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Temperature dependence of the electrical conductivity of granite and quartz-monzonite from south Bulgaria: geodynamic inferences

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Abstract: *The temperature dependence of the electrical conductivity for granite and quartz-monzonite specimens from South Bulgaria has been studied, using equipment of the Geophysical Institute of Czech Academy of Sciences, which enables the automatic control of the experiment. Comparisons between electrical conductivity curves measurements under laboratory and the real local deep geothermal conditions have been made in order to evaluate the influence of the mineral transitions on the formation of geophysical layers in the Earth's crust. The abrupt decrease in electrical conductivity at* 200^o*-330°C correlates with the beginning of the transition magnetite-maghemite. The maximum of electrical conductivity in the temperature interval 750-820°C in granite coincides with the transition of* β*-quartz to* β_2*-tridymite. All these mineral transitions are accompanied by volume changes. The probable fluctuations of the heat flow in the Earth's crust in South Bulgaria, near the critical phase transition zones, are the cause of the volume changes in the rocks, the consecutive increase in the stress and the restoration of the tectonic equilibrium by weak earthquakes sequences. The hypothesis for sinking of the tectonic block is not acceptable because the recent vertical movements are positive - 1 to 2 mm/year. What remains is the hypothesis of progressing of the thermal flow from the deep parts of the Earth's crust and upper mantle towards the most shallow layers of the crust. The area of the most active influence of the heat flow from the asthenosphere uplifting is exactly the zone of the Maritza fault, from where the studied specimens originate.*

Key Words: *Electrical Conductivity, Temperature Dependence, Granite, Monzonite, Phase Transitions, Earthquakes.*

INTRODUCTION

The sensitivity of the electrical properties of minerals and rocks to the thermobaric changes provides the possibility for using laboratory tests to construct models of the Earth's crust. These models have to be adequate to the tectonic conditions and the recent geodynamic processes in the given region. The laboratory studies of the temperature dependence of the electrical conductivity presented in this paper limit the possibility to construct complete analogies to the state of the substance in the Earth's crust and upper mantle, because of the elimination of such a factor as the baric pressure. However, some important comparisons can be made because the increase in the electrical conductivity in the Earth’s crust does not depend of the pressure rise (Lastovickova, 1991).

The present paper discusses the results of the study of representative specimens from two petrographic species from Southern Bulgaria - granite from Boshulia and quartz-monzonite from Plovdiv. These two sites are in the area of the seismically active Maritza deep fault zone (Fig. 1), characterised also by heat flow values in the range of 50-60 mW/m^2 (Hurtig, 1992). The electrical conductivity laboratory studies were performed by M. Lastovickova in the Geophysical Institute of the Czech Academy of Sciences. Their interpretation as an effect of the mineral transitions was made by Y. Yanev and the local geodynamic model was elaborated by S. Shanov.

DESCRIPTION OF THE STUDIED ROCK SPECIES

The granite from Boshulia, near the town of Pazardjik, Southern Bulgaria (Fig. 1) is composed of: quartz (25-37%), K-feldspar (25-35%), plagioclase (20-35%), biotite (2-8%), amphibole (0-5%) and

