Mineralogical characterization and evaluation of chromite ore in Grevena and Kozani Vourinos massif, Western Macedonia, Greece

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Abstract

**Purpose.** Chrome samples from Aetoraches mine area in the southern part of the Vourinos complex in Western Macedonia, Greece were examined from mineralogical-geochemical perspective.

**Methods.** X-ray Diffraction (XRD) mineral phase analysis, elemental Scanning Electron Microscopy coupled with Energy Dispersive Spectroscopy (SEM-EDS) analysis and Thermogravimetry/Differential Thermogravimetry (TG/DTG) were carried out.

**Findings.** The XRD results showed that all the samples contain mainly magnesium- and aluminum-chromite (“aluminum-picrochromite”) phases, along with forsterite (magnesian olivine), serpentine and chlorite occurrences. Based on the SEM-EDS results, the computed average chemical formula indicative of this specific chromite type is: (FeO0.4MgO0.2)(Cr1.6Al0.4)O4. The TG-DTG weight losses found to be in the range of 4.4-14.36%, at temperatures between 600 and 750°C, indicated the presence of the hydroxyl-rich silicate minerals, serpentine and chlorite, in agreement to the Loss of Ignition (LOI) results. The mineral phases detected in the present analyses appear in the dunite/diorite/harzburgite/peridotite main rocks of the ophiolitic complex that hosts the chromite ore.

**Originality.** In the current research, an original characterization, via thorough elemental, phase and thermal analysis, is carried out aiming to enlighten the geochemistry aspects of the Vourinos chromite complex, Region of Western Macedonia, Greece, particularly of easily accessible and exploitable chromite deposits of the Aetoraches mine area.

**Practical implications.** The chromite mineral, and especially the metallurgical type, is of substantial importance in metal industry. In that sense, the findings of the present investigation of chromite purity and mineral structure is a prerequisite for future exploitation of the Aetoraches chromite deposits in particular and broadly for the ongoing exploitation of chromite ore in the Vourinos complex, situated in Region of Western Macedonia, Greece, an area with high unemployment and rather slow economic growth.

**Keywords:** chromite ore, Vourinos massif, Aetoraches mine area, mineralogical characterization, geochemistry, XRD, SEM-EDS, TG/DTG

1. Introduction

Chromite is a mineral that belongs to the spinel group and is found in nature in ultrabasic rocks (dunite, harzburgite). The technological classification of chromite ores into categories depends on the Cr/Fe ratio and the aluminum content as follows: metallurgical chromite type Cr/Fe > 2.8:1; refractory chromite type Cr/Fe < 2.5:1. This mineral, a ferrous and chromium variant of spinel (MgAl2O4) with the general chemical formula (Mg, Fe2+) (Cr, Al, Fe3+)2O4 constitutes an insignificant phase of basic and ultrabasic rocks and is of petrogenetic significance [1], while the combination with the content of various trace elements in chromatic ores appears to have particular importance for chromitogenesis.

Generally, chemical composition of the chromite is characterized by large variation, mainly in trivalent elements, from Cr-rich (metallurgical type) to Al-rich (refractory type). Various trace elements, such as elements of the platinum group (Os, Ir, Ru, Rh, Pt and Pd), or PGE, Ni, Cu, Co, V, Zn and Ti could likely appear as self-existing minerals (PGM, oxides of Ti) or replace major elements on the chromite lattice. For instance, V and Ti replace Cr and Al into octahedral positions, while Mn, Zn and Co substitute Mg and Fe2+ into tetrahedral positions of chromite [2, 3].

Some ophiolitic complexes host large deposits of chromite of metallurgical type (i.e. the ophiolite complexes of Vourinos Greece, Bulqiza Albania, the Acjoie on Philippines) or only of refractory type (Othrys Greece, Coto in the Philip-
pines). Other complexes contain the two types of Cr- and Al-rich chromites (Pindos, Skyros, Rhodope massive in Greece) [4][7]. Important chromite-bearing occurrences in Greece could be found in Halkidiki (80 km long and 10 km wide), Pieria (Livadi area), Soufli, Veria, Rhodes and finally the Pindos ophiolitic complex.

In the ophiolitic complexes that host a chromite type, the contents of Ti, V, Zn, Co, and Cu are higher in the refractory type (Othrys) than in the metallurgical one (Vourinos), consistent with the behavior of Cr, Al and trace elements during its process of partial melting [8]. Greece could be one of the chromite producing countries with potential exploitable reserves of over 5 million tons with a floating content between 8 and 54% Cr₂O₃. A new promising investment is expected in the wider Kozani-Grevena area of the Western Macedonia Prefecture, for extraction and processing/enrichment of chromite by the mining company Hellenic Mines S.A.

