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GEOLOGY

Parameters of High-Temperature Conductivity of Alpine-Type Dunite–Harzburgite Ultramafic Rocks of the Urals as a Possible Guide for Their Potential Chromite Mineralization

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Numerous deposits and occurrences of high-quality chromites in the Urals are related to the Alpine-type dunite–harzburgite ultramafic rocks. The chromite ore mineralization is characterized by extremely complicate localization conditions and wide variability of typomorphic features. Diverse viewpoints on genesis and formation conditions of chromite mineralization do not allow unequivocal judgment on the potential of particular ultramafic massifs (see, for example, [1–5]). The existing geophysical methods do not yield an adequate effect [6]. The development of new methods for the forecasting and evaluation of chromite deposits is very topical. The study of high-temperature conductivity probably will allow us to elaborate new untraditional prospecting guides.

The relationship between electric resistance and temperature at 20–900°C has been established previously for several serpentinized ultramafic massifs of the Urals [7]. The parameters of high-temperature conductivity (activation energy E_0 and coefficient of electric resistance R_0 numerically equal to electric resistance R at $\{1/T\} = 0$ in the region of self-conductance) were also established. The linear relationship $\log R_0 = a - bE_0$ has been revealed for all studied objects. Coefficient b varies from 5.8 to 13.2 depending on the affiliation of serpentinites to a certain type of ultramafic rocks. Coefficient a remains virtually the same (7.0–7.4) for all studied samples. Parameters E_0 and $\log R_0$ make it possible to judge the affiliation of the studied sample to ultramafic rocks of a certain lithostructural complex of rock association. For ultramafics of the dunite–harzburgite association, coefficients a and b are equal to 7.2 and 12.8, respectively. As has been shown, the linear relationship $\log R_0 = a - bE_0$, with respective coefficients a and b, is valid for the rocks of barren massifs and local areas therein. It was noted that parameters E_0 and $\log R_0$ for the samples taken close to the ore occurrences deviate from the values that characterize the samples from barren massifs and local areas. The data points of these samples in E_0–$\log R_0$ coordinates depart from the general $\log R_0 = a - bE_0$ trend established previously [7] for ultramafic rocks of the Alpine-type dunite–harzburgite association. This departure shows inverse correlation with the sampling distance relative to the ore zone [8].

The present work further develops the aforementioned investigations. Its main objective was to study variation of conductivity (electric parameters) of serpentinites that host chromite mineralization with physical, physicochemical, and mineralogical–petrographic methods. The techniques of measurement of high-temperature conductivity of rock specimens and electric parameters have been described in [7, 9]. The samples for study were cut as cubes, 0.015 m along the edge. The heating rate was 0.066°C/s. Temperature was measured with a chromel–alumel thermocouple. The DC electric resistivity was measured with a two-electrode set at 10° intervals within a temperature range of 20–900°C (E6-13 teraohmmeter, dynamic range 10–10^{14} Ω, and variation of the relative measurement uncertainty from ±2.5% at the beginning to 4% at the end of the dynamic range).

To determine the electric parameters, the curves of high-temperature conductivity were plotted in $\log R - 1/T$ coordinates. Activation energy E_0 was determined from the slope of the tangent to curve $\log R = f(1/T)$ at a cer-

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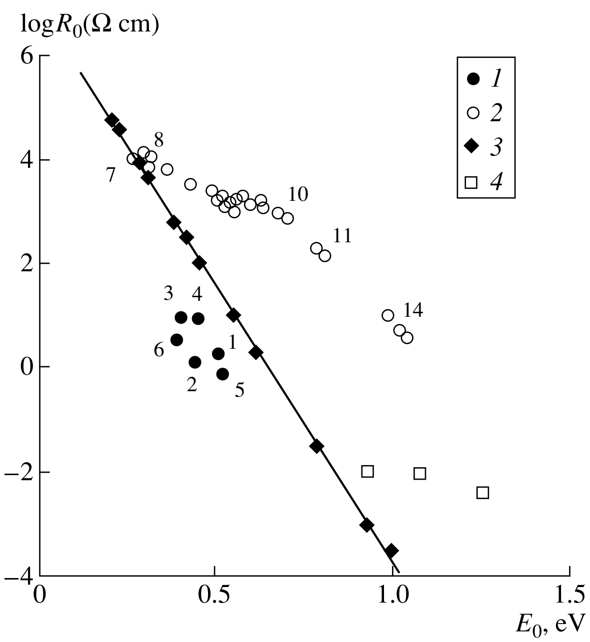
Mineral composition of the studied serpentinites, %