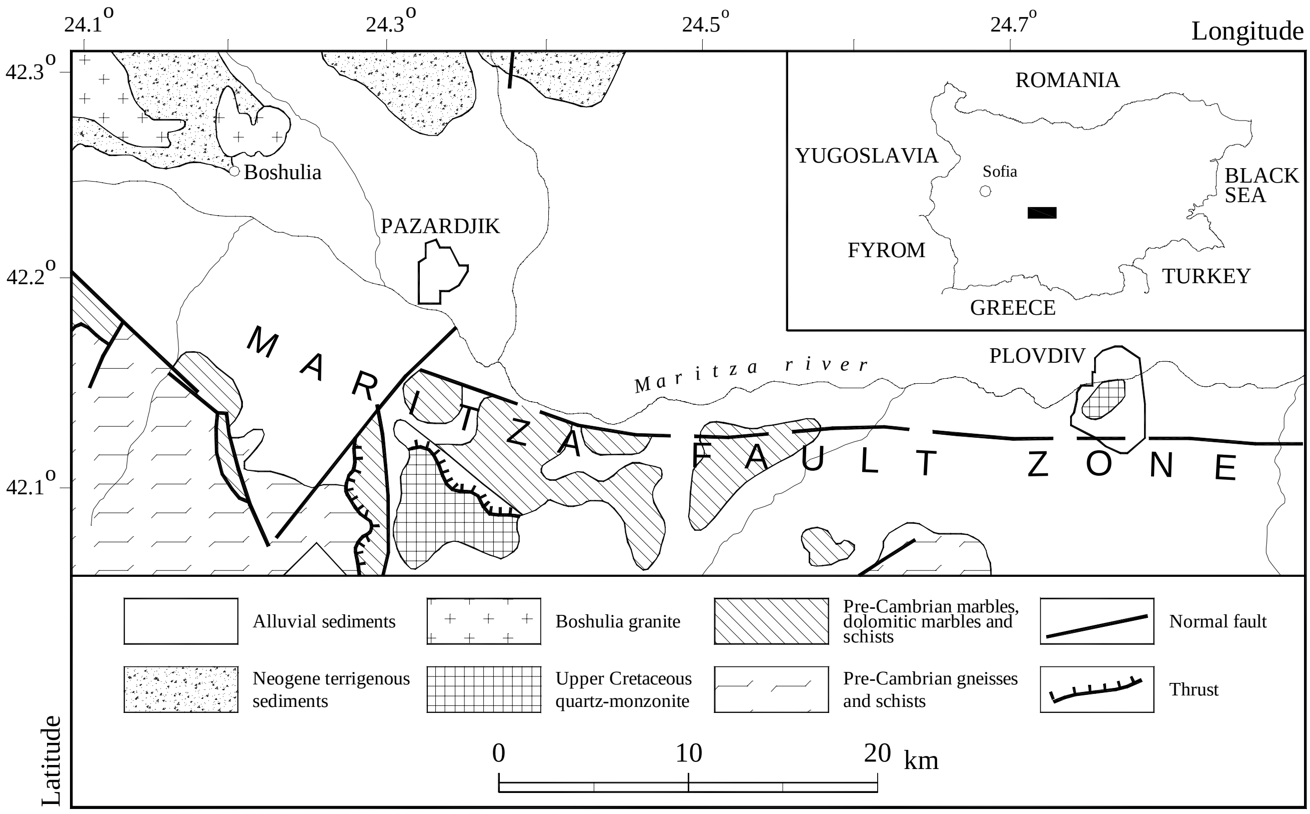


FIG. 1. Geological sketch map of a part of the Maritza deep fault zone (Bulgaria).

accessory magnetite, titanite and apatite (Boyadjiev and Chipchakova, 1964). The volume percentage was determined by microscopic counting. According to the chemical composition, the normative magnetite quantity is 2% (calculated after the C.I.P.W. method). The representative specimen was taken from an outcrop.

The quartz-monzonite from the outcrops inside the town of Plovdiv (Fig. 1) is composed of: plagioclase (39-43%), K-feldspar (23-35,5%), quartz (11-12,5%), amphibole (3,8-7,6%), pyroxene (1%) and accessory magnetite (1,1%), apatite (0,3-1,7%), zircon and allanite (Rozloznik, 1940). According to the chemical composition (Boyadjiev, 1973) the normative magnetite quantity, calculated after the C.I.P.W. method, is 4%. The studied specimen was also taken from an outcrop.

In both cases the modal mineral composition is known and for the interpretations, it is better to use this information rather than the calculated values. But the case is different for magnetite. Its crystals are so small in dimension that normally their counting is very difficult by microscope and the accuracy of the quantitative determination is very low. The C.I.P.W. norms help in the comparison of the magnetite quantity in both types of specimens. The direct comparison of the chemical composition also shows that the quartz-monzonite is richer than the granite in Fe-bearing minerals.

METHOD OF MEASURING THE ELECTRICAL CONDUCTIVITY

The method for measuring the temperature dependence of the electrical conductivity of rocks and minerals has been developed at the Geophysical Institute of the Czech Academy of Sciences. A microcomputer and related equipment permitted the automatic control of the experiment, collection, evaluation, graphic display and storage of the results (Lastovickova and Klima, 1988).