In the current study, a thorough elemental, phase and thermal analysis is carried out, aiming to shed light on the geochemistry and exploitation aspects of the Vourinos complex and especially of the easily accessible and exploitable chromite deposits of the Aetorachi mine area.

2. Geologic and geotectonic setting

Most ophiolitic complexes included in the Greek mountain ranges mainly appear in the central and northern section of the country:

a) the series of ophiolites in the western margin of the Pelagonian massif (ophiolitic complexes of Orthis and Pindos mountains), in the Pelagonian mountain range (Vourinos massif) and in the eastern margin of Pelagonian range (Vernio, Veria and Eastern Thessaly);

b) in the Western Halkidiki (Vavdos, Ormylia Gerakini);

c) in Serbo-Macedonian massif (Gomati, Nigrita) and Rodopi mountain range (Soufli, Exohi Drama) [6].

The geotectonic environment where the ophiolitic complexes are formed is positioned above a submerged plate or as it could be called supra subduction zone, where in most cases an evolution of the geotectonic environment is observed. Most peridotites, accompanied by dunites are in Greece characterized by a relatively strong degree of extraction [2].

Some ophiolitic complexes are known to host exclusively large metallurgical chromite deposits, such as the massifs of Vourinos, Bulgaria, Albania, Acoje in the Philippines, or only refractory type (Othrys Greece, Coto in the Philippines) and others containing the two types of Cr- and Al-rich chromites, for example Pindos, Skyros, and Rhodope massif [4], [7].

Since the ophiolitic complexes to which Al- and Cr-rich chromite deposits or chromium occurrences are linked with, are characterized by petrological and geochemical characteristics that are consistent with a specific geotectonic environment, the composition of chromite ores is related to the composition of the parent magma and this in turn with the geotectonic environment.

In Region of Western Macedonia, Northern Greece, chromite deposits are observed both in Pindos and Vourinos ophiolite complex. However, Vourinos ophiolites [9] (Fig. 1) are much larger and most exploited [10], [11]. The ophiolitic complex of Vourinos is a Jurassic emplacement (Upper Liassic-Lower Malm) representing alterations of dunite and harzburgite with compact peridotites embedded by mainly pegmatites of gabbro-pyroxenite in the transition zone.

In particular, this complex represents a mid-Jurassic ophiolitic slab thrusted during upper Jurassic time towards the east over the Pelagian Margin representing a sedimentary-tectonic mélange [12]. A serpentinite alteration zone after dunite and harzburgite is observed, showing a main direction SE-NW close to Chromium village. In the past, many chromite mines were operating in several localities of Northern, Central and Southern Vourinos district [11] (Fig. 2).

3. Materials and methods
3.1. Sampling

Various chromatite mines of Vourinos complex were mined in the past. In Table 1, the most significant of those are shown.

All samples characterized in this study were collected from “Aetorache” area in the North of Vourinos complex. Specifically two samples were collected from each site. The GPS coordinates of each site are 40°06’23.6″, 21°43’09.2″ for position A and 40°06’24.1″, 21°43’09.1″ for position B.

In Table 2, sampling areas and sample names are listed while, in Figure 3, photographs of the two sampling positions are shown.
Table 1. Selected data of main chromatite mines of Vourinos complex mined in the past

<table>
<thead>
<tr>
<th>Mine</th>
<th>Location</th>
<th>Reserves</th>
<th>Form</th>
<th>Host</th>
</tr>
</thead>
<tbody>
<tr>
<td>Xerolivado</td>
<td>Centre of the southern Vourinos</td>
<td>The largest ore body in the complex. Its total reserves are estimated at about 3.2 Mt of which 2.2 Mt has been exploited</td>
<td>Schlieren chromite ores. Also pods of massive ore bodies</td>
<td>Hosted by the largest dunite body within Vourinos</td>
</tr>
<tr>
<td>(Skoumtsa)</td>
<td>Vourinos District</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Aetorache</td>
<td>Southern Vourinos District to the north of Xerolivado mine</td>
<td>A hundred of thousands of tons</td>
<td>Often massive with minor schlieren and disseminated ores</td>
<td>Hosted by dunite within regional harzburgite</td>
</tr>
<tr>
<td>Rizo</td>
<td>Northern Vourinos district</td>
<td>A hundred of thousands of tons</td>
<td>Dominantly disseminated ore with small massive chromitite lenses</td>
<td>Hosted by dunites – harzburgites and serpentinites</td>
</tr>
<tr>
<td>Potamia</td>
<td>Small mine to the south of the Xerolivado mine</td>
<td>Reserves are calculated to just 30.000 t</td>
<td>Disseminated and rare schlieren ore</td>
<td>Hosted by a thin dunite envelope within regional harzburgite</td>
</tr>
<tr>
<td>Fouroio</td>
<td>Located in the easternmost part of southern Vourinos</td>
<td>Only some thousands tons</td>
<td>Disseminated ore out of the metalliferous zone</td>
<td></td>
</tr>
</tbody>
</table>

