ELECTRIC PROPERTIES OF THE ROMANIAN LITHOSPHERE, BASED ON MAGNETOTELLURIC DATA

DUMITRU STĂNICĂ, MARIA STĂNICĂ, RĂZVAN GRECULEASA,
DRAGOŞ ARMAND STĂNICĂ, VENERA DOBRICĂ, CRIŞAN DEMETRESCU

"Sabba S. Ştefănescu" Institute of Geodynamics of the Romanian Academy,
19–21, Jean-Louis Calderon St., 020032 Bucharest, Romania, dstanica@geodin.ro

In this paper we present a lithospheric model for the electrical properties on the Romanian territory, based on the existing magnetotelluric (MT) data, to which new information acquired by measurements performed in the 2012–2016 timespan have been added. The MT crustal and upper mantle models of resistivity, conductivity and electric resistance have been determined for a number of lithospheric volumes in which the Romanian territory was divided. A grid superimposed on the geological map with magnetotelluric geotransects, on which these models are based, allows retrieving and detailing of the information that, as a matter of fact, refers to the major geotectonic units. Finally, three lithospheric maps (resistivity, conductivity, electrical resistance), based on the MT models, are presented.

Key words: EM models, lithospheric geoelectric properties, magnetotelluric data, Romania.

1. INTRODUCTION

The results obtained within the frame of this paper seek to get a better understanding of the geoelectric structure on the Romanian lithosphere, using electromagnetic (EM) data. The magnetotelluric (MT) and geomagnetic (GM) methods are EM geophysical techniques that image the electrical properties distribution from the Earth's surface to different depths by using the natural sources of external origin. When this external energy, known as the primary electromagnetic field, reaches the Earth's surface, a part of it is reflected back and the other one penetrates into the Earth. As the Earth acts as a good conductor, so-called telluric currents are induced; they generate in turn a secondary magnetic field.

The MT method is based on the simultaneous measurement of total electromagnetic field, that supposes time variation of both magnetic field B(t) and induced electric field E(t). The electric properties (resistivity/conductivity) of the Earth (crust and upper mantle) can be determined from the relationship between the components of the measured electric (E) and magnetic (B) field variations, or by the MT transfer functions. According to the property of electromagnetic waves in the conductors, the penetration of electromagnetic waves depends on both the frequency and resistivity of the investigated body.

The basis of the MT method was set in the first half of the XXth century by Tikhonov (1950) and Cagniard (1953). Since the beginning, the important developments in formulation, instrumentation and interpretation techniques have made MT as a competitive geophysical tool, suitable to bring information on a broad range of geological targets, including geoelectric structure of lithosphere (Haak and Hutton, 1986; Praus *et al.*, 1990; Bahr *et al.*, 1993; Korja, Hjelt, 1993).

In this paper we present a model for the vertical distribution of crust and mantle electric resistivity on the Romanian territory, as well as for the lateral distribution on the same territory of bulk lithospheric electric properties (resistivity, conductivity, resistance). Reinterpreted MT data and new MT soundings were used.

2. BASIC THEORETICAL CONCEPTS OF THE MAGNETOTELLURIC METHOD

The electromagnetic fields within a material of a non-accelerated reference frame can be described by Maxwell's equations which can be related through their constitutive relationship:

$$\mathbf{J} = \boldsymbol{\sigma}\, \mathbf{E}$$
$$\mathbf{D} = \boldsymbol{\varepsilon}\, \mathbf{E} \qquad (1)$$
$$\mathbf{B} = \boldsymbol{\mu}\, \mathbf{H},$$

where J is the current density (Am^{-1}); D is the displacement current in (C/m^2); B is the magnetic induction [Tesla (T) = Vsm^{-2}]; E (V/m) and H (A/m) are the electric and magnetic fields; σ, ε and μ describe intrinsic properties of the materials through which the electromagnetic fields propagate; σ (S/m) is the electrical conductivity [its reciprocal being the resistivity $\rho = 1/\sigma$ (Ω.m)]; ε (F/m) is the dielectric permittivity and μ (H/m) is the magnetic permeability. These quantities are scalar ones in isotropic media. In anisotropic ones they must be expressed tensorially. In this work, it will be assumed that the Earth properties are anisotropic.

The electrical conductivity of the Earth varies having a wide spectrum up to several orders of magnitude and is sensitive to small changes in minor constituents of the rock. Since conductivity of most rock materials is very low (10^{-5} S/m), the conductivity of the rock unit depends, in general, on the interconnectivity of minor constituents (fluids or partial melting) or the presence of highly conducting materials such as graphite (Simpson, Bahr, 2005).

Due to the nature of the electromagnetic sources used in MT, the properties of the Earth materials and the depth of investigations considered, two hypotheses are applicable (Cagniard, 1953; Keller, Frischknecht, 1966; Simpson, Bahr, 2005):

(1) Quasi-stationary approximation: Displacement currents ($\delta D/\delta t$) can be neglected relative to conductivity currents (J) for the period range 10^{-5}s–10^{5}s and for not extremely low conductivity values. Therefore, the propagation of the electromagnetic fields through the Earth can be explained as a diffusive process, which makes it possible to obtain responses that are volumetric averages of the measured Earth conductivities;

(2) Plane wave hypothesis: The primary electromagnetic field is a plane wave that propagates vertically down towards the Earth surface (z direction).