The AC (10^3 Hz) electrical conductivity of rocks is measured in a through-flow argon atmosphere (the pressure of O2 is about 10-1 Pa) within the temperature range of 30 to 1000°C using the two-electrode method. The measured sample is placed inside on electrical furnace in an argon atmosphere in a ceramic holder. Pt electrodes connect it with an automatic bridge with four weirs excluding any influence of the leads. The automatic bridge measures the electrical conductivity on one channel and the voltage of the PtRh thermocouple on the other channel. This thermocouple is located very close to the sample and serves as an indicator of the temperature of the measured sample. The temperature regulator is controlled by two NiCr-Ni thermocouples.

TEMPERATURE DEPENDENCE OF THE ELECTRICAL CONDUCTIVITY

The electrical conductivity of rocks is highly sensitive to temperature changes. The temperature dependence of the electrical conductivity $\sigma(T)$ of minerals and rocks in the lithosphere can be expressed as (Lastovickova and Klima,1988):

$$\sigma(T) = \sigma_{0i} \exp(-E_i/kT) = \sigma_i(T),\ i = 1,2,3\ldots\ldots\ldots n$$

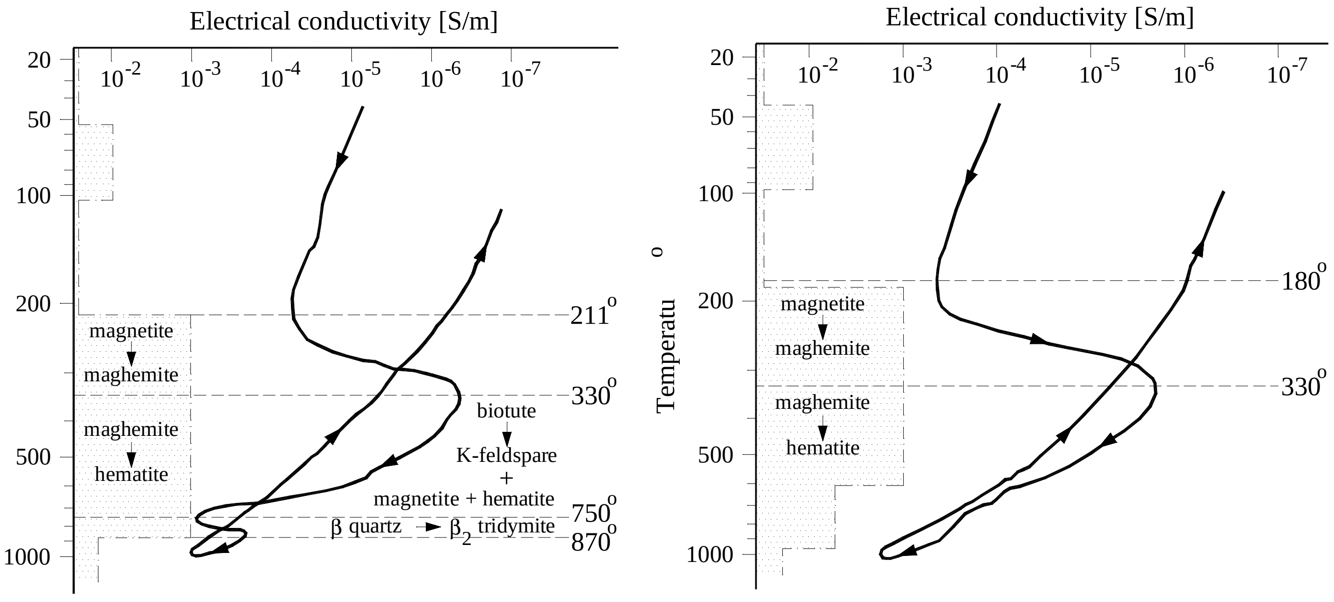
where T is the absolute temperature in K, k is the Boltzmann constant - $0{,}862.10^{-4}$eV K^{-1}, and E is the activation energy in eV. The charge carriers are ions, ion-vacancies, electrons, or holes. The total conductivity is the sum of the individual conductivities of all components $\sigma_i(T)$. Each $\sigma_i(T)$ is predominant in a certain temperature range, σ_{0i} being the initial electrical conductivity before the heating.

