental and innovative studies, conducted by regular staff.

In 2009 one of geophysical laboratories, laboratory of electromagnetic (EM) soundings, was named after Prof. M.N. Berdichevsky, who was its leader for 40 years. He gave lectures on the theory of geophysical fields and the theory of EM soundings, guided the development of magnetotelluric data analysis and interpretation methods, as well as deep resistivity studies. This work is now continued by his followers.

Geophysical base of MSU Geological Faculty exists since 1992 and was significantly enhanced since that time, mainly due to Associate Professor A.G. Yakovlev. The base is situated in Alexandrovka village, 230 km to the south-west from Moscow in the picturesque place in the National park of Ugra river, with a low level of industrial noise. In summer and winter students from MSU and other universities practice here in application of geophysical methods. Field seminars for specialists are also performed in Alexandrovka, and new geophysical technologies are tested here. Recently a 300 m deep borehole was drilled to study well logging methods. Geophysical observatory is being organized there to monitor EM and seismic variations.
In 2007 personnel of the Chair of Geophysical Methods created a “Foundation for Assistance in Development of Geophysical Studies in Geology and Ecology”. One of its main activities is the assistance in development of geophysical base in Alexandrovka. Any kind of help well be accepted with thanks, please contact Head of Chair of Geophysical Methods, Professor A.A. Bulychev (+7(905)939-5766, aabul@geophys.geol.msu.ru).

THE “NORD-WEST” COMPANY

Company profile

Nord-West Company is a Russian leading provider of electromagnetic imaging services, including surveying, data processing, and data interpretation services. We conduct extensive geophysical industrial projects in Russia and overseas. We provide more than 20 surveys annually.

Nord-West Ltd. is actually a production department of the Moscow State University, Department of Geophysics and represents the oldest EM prospecting school in Russia. For many years research and development activity of Nord-West Ltd. was supervised by Professor Berdichevsky. Many employers in the company are his former students. University professors, scientists, post-graduates of the Moscow State University participate in the production work carried out by Nord-West Ltd. providing a high scientific level of production work under way.

The main activities of the company are:
- non-seismic geophysical prospecting including:
  - survey design and planning,
  - field surveys and techniques,
  - data analysis and interpretation;
- instrumentation production and selling;
- software development;
- personnel training;
- drilling activity;
- academic activities (organization of educational and field training campaigns for students of Moscow State University and other institutes and universities).
A foreground **direction of our activities** is electromagnetic and electrical resistivity studies aimed for various tasks:

### Regional studies

Studies of conductivity structure of the Earth’s and upper mantle along regional profiles a few hundred to a few thousand kilometers long, verified by deep drilling.

### Oil and Gas exploration

Delineation of sedimentary structures of hydrocarbon potential and assessment of the reservoir properties of specific layers.

### Ore deposits exploration

Prospecting and exploration of sulphide ore deposits. Complex geophysical studies of the ore fields.

### Solid mineral resources exploration

Reconnaissance of diamond-bearing provinces and detection of kimberlitic pipes. Delineation uranium-perspective valleys.

### Geothermal exploration

Nowadays the geothermal deposits are found and explored in 80 countries, and 58 of these are making good use of the Earth energy.

### Near surface studies

Hydrological, ecological, engineering and other near surface studies.

### Inspection & monitoring


Depending on tasks and targets various **electromagnetic methods** are used:

- broadband and audio magnetotellurics,
- transient and frequency control source soundings,
- induced polarization,
- various modifications of electrical prospecting techniques.

The advantage of Nord-West Ltd. is ability to carry out **turnkey jobs** comprise the entire cycle of geophysical studies – from field observations to processing and interpretation of the obtained data.

Our company has accumulated **great experience** in different geophysical projects resolving challenging problems in different environments. Nord-West Ltd. has been the country's leading contractor in electromagnetic imaging surveys administered under programs of the Ministry of Natural Resources of Russia, oil and mining companies.

The most of the workload is related to regional studies and hydrocarbon prospecting by means of MT sounding method.

More than 50 geophysical projects were executed during period since 2006 till 2009. About 10000 km of profiles were made with more that 10000 observation sites occupied.

Nord-West Company was set up in 1995 as a spinout from Geophysical Department of the most prestigious Russian Moscow State University. With an office in Moscow we serve clients from Russia and overseas in various electromagnetic prospecting techniques.
The majority of experts in the company has graduated from the Moscow State University and has extensive experience in the field of electromagnetic methods of studies.

Nord-West Ltd. owns modern high-tech geophysical instrumentation of its own production as well as produced by the leading national and international manufacturers.

Since 1999 Nord-West Ltd. has been closely cooperating with one of the leading world manufacturers of equipment for electromagnetic measurements «Phoenix Geophysics» (Canada) and officially represents it in Russia. Nord-West Ltd. owns 52 MTU instruments made by «Phoenix Geophysics». Since 2006 Nord-West Ltd. has been an official dealer of IRIS Instruments, France, the manufacturer of Syscal Pro equipment for conducting works by means of electrotomography. The big equipment stock of high-tech geophysical equipment gives Nord-West Ltd. big advantages in terms of volume and quality of the works performed.

Nord-West Company continuously attends for improving personal skills of the staff in serving geophysical instruments. The company’s specialists undergo a regular training in “Phoenix Geophysics” office in Toronto. The aim of those courses is training to repair and maintenance service of the geophysical equipment of “Phoenix Geophysics” production. On courses the listeners get acquainted with new hard and software developments of the Canadian company. On completing training the Nord-West employee are certified as “Phoenix Geophysics” instructors.

To process and interpret MT data cutting edge program software worked out in Russia and abroad is applied. Additionally software package developed by Nord-West Ltd. experts jointly with Department of Geophysics of the Moscow State University is used. Software in use makes it possible to obtain initial high quality data and to do 1D-, 2D-, 3D-interpretation of EM data obtained.

A very important role in Nord-West Ltd. activity plays a field camp in village of Alexandrovka 100 km south from Moscow. This testing site was established 15 years ago jointly with Geophysical department of Moscow State University for student's practical studies. Now Alexandrovka is recognized by all geophysical communities of Russia and the CIS as a site for running international seminars, workshops, testing of new geophysical instruments.

Since 1998 Alexandrovka became inter-universities testing site, where students from the Geological faculty Moscow State Universities, Geophysical faculty of MSGRU, Dubinsky "University of the nature of man and society", geological faculty of the Saratov university do their practical work.

The testing site in Aleksandrovka is also a venue for Russian and international electroprospecting schools and workshops. Since 2001 Nord-West Ltd. together with the "Phoenix Geophysics" has been running the annual international school-workshop on electroprospecting. This seminar includes:
Equipped maintenance service "Phoenix Geophysics", available in the Russian organizations
Updating of the software for data processing
Assistance in processing and interpretation of the data
Recommendations about usage of modern technologies with reference to geological
conditions and problems to be solved

The technological level of production of Nord-West Ltd. meets the highest world standards. The
combination of high scientific and technological level and the ability to implement complicated
orders in short time raises of Nord-West Ltd. competitiveness among many other players in the
geophysical services market.

For more detailed information visit our website http://www.nw-geophysics.com