The following assumptions are applicable in electromagnetic induction in the Earth:

- The Earth does not generate electromagnetic (EM) energy, but only dissipates or absorbs it;
- Maxwell's electromagnetic (EM) equations are obeyed;
- All electromagnetic fields are treated as conservative and analytic away from their sources.

The true resistivity (Cagniard, 1953) of the 1-D half-space is:

$$\rho = 0.2T\,(|Ex|^2/|Hy|^2), \qquad (2)$$

where Ex and Hy are electric and magnetic field wave vectors orthogonal to each other, the ratio Ex/Hy, named as the impedance (Z), is a characteristic measure of the EM properties of the subsurface medium, and constitutes the basic MT response function, and T is the period of the EM field oscillation.

In the case of horizontally layered structure (1–D), the true resistivity "ρ" in Eq. 2 becomes an apparent resistivity (ρa), as follows:

$$\rho a = 0.2T\,(|Ex|^2/|Hy|^2). \qquad (3)$$

Due to the symmetry of the problem, estimations of the characteristic impedance (Z) for either a homogeneous or a layered Earth do not depend on orientation of measuring axes in the horizontal plane, so that the North and East electric field components are related to the orthogonal magnetic field components through the following linear equations:

$$Ex = Z\,Hy \text{ and } Ey = -\,Z\,Hx. \qquad (4)$$

Thus, in this case, at any particular period, an electric field component is linearly related to its orthogonal magnetic field component through a single valued complex scalar transfer function.

For a 2–D geoelectrical structure, a general MT field can be separated into two distinct modes, and these are generally referred to as E and H polarizations, but in a more complicated structure, the coupling between electric and magnetic fields is more complex and, near a lateral inhomogenity, the electric fields are strongly distorted whereas magnetic fields may be relatively less distorted.

In case of a 3–D geoelectric structure, the orthogonal components of the horizontal electric and magnetic fields are related through a complex impedance tensor (Z), expressed in matrix form as:

$$\begin{pmatrix} E_x \\ E_y \end{pmatrix} = \begin{pmatrix} Z_{xx} & Z_{xy} \\ Z_{yx} & Z_{yy} \end{pmatrix} \cdot \begin{pmatrix} H_x \\ H_y \end{pmatrix}, \qquad (5)$$

where E_x, E_y and H_x, H_y are horizontal components of the electric and magnetic fields, Z_{xx}, Z_{yy} and Z_{xy}, Z_{yx} are diagonal and off-diagonal elements of the impedance tensor.

3. DATA AND METHOD

All the above relations, together with the specific inversion and modeling codes, have been used to obtain the lithospheric electrical conductivity distribution for the major geotectonic units on the Romanian territory (Stănică, Stănică, 1993; Stănică, Stănică, 1996; Stănică, Stănică, 1998; Stănică *et al.*, 1999; Stănică *et al.*, 2004). In this paper, existing magnetotelluric data (Pinna *et al.*, 1992; Stănică, Stănică, 1993; Săndulescu *et al.*, 1993; Stănică, Stănică, 1996; Stănică, Stănică, 1998; Stănică *et al.*, 1999; Stănică *et al.*, 2000, Stănică *et al.*, 2004), acquired by MT soundings along geotransects crossing several tectonic units, have been reinterpreted and used. Also, new crustal MT soundings, namely two in the Transylvanian Depression (near Luduş and Bazna localities) and two in the Vrancea foredeep (Lopătari and Vintilă Vodă), acquired in the timespan 2012–2016 to supplement the information in case of these tectonic units, have been added.

The vertical distribution of lithosphere electrical resistivity is described by 1–D models adopted from a full 2–D modelling, finite element code (Wannamaker *et al.*, 1987; Stănică *et al.*, 1999), applied to all geotransects. From the MT 1–D vertical resistivity models for the main tectonic units, bulk lithospheric resistivity, conductivity, and electrical resistance have been derived.

4. RESULTS AND DISCUSSION

Seven MT 1–D vertical distribution of electric resistivity (Figs. 1– 7) were derived for the following major geotectonic units: (1) East European Platform + Scythian Platform + East Carpathians Foredeep + North Dobrogean Orogen; (2) Transylvanian Depression; (3) Pannonian Depression; (4) Moesian Platform + Southern Carpathians Foredeep; (5) East Carpathians + Neogene Volcanic Chain; (6) South Carpathians; (7) Apuseni Mountains. Results are synthesized in Table 1. To model the lateral distribution, the Romanian lithosphere is divided into vertical volumes according to the cells in Fig. 8; the cells are given a number tag, corresponding to the seven MT models. Some cells showing a finer geological structure (especially in the Carpathian area) are characterized by two different vertical MT models, according to the geological structure illustrated in Fig. 8, too. The MT transects on which the 1–D models are based are marked in the same figure. Based on data of Table 1, the electric properties characterizing the entire lithosphere, namely resistivity, conductivity, and electrical resistance, were calculated, taking into account the thickness of the layers (Table 2). In Figs. 9–11 maps of the calculated parameters are presented.