In all cases, the change of the electrical conductivity in rocks with the temperature change can be analysed as a function of the mineral composition, the structure and the quantity of the high electrical conductive minerals, such as magnetite. The electrolyte conduction is not discussed in this study, because of the method of specimens preparation (powdered rock specimens additionally formatted in tablets).

For the cases studied (Fig. 2) the electrical conductivity increases, with increasing the temperature up to 2000°C. The electrical conductivity of quartz-monzonite (Fig.2b) is one order of magnitude higher than that of granite. The jumps of the electrical conductivity curves during the further temperature rise can be explained by some phase transitions of the minerals in the rocks. Thus, the abrupt decrease in the electrical conductivity between 180-210°C and 330 -340°C could be related to the transition at this temperature of magnetite (Fe_3O_4) to maghemite (γFe_2O_3) following the reaction (Lepp, 1957):

$$4\,Fe_3O_4 + O_2 \Rightarrow 6\,\gamma Fe_2O_3$$

Since the electrical conductivity of rocks is measured in a through-flow argon atmosphere, the necessary oxygen for this reaction is probably provided by the water released from the water containing minerals and its dissociation. Maghemite is less conductive electrically than magnetite. This is also claimed by Lebedev *et al.* (1988) for rocks from the Ukrainian Shield. According to David and Welch (1956) this reaction could be facilitated by the high water content. We have no data on the water content in depth. The reaction ends at about 375°C. Above this temperature, the electrical conductivity increases. This is due to other phase transitions of Fe-containing minerals: maghemite changes to hematite in the temperature interval 575°-700°C; Fe^{+2} in the amphibole is oxidised to Fe^{+3} in the temperature interval from 550° to 900°C (Minerals,



a) Granite

b) Quartz - Monzonite

FIG. 2. Electrical conductivity curve versus temperature for Boshulia granite (a) and for Plovdiv quartz-monzonite (b), with the possible mineral transitions. The grey area corresponds to the crustal conductivity model, according to the mangetotelluric sounding (Dachev, 1988).

1981). The electrical conductivity increases as well due to the decomposition of biotite (in the granite sample only) for the oxygen fugacity, corresponding to the hematite-magnetite buffer and temperature of 450° -500°C (depending on the water pressure). The biotite decomposes in K-feldspar + magnetite + hematite (Eugster, 1956).

The next abrupt decrease in electrical conductivity in the temperature interval 750° - 820°C (in the granite specimen only - Fig. 2a) coincides with the zone of transition of β-quartz in β_2-tridymite. According to Chelidze *et al.* (1984) a clear anomaly exists in the quartz conductivity at about 870° C, related to the quartz-tridymite transition, as the intergrowing during this phase transition abruptly decreases the electrical conductivity. The critical point of this transition is 867 °C for pure minerals, but it can at lower temperatures, in the presence of additional components (Pixa and Saucier, 1974). For the quartz-monzonite, where the quartz content is considerably lower, the corresponding minimum of the electrical conductivity curve is not visible (Fig. 2b).

With the decrease in temperature, the electrical conductivity also decreases gradually without jumps. This hysteresis is explained as a transition of Fe-containing minerals, especially of hematite (Parhomenko *et al.*, 1991).

All mineral transitions are related to volume changes. The mole volume of maghemite is 7% smaller than that of magnetite; the mole volume of hematite is 8% greater than that of maghemite (after Handbook, 1966). The other phase transitions are also related to volume changes, but it is difficult to make quantitative evaluations. Some transitions may not be reflected in the electrical conductivity curve, but they lead to significant volume changes (for example, the transition of β-quartz to β_2-quartz at a temperature of 573°C, which causes about 5% volume change).

STATIONARY MODEL

The phase transitions described could take place in a real geodynamic situation if an increase in temperature occurs at determined levels in the Earth's crust, caused by regional changes of the heat flow. The increase in pressure does not influence the electrical conductivity, but it changes the points of the phase transitions.