<table>
<tr><th rowspan="2">Mineral</th><th colspan="12">Sample no.</th></tr>
<tr><th>7</th><th>8</th><th>9</th><th>10</th><th>11</th><th>12</th><th>13</th><th>14</th><th>15</th><th>16</th><th>17</th><th>18</th></tr>
<tr><td>Olivine</td><td>58</td><td>40</td><td>5</td><td></td><td></td><td>3</td><td></td><td></td><td>65</td><td>45</td><td>50</td><td>55</td></tr>
<tr><td>Hypersthene</td><td rowspan="2">10</td><td rowspan="2">6</td><td></td><td></td><td></td><td>20</td><td></td><td></td><td rowspan="2">5</td><td rowspan="2">5</td><td rowspan="2">5</td><td rowspan="2">2</td></tr>
<tr><td>Augite</td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Hornblende</td><td>8</td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td>7</td><td></td><td>3</td></tr>
<tr><td>Antigorite</td><td rowspan="2">16</td><td rowspan="2">44</td><td>45</td><td rowspan="2">65</td><td>60</td><td>55</td><td rowspan="2">50</td><td rowspan="2">70</td><td rowspan="2">29</td><td rowspan="2">35</td><td rowspan="2">40</td><td rowspan="2">38</td></tr>
<tr><td>Chrysotile</td><td>10</td><td>12</td><td></td></tr>
<tr><td>Serpophite</td><td></td><td></td><td>5</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Talc</td><td>6</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Brucite</td><td></td><td></td><td></td><td></td><td></td><td></td><td>1</td><td>10</td><td></td><td>5</td><td></td><td></td></tr>
<tr><td>Spinel</td><td></td><td></td><td>35</td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td><td></td></tr>
<tr><td>Carbonate</td><td></td><td></td><td></td><td>30</td><td>18</td><td>17</td><td>43</td><td></td><td></td><td>2</td><td>1</td><td>1</td></tr>
<tr><td>Ore</td><td>2</td><td>5</td><td></td><td>5</td><td>10</td><td>5</td><td>6</td><td>20</td><td>1</td><td>1</td><td>4</td><td>1</td></tr>
</table>

tain point of the straight segment where this curve was not distorted by anomalous effects. The coefficient of conductivity R_0 was determined as an intercept of the tangent on the ordinate axis. The parameters of high-temperature conductivity E_0 and $\log R_0$ in the region of self-conductance were determined in all samples precisely in this way.



Relationship between E_0 and $\log R_0$ in the studied samples of serpentinites and chromite ore. (*1*) Massive chromite ore of the Podennoe deposit; (*2*) serpentinite from the Podennoe deposit; (*3*) serpentinite from other ultramafic massifs [7]; (*4*) serpentinite from the P'yanoborsk deposit in the Klyuchevsky massif. The straight line demonstrates correlation $\log R_0 = f(E_0)$ for serpentinites from barren dunite–harzburgite massifs and local areas therein [7]. Numerals in the figure are sample numbers.

Samples of ore and host rocks were taken from the Podennoe chromite deposit localized in the Alapaevsk ultramafic massif. The chromite ore samples were taken from the open pit and the host rock samples were taken at different distances from the orebodies. In total, we took 6 ore samples and 12 serpentinite samples. Each sample was cut into 5 cubes to investigate the high-temperature conductivity. Thin sections were prepared from all samples and examined under a microscope (chromite ores were additionally investigated in polished sections).

All samples consisted of chromite (80–90%) and serpentine (5–20%). The subordinate and rare minerals are represented by magnetite (from traces to 3%), hornblende (from single grains to 1%), carbonate (4%, sample 4), spinel (2%, sample 3), and pyrite (<1%, sample 5). Chromite is completely opaque in the transmitted light (samples 1 and 4), locally translucent (sample 2), completely dark (sample 3), from dark to ruby-colored (sample 5), or completely translucent with a reddish color (sample 6). Magnetization of some chromite samples is caused by occurrence of magnetite (chromite is nonmagnetic). The translucence is typical of the Fe-poor and Mg-rich Cr-picotite (Mg, Fe)Cr_2O_4–$MgCr_2O_4$. The host rocks are chrysotile–antigorite serpentinites. Numerous relicts of olivine and bastite, as well as structural–textural features of serpentinites, indicate that the protolith was composed of dunite and harzburgite, which underwent subsequent retrograde metamorphism. The samples are represented by partly serpentinized harzburgite, serpentinite, and carbonated serpentinite. The major minerals are olivine (0–65%), serpentine (16–65%), pyroxene (0–20%), and ore minerals (1–20%). The subordinate minerals are hornblende (0–5%), brucite (1–10%), talc (6%), and spinel

(5%). The mineral composition of particular samples is presented in the table. In terms of grade of metamorphism, the rocks may be classified into slightly metamorphosed (samples 7, 15), moderately metamorphosed (samples 8, 16–18), strongly metamorphosed (samples 9, 12), and completely metamorphosed (samples 10, 11, 13, 14) varieties. Some rocks underwent carbonatization (samples 10–13) and ore metasomatism (samples 11 and 14).

The figure demonstrates the relationship between E_0 and $\log R_0$ in the studied samples of serpentinites and chromite ore. For the sake of simplicity, the figure presents only a part of the results that exhibit variation of parameters with metamorphic grade. Some data points are supplemented with numbers of the samples mentioned in the text and the table in order to track the dependence of electric parameters on metamorphic grade. The parameters of some serpentinite samples from the P'yanoborsk deposit located in the Klyuchevsky Massif are shown for comparative purposes.

CONCLUSIONS

Relationships between electric resistivity and temperature within an interval of 20–900°C were obtained for the samples of ore and host rocks from the Podennoe chromite deposit. We have established parameters of high-temperature conductivity (activation energy E_0 and coefficient of electric resistance $\log R_0$). The results obtained confirm the previously drawn conclusion: the $\log R_0 = a - bE_0$ relationship with coefficients typical of Alpine-type ultramafics is valid for barren massifs and local areas therein. The data points of chromite-bearings massifs and local areas deviate from this general trend. The deviation shows inverse correlation with the sampling distance relative to the ore zone. This relationship probably may serve as a prospecting guide for chromite mineralization within ultramafic massifs or local areas therein. Energy of activation decreases with the grade of metamorphism in consistence with results of previous investigations [10]. The scatter of data points for chromite ore is statistically stable and accounts only for compositional variation of Cr-spinel.

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