Mean to low values of resistivity / mean to high values of conductivity characterize the two main platforms (East European and Moesian) and the Carpathian orogen. The Pannonian Depression shows the lowest resistivity / the largest conductivity on the study area, while the Transylvanian Depression and Apuseni Mountains show high resistivity / low conductivity values. The electrical resistance of the lithosphere is somewhat more variable on the Romanian territory, showing high values for the East European Platform and Eastern Carpathians, moderate to high for the Moesian Platform and Southern Carpathians, moderate to low values for the Transylvanian Depression, and low values for the Pannonian Depression. We remind here that the discussed parameter values refer to the central point of various squares of Fig. 8 and, consequently, a more detailed information on the distribution of the lithosphere electrical properties cannot be obtained.

East European Platform + Scythian Platform + Eastern Carpathians Foredeep+ North-Dobrogean Orogen

1D MT lithospheric resistivity model

Layers	ρ [Ωm]	H [km]	Observations
1	10	10	Sedimentary cover of the platform
2	1000	35	Crust
3	10	10	Crust-upper mantle transition zone
4	500	120	Upper mantle
5	10		Asthenosphere

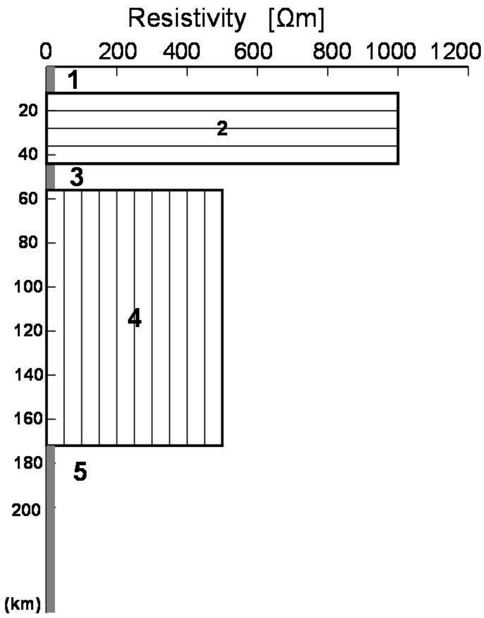


Fig. 1 – 1–D MT model of lithospheric resistivity for the East European Platform + Scythian Platform + Eastern Carpathians Foredeep+ North-Dobrogean Orogen.

Transylvanian Depression

1D MT lithospheric resistivity model

Layers	ρ [Ωm]	H [km]	Observations
1	5	4	Post - tectogenetic sedimentary cover
2	500	2	Central-East Carpathian Nappes Systems (Crystalline basement)
3	700	24	Crust
4	10	10	Crust-upper mantle transition zone
5	500	40	Upper mantle
6	10		Asthenosphere

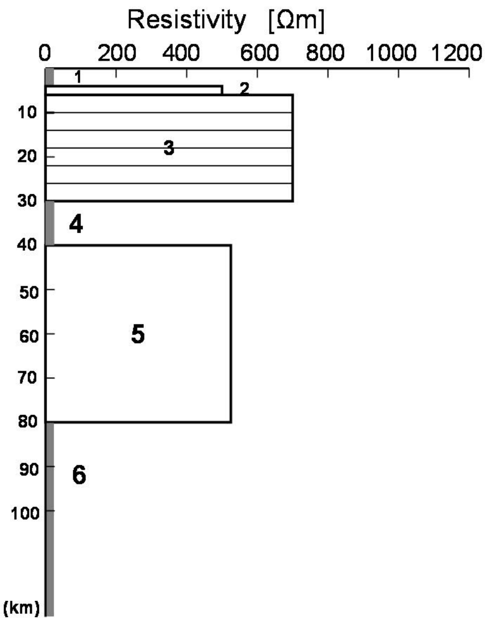


Fig. 2 – 1–D model of lithospheric resistivity for the Transylvanian Depression.

Pannonian Depression

1D MT lithospheric resistivity model

Layers	ρ [Ωm]	H [km]	Observations
1	5	4	Sedimentary cover
2	700	16	Crust
3	10	10	Crust-upper mantle transition zone
4	500	30	Upper mantle
5	10		Asthenosphere

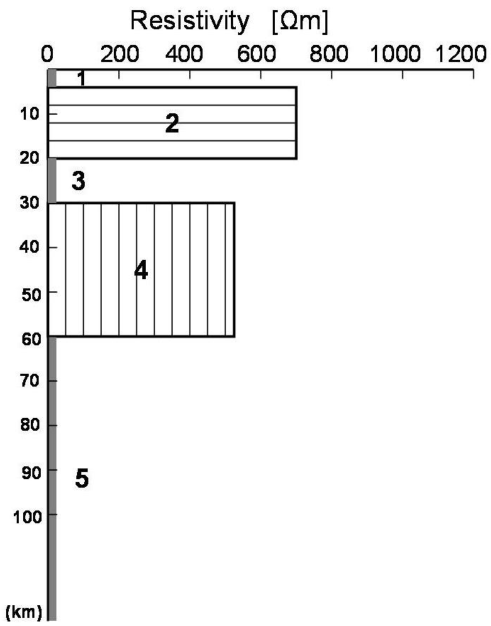


Fig. 3 – 1–D model of lithospheric resistivity for the Pannonian Depression.