For the region studied, an evaluation of the probable temperatures at depth was published by Dachev (1988). One could equate the temperature axis of the laboratory-obtained curves of electrical conductivity with the corresponding depth axis in the Earth's crust. Besides, magnetotelluric soundings in the region (Dachev, 1988) and sufficiently well localised earthquake hypocenters (Stoyanov *et al.*, 1984) add constraints to the elaboration of an adequate geodynamic model of the studied region. These comparisons are illustrated in Figures 3 and 4. The curves of the absolute values of the electrical conductivity gradient versus temperature are also plotted. The following comments on the two figures can be made:

1) The magnetotelluric model does not exactly coincide with the electric conductivity curves from the specimens, because these specimens are representative of part of the rocks in the Earth’s crust. The presented phase transitions of the Fe-containing minerals occur for plenty of rocks. Magnetite, biotite and amphibole are widely presented in the rocks from the deep part of the crust.

2) At a depth of about 8-9 km in the Earth's crust a characteristic transition occurs from the layer with electrical resistivity of 10 Ωm to the layer with electrical resistivity of about 1000 Ωm, according to the magnetotelluric sounding (Dachev, 1988). This transition occurs in the temperature zone of 200°C and is probably related to the transition from magnetite to maghemite. The process is accompanied by a decrease in electrical conductivity (or the corresponding increase in electrical resistivity).

3) Inside the temperature interval 200° - 330°C, corresponding to depths between 9 and 15 km, the magnetite-maghemite transition is very fast (high gradient of the electrical conductivity). The maximum of curve lg (E.C.) is at a temperature of 270°C. At the temperature of about 330°C the electrical conductivity rises again reaching a maximum at 750°C (for the granite specimen). This is probably related to the transition maghemite ⇒ hematite, as well as to the decomposition of biotite to hematite + magnetite + K-feldspar, and the decomposition of amphibole. Note that a temperature of 330°- 340°C could be appropriate for the boundary inside the Earth's crust, called "Conrad". Its occurence as a seismic refraction boundary has to be perceived as an effect of the transition of rocks to a new physico-mechanical state (Shanov and Kostadinov, 1992).

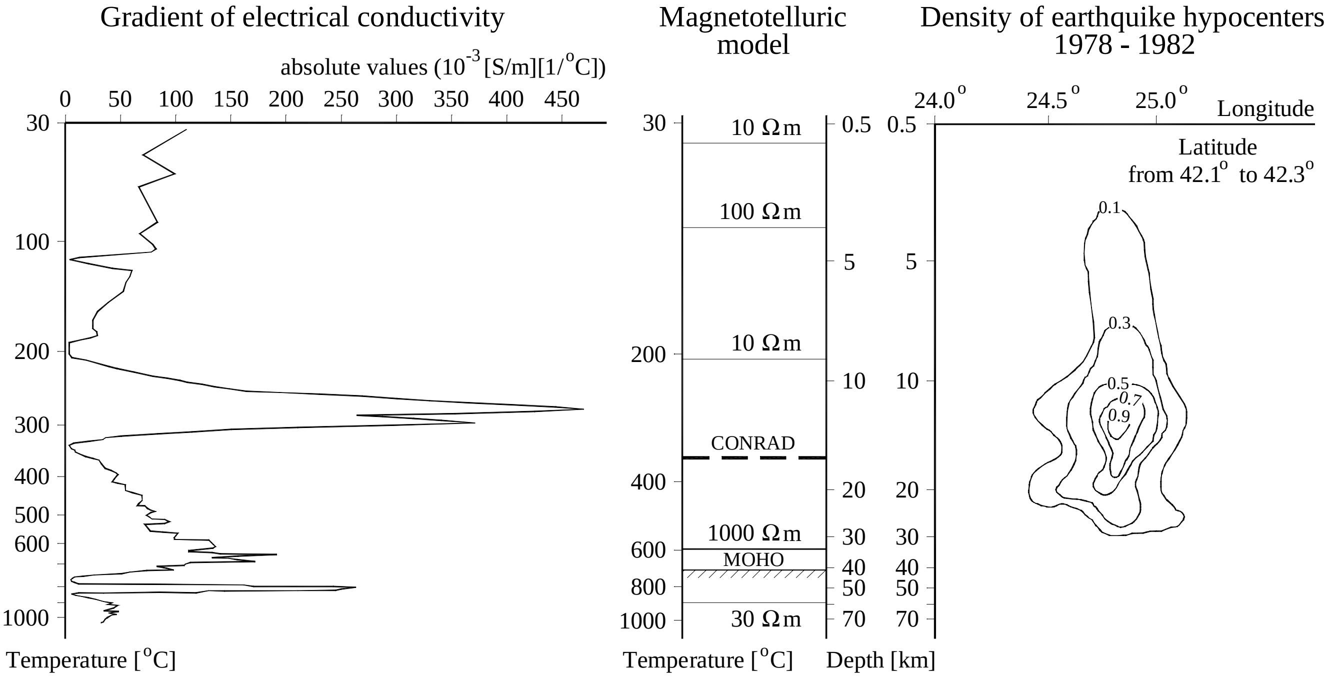
4) The process of increase in electrical conductivity under laboratory conditions is accelerated near a temperature of 600°C and attenuated at a temperature of 750° - 770°C. The maximum electrical conductivity in this interval could be treated as a laboratory inference of the complex processes near the Moho discontinuity. The corresponding depth is marked by a decrease in the electrical resistivity, according to the magnetotelluric sounding (Dachev, 1988).