Table 2. Sampling area, positions and sample names

<table>
<thead>
<tr>
<th>Area</th>
<th>Position</th>
<th>Sample name</th>
</tr>
</thead>
<tbody>
<tr>
<td>Aetorache</td>
<td>A</td>
<td>A1</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>B1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>B2</td>
</tr>
</tbody>
</table>

Figure 3. Photographs of the two sampling positions, where the four samples were collected

3.2. Analytical methods

X-Ray Diffraction (XRD) was carried out in order to identify the mineralogical phases which are present in the chromatite samples. In order to conduct the XRD measurements, the chromatite samples were mechanically crushed and sieved through a 45 μm stainless steel sieve to obtain fine powder. XRD analysis was performed using a SIEMENS 5005 Diffractometer (Ni filtered, Cu Kα = 1.54050 Å). The 2θ scan range varied from 2 to 65°. Phase identification and quantification were carried out by matching the acquired diffractograms with the EVA software, COD-AMCSD database. The phase identification and the XRD measurement procedure includes approximate instrumental error 2 wt %, regarding the phase composition.

Morphological examination was conducted by means of Scanning Electron Microscopy (SEM), using a JEOL 6610LV. The elemental analysis was carried out using an X-Max 80 (Oxford Instruments) Energy Dispersive Spectroscopy (EDS) detector attached to the SEM. Images, elements maps and spectra were obtained and analysed using AZtech-Nanoanalysis software. Prior to SEM observation all samples were coated with carbon to avoid charging under the electron beam.

Loss on Ignition (LOI) measurements were conducted using a LECO TGA701, in the low temperature range of 25-107°C with a heating rate of 6°C/min in N₂ atmosphere, while in the high temperature range of 107-950°C with a heating rate 43°C/min and O₂ atmosphere.

Thermogravimetric analyses (TG/DTG) were conducted using a LECO TGA701 device in the temperature range of 25 to 1000°C with a heating rate 10°C/min, under air atmosphere with a flow rate of 3 L/min.

All analytical methods and measurement, except XRD methodology, were conducted in the laboratory of Applied Geochemistry, Mineral Resources Engineering Department, at University of Western Macedonia, Greece.

4. Results and discussion

In Figure 4, the XRD patterns of the A1 (a) and A2 (b) samples are shown, while the characteristic peaks corresponding to the major crystallographic phases are indicated. Phase identification analysis on samples A1 and A2 has shown that chromite is found in two forms: magnesio-chromite (Mg, Fe)(Cr, Al)₂O₄ and aluminium chromite Fe₃(Al, Cr)₂O₆. Moreover, on these samples, forsterite (Mg₂SiO₄) and clinohumosite Mg₃Si₂O₅(OH)₄ phases were detected.

In Figure 5, the XRD patterns of the B1 (a) and B2 (b) samples are presented, where the characteristic peaks corresponding to the major crystallographic phases are indicated. Phase identification analysis on samples B1 and B2 has shown that except the aforementioned crystallographic phases detected in A1 and A2 samples, pyroaurite Mg₆Fe₂CO₃(OH)₁₁·4H₂O and clinochlore Mg₅Al(Si₃Al)O₁₆(OH)₈ may also be present in these samples.

In Table 3, the major phase analysis results from the XRD measurements are summarized. In overall, XRD results interpretation indicates that all samples collected from the investigation site (Aetorache, North Vourinos) mainly contain magnesium and aluminium chromite (“aluminium picrochromite”), accompanied with forsterite minerals (magnesium containing olivine), serpentine and chlorite occurrences.
Additionally, occupancies of the pseudo calcite-hydrotalcite group (pyroaurite, stichtite) are observed. These minerals occur in dunite/diorite/harzburgite/peridotite assemblage as the main rocks of the ophiolite complex which host the chromite ore.

LOI (Loss of Ignition) measurement results are summarized in Table 4. According to these results, it is clear that samples with high amounts of minerals belonging to serpentine group and moderate amounts of chlorite group minerals and pyroaurite correspond to higher LOI values (11.04 to 12.96%, on dry basis) likely at lower temperatures.

On the other hand, samples with chromite dominated assemblages show lower values of LOI (3.86 to 4.23%) probably at higher temperatures mainly due to the presence of minor hydrous and carbonaceous phases and the high resistance character of chromite to decompose at moderate temperatures.

Thermogravimetry (TG) and Differential Thermogravimetry (DTG) results for samples A1 (a), A2 (b) and B1 (a), B2 (b) are recorded below in Figures 6