Moesian Platform + Southern Carpathians Foredeep

1D MT lithospheric resistivity model

Layers	ρ [Ωm]	H [km]	Observations
1	10	10	Sedimentary cover of the platform
2	1000	30	Crust
3	10	10	Crust-upper mantle transition zone
4	500	80	Upper mantle
5	10		Asthenosphere

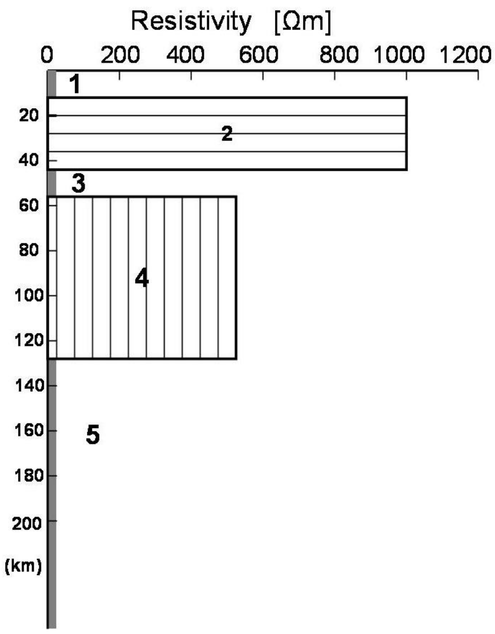


Fig. 4 – 1–D model of lithospheric resistivity for the Moesian Platform + Southern Carpathians Foredeep.

East Carpathians

1D MT lithospheric resistivity model

Layers	ρ [Ωm]	H [km]	Observations
1	100	3	Central East Carpathian Nappes System
2	80	5	Flysch Nappes System
3	10	4	Sedimentary cover
4	100	30	Crystalline basement of the East European and Scythian platforms + crust
5	10	10	Crust-Upper mantle transition zone
6	500	120	Upper mantle
7	10		Asthenosphere

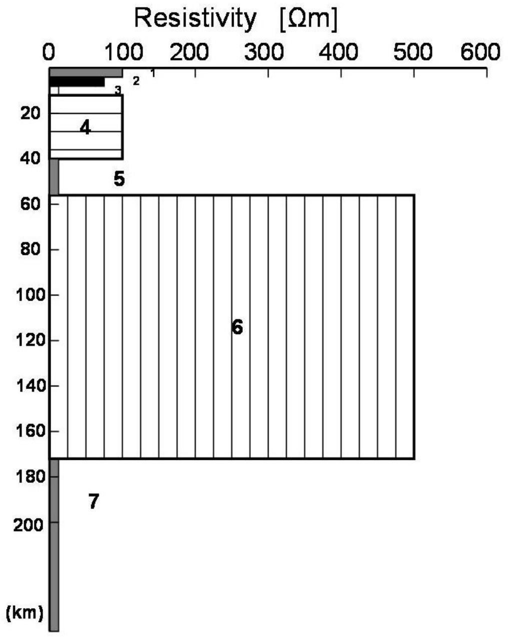


Fig. 5 – 1–D model of lithospheric resistivity for the East Carpathians + Neogene volcanic chain.

South Carpathians

1D MT lithospheric resistivity model

Layers	ρ [Ωm]	H [km]	Observations
1	100	6	Getic Nappes
2	300	7	Danubian Unit
3	1000	30	Crystalline basement of the Moesian Platform + crust
4	10	10	Crust-Upper mantle transition zone
5	500	75	Upper mantle
6	10		Asthenosphere

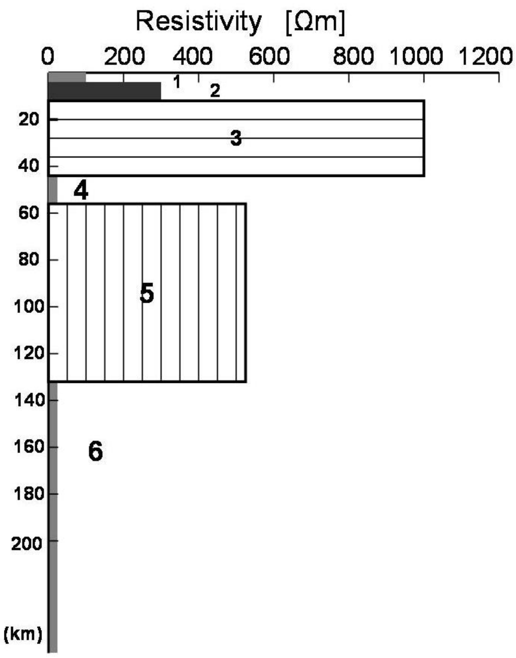
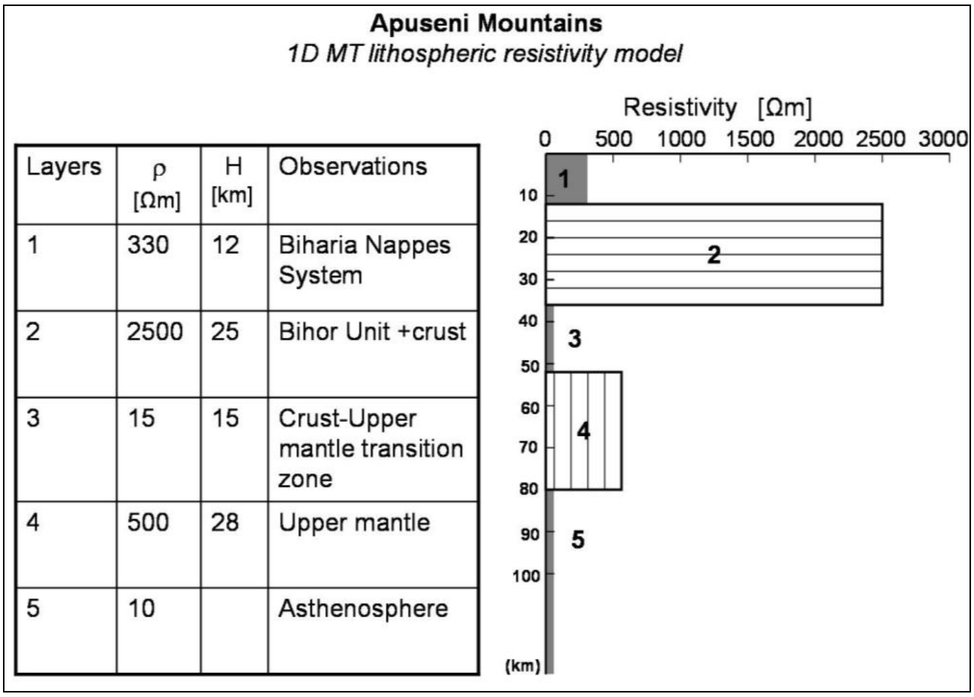