5) Above a temperature of 800°C, under conditions similar to those in the upper mantle, a decrease in the electrical resistivity is suggested (Dachev, 1988).

6) One remarkable analogy in the model is the coincidence between 10 and 20 km of the maximum gradient of electrical conductivity (Fig. 3a and Fig. 4a) with the concentration of weak earthquakes (Fig. 3c and Fig. 4c).

DISCUSSION ON THE GEODYNAMIC INFERENCES

It was mentioned that with the change in temperature, the phase transitions are accompanied by significant changes in rock volume. In the Earth's crust this could generate a significant increase in stress. This problem was discussed by Austrheim *et al.* (1996). The transformation-induced faulting, when exothermic reaction occurs, is present during the ilmenite ⇔ petrovskite transition. This assertion was discussed by Doglioni *et al.* (1999) and based on the arguments for the occurrence of the transition in the subducting lithosphere (Green and Zhou, 1996). According to a quantitative evaluation performed by Kalinin and Rodkin (1989) the avalanche-like phase transition is caused and speeded up by the kinetic effect of the temperature increase. Quick jumps of phase transitions have been observed at moderate and lower temperatures for phase transitions with large values of activation energy. The same authors have evaluated the volume changes for the main crust and upper mantle phase transitions to be about 10%, which is in agreement with the above volume differences given for mineral transitions in the rocks. Hence, the reason is obvious for the increase in the local weak seismicity, exactly at depths, where the process is most sensitive to temperature changes. The additional stress causes a series of weak earthquakes in order to restore the tectonic equilibrium. It is difficult to relate the weak background seismicity to the occurrence of strong tectonic earthquakes. Figure 3 shows that the strongest earthquakes in the vicinity where the specimens were collected, have hypocenters outside the zone of the maximum concentration of weak earthquakes.



a b c

GRANITE

FIG. 3. Electrical conductivity gradient absolute value curve versus temperature for Boshulia granite (a), and the corresponding electrical resistivity section of the Earth's crust, according to magnetotelluric sounding in South Bulgaria (b). The density of the earthquake hypocenters (c) is calculated along parallel 42.2°.