Fig. 6 – 1–D model of lithospheric resistivity for the South Carpathians.



Layers	ρ [Ωm]	H [km]	Observations
1	330	12	Biharia Nappes System
2	2500	25	Bihor Unit +crust
3	15	15	Crust-Upper mantle transition zone
4	500	28	Upper mantle
5	10		Asthenosphere

Fig. 7 – 1–D model of lithospheric resistivity for the Apuseni Mountains.

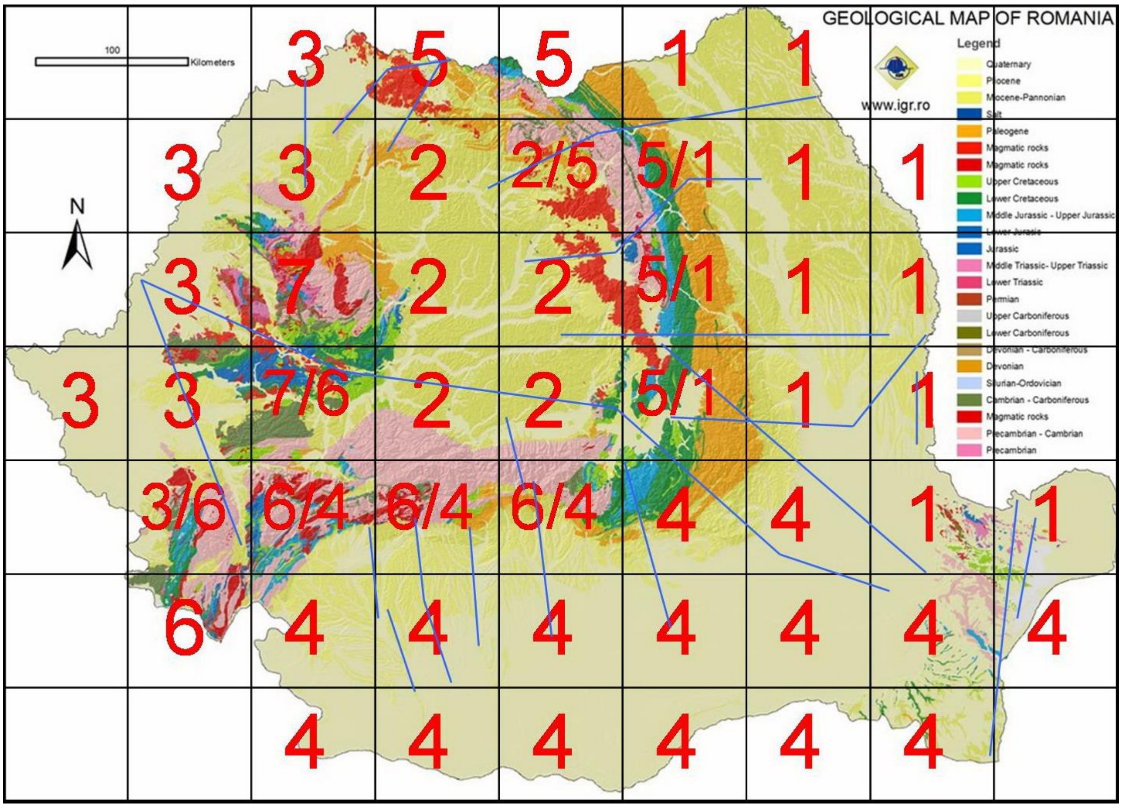


Fig. 8 – Geological map of Romania (after IGR) with the MT geotransects (blue lines) and square cells, numbered from 1 to 7, corresponding to the 1–D MT lithospheric models.

Table 1

1–D models with vertical distribution of the resistivity of the main lithosphere layers, for the seven major tectonic units identified on the Romanian territory

Tectonic unit Model no.	Thickness (d) [km]	Resistivity (ρ) [Ω m = VmA^{-1}]
1. East European Platform + Scythian Platform + Carpathian Foredeep + North-Dobrogean Orogen		
Crust	10	10
	35	1000
	10	10
Lithospheric Mantle	120	500
2. Transylvanian Depression		
Crust	5	5
	2	500
	20	700
	10	10
Lithospheric Mantle	40	500
3. Pannonian Depression		
Crust	4	5
	16	700
	10	10
Lithospheric Mantle	30	500
4. Moesian Platform		
Crust	10	10
	30	1000
	10	10
Lithospheric Mantle	80	500
5. East Carpathians		
Crust	3	100
	5	80
	17	10
	30	1000
	10	10
Lithospheric Mantle	120	500
6. South Carpathians		
Crust	6	100
	7	300
	30	1000
	10	10
Lithospheric Mantle	75	500
7. Apuseni Mountains		
Crust	12	330
	25	2500
	15	15
Lithospheric Mantle	28	500

Table 2

Lithospheric bulk electric properties for the seven types of structures, identified on the Romanian territory

Tectonic unit	Resistivity (ρ) [Ω m = VmA^{-1}]	Conductivity (σ) x 10^{-4} [S/m = $AV^{-1}m^{-1}$]	Resistance (R) [Ω = VA^{-1}]
East European Platform + Scythian Platform + Carpathian Foredeep + North-Dobrogean Orogen	544	18,4	95200
Transylvanian Depression	772	12,96	62525
Pannonian Depression	439	22,8	26320
Moesian Platform	540	18,5	70200
East Carpathians	528	18,9	90840
South Carpathians	549	18,2	70300
Apuseni Mountains	1009	9,9	80685

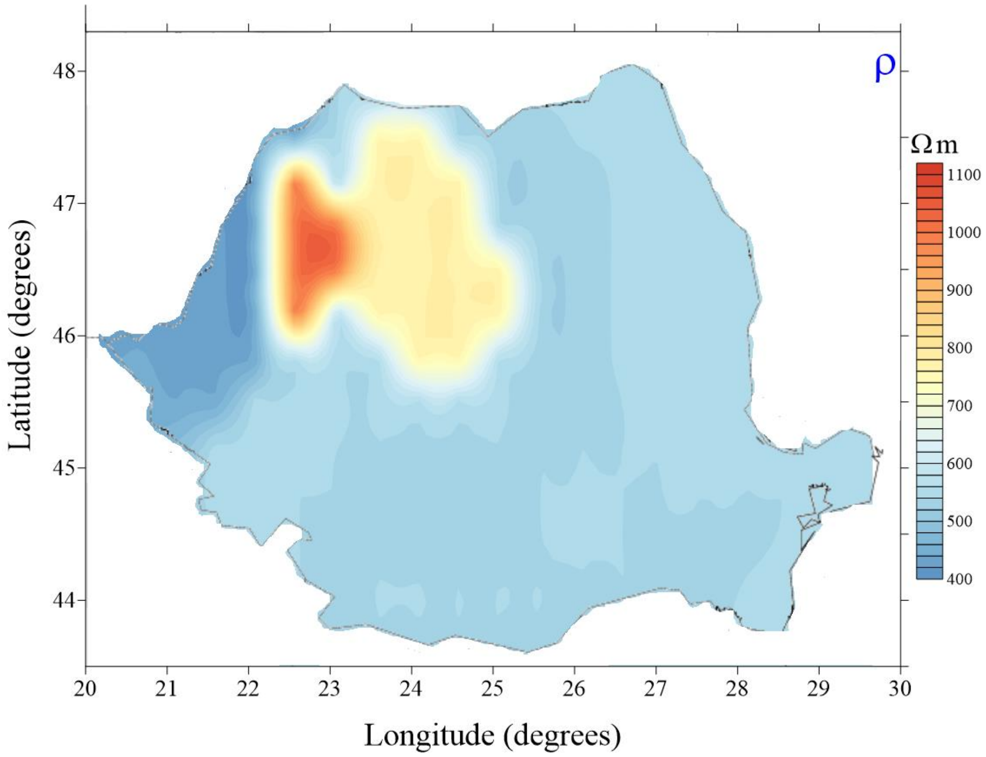


Fig. 9 – The geographical distribution of lithospheric resistivity (**ρ**)**,** based on 1–D MT models.