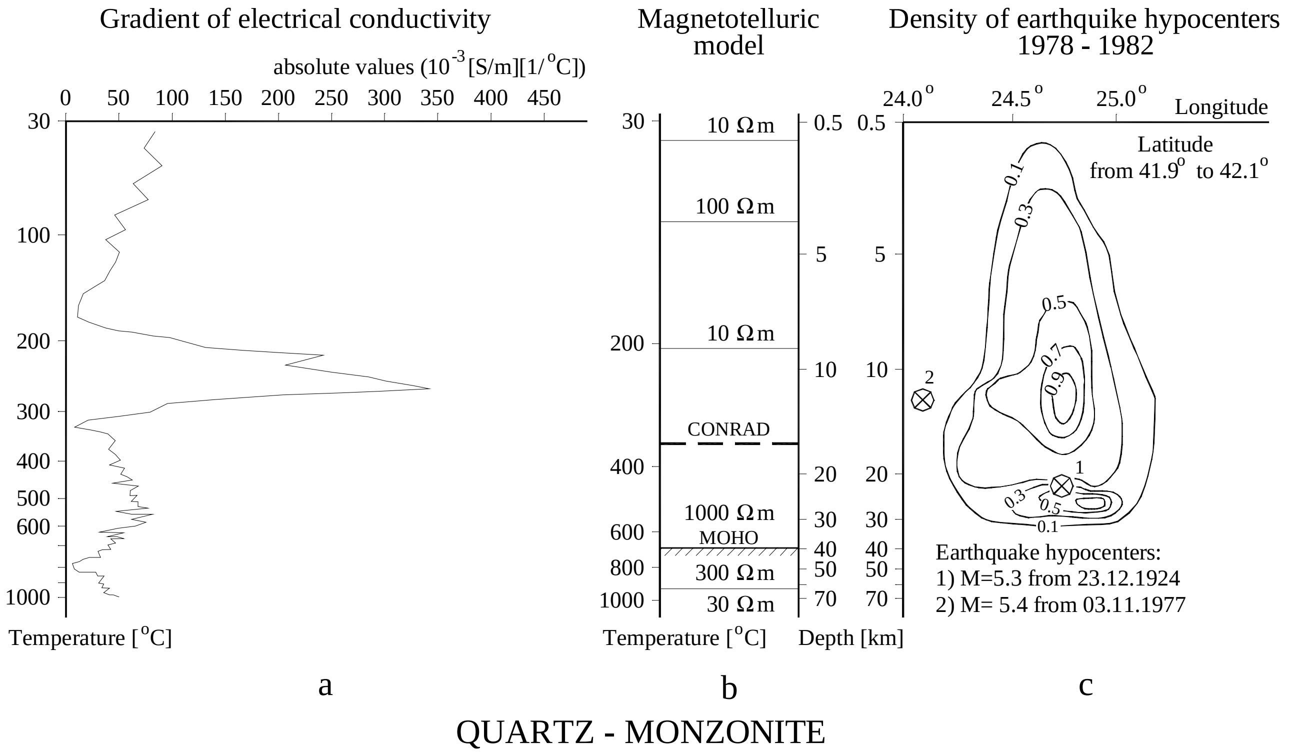


FIG. 4. Electrical conductivity gradient absolute value curve versus temperature for Plovdiv quartz monzonite (a), and the corresponding electrical resistivity section of the Earth's crust, according to magnetotelluric sounding in South Bulgaria (b). The density of the earthquake hypocenters (c) is calculated along parallel 42.0°.

The question is to what may cause the possible temperature changes in the Earth's crust in time is more complicated. In the zones of active contemporary subduction and the associated volcanic arcs, the temperature variations can be explained. In the studied region of the Central Balkan Peninsula, the hypothesis of tectonic blocks sinking is not acceptable because the recent vertical surface movements are positive - 1 to 2 mm/a (Totomanov and Vrablianski, 1980). We can only hypothesise the possibility of a progressing thermal flow from great crustal depths and the upper mantle to the most shallow layers of the crust. The area of the most active influence of heat flow from an uplifting asthenosphere is exactly the zone of the Maritza fault from where the studied specimens were taken.

CONCLUSION

The presented comparison between the results of laboratory studies of granite and quartz-monzonite specimens concerning changes of electrical conductivity with temperature, and the geodynamic features of Southern Bulgaria, suggests a geodynamic model of the processes in the Earth's crust.

An important result is the relationship between the weak background seismicity and the phase transitions in the Earth's crust. This process could result from an increase in temperature caused by the progression of heat flow from the asthenosphere into the shallow layers of the crust at the frontal part of a remaining dense plate from the paleosubduction zone beneath the Rhodopes.

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