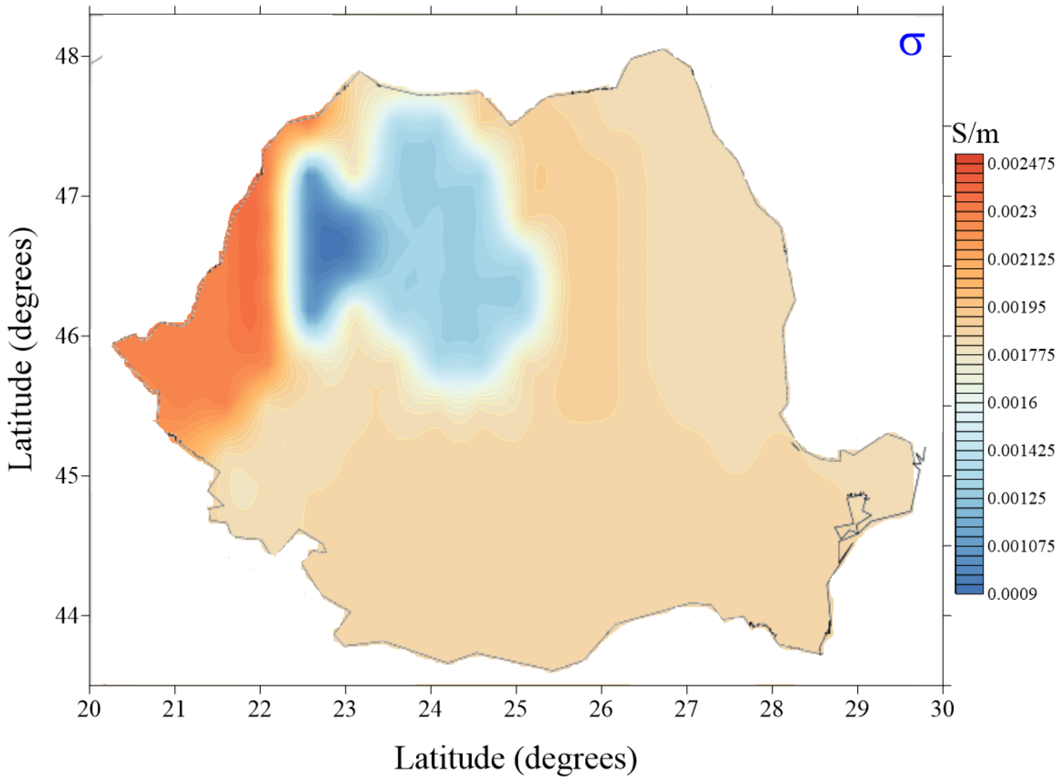


Fig. 10 – The geographical distribution of lithospheric conductivity (σ)**,** based on 1–D MT models.

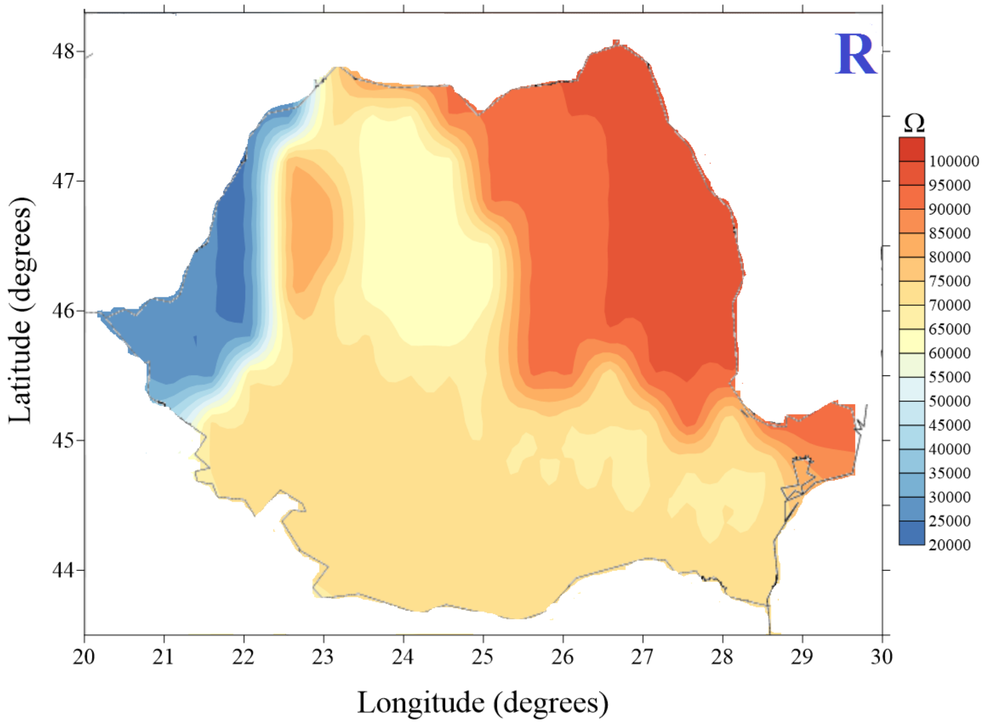


Fig. 11 – The geographical distribution of lithospheric electric resistance (**R**), based on 1–D MT models.

4. CONCLUSION

This paper represents a synthetic review on the magnetotelluric method applied to understanding the lithospheric electrical properties on the Romanian territory. A reinterpretation of existing MT data and new MT measurements has been necessary to undertake such a project. The main results may be summarized, as follows:

- The electrical resistivity of various crustal layers and of the lithospheric mantle was determined from MT transects for the main seven tectonic units in the study area, resulting in a cell model of 1-D vertical distribution;
- The bulk lithospheric geoelectric properties on the Romanian territory have been determined, based on the cell lithospheric resistivity model. Maps of the lithosphere resistivity, conductivity and electric resistance have been carried out.

The magnetotelluric method brings important information on the electric structure of the lithosphere and the present synthesis offers a comprehensive view on it for the Romanian territory. Though the method solves problems at geographical scales represented by lithospheric blocks with horizontal dimensions of tens of kilometers and is limited to the lithospheric depths of about 180 km, the present results are an important progress at the European continent scale, when compared to other models in use, in which the lithosphere electric properties for the Romanian territory are described by means of only 2–3 blocks (*e.g.* Adam *et al.*, 2012).

Acknowledgements. The support provided by the project UEFISCDI IDEI 93/2011 is fully acknowledged.

REFERENCES

ADAM, A., PRACSER, E., WESZTERGOM, V. (2012), *Estimation of the electric resistivity distribution (EURHOM) in the European lithosphere in the frame of* *the EURISGIC WP2 project*. Acta Geod. Geophys. Hung., **47**, 377–387, doi:10.1556/AGeod.47.2012.4.1.

BAHR, K., OLSEN, N., SHANKLAND, T.J. (1993), *On the combination of the magnetotelluric and geomagnetic deep sounding method for resolving an electrical conductivity increase at 400 km depth*. Geophys. Res. Lett., **20**, 2937–2940.

CAGNIARD, L. (1953), *Basic theory of the magnetotelluric method of geophysical prospecting*. Geophysics, **18**, 605–635.

HAAK, V., HUTTON, V.R.S. (1986), *Electrical resistivity in continental lower crust.* In: J.B. DAWSON, D.A. CARSWELL, J. HALL, K.H. WEDEPOHL (Eds.), *The Nature of the lower Continental Crust.* Geological Society Special Publication, **24**, 35–49, Blackwell Scientific Publications, Oxford.

KELLER, G.V., FRISCHKNECHT, F.C. (1966), *Electrical methods in geophysical prospecting*. In: A.L. CULLEN, V.A. FOCK, J.R. WAIT (Eds.), International Series of Monographs in Electromagnetic Waves, **10**, Pergammon Press, Oxford.

KORJA, T., HJELT, S.-E. (1993), *Electromagnetic studies in the Fennoscandian Shield-electrical conductivity of Precambrian crust.* Phys. Earth Planet. Inter., **81**,107–138.

PRAUS, O., PECOVA, J., PETR, V., BABUSKA, V., PLOMEROVA, J. (1990), *Magnetotelluric and seismological determination of the lithosphere-asthenosphere transition in Central Europe*. Phys. Earth Planet. Inter., **60**, 212–228.

PINNA, E., SOARE, A., STĂNICĂ, D., STĂNICĂ, M. (1992), *Carpathian conductivity anomaly and its relation to deep substratum structure.* Acta Geod. Geophys. Montan., **27**, 35–45.

SIMPSON, F., BAHR, K. (2005), Practical magnetotellurics, Cambridge University Press, pp. 254.

STĂNICĂ, D., STĂNICĂ, M. (1993), *An electrical resistivity lithospheric model in the Carpathian Orogen from Romania*. Phys. Earth Planet. Inter., Crustal–Scale Studies, **81**, 99–105.

SĂNDULESCU, M., VISARION, M., STĂNICĂ, D**.**, STĂNICĂ, M., ATANASIU, L. (1993), *Deep structure of the Inner Carpathians in the Maramureş–Tisa Zone (East Carpathians)*. Rom. J. Geophys., **6**, 67–76.

STĂNICĂ, M., STĂNICĂ, D**. (**1996), *Magnetotelluric studies in the Tethyan Suture Zone on the Pannono-Carpathian Geotransect.* Rev. Roum. Géophys., **40**, 71–80.

STĂNICĂ, D., STĂNICĂ, M. (1998), *2D modelling of the geoelectrical structure in the area of the deep-focus Vrancea Earthquakes*. Monograph of Southern Carpathians, Reports on Geodesy, **7**, 193–203.

STĂNICĂ, M., STĂNICĂ, D., MARIN-FURNICĂ, C. (1999), *The placement of the Trans-European Suture Zone by electromagnetic arguments on the Romanian territory*. Earth, Planets and Space, **51**, 1073–1078.

STĂNICĂ, D**.,** STĂNICĂ, M., ASIMOPOLOS, L. (2000), *The main Tethyan suture zone revealed by magnetotelluric tomography.* Rev. Roum. Géophys., **44**, p.123–130.

STĂNICĂ, D., STĂNICĂ, M., PICCARDI, L., TONDI, E., CELLO, G. (2004), *Evidence of geodynamic torsion in the Vrancea zone (Eastern Carpathians).* Rev. Roum. Géophys., **48**, 15–21.

STĂNICĂ, D., STĂNICĂ**,** D.A. (2012), *Earthquakes precursors*, in SEBASTIANO D'AMICO (Ed.), Earthquake Research and Analysis – Statistical Studies, Observations and Planning, Book 5, Chapter 4, Tech. open access publisher.

TIKHONOV, A.N. (1950), *The determination of the electrical properties of deep layers of the Earth's crust.* Dokl. Akad. Nauk. SSR, **73**, 295–297, (in Russian).

WANNAMAKER, P.E., STODT, J.A., RIJO, L. (1987), *A stabile finite element solution for two-dimensional magnetotelluric modeling*. Geophys. J. R. Astr. Soc., **88**, 277–296.

Received: October 19, 2016
Accepted for publication:November 21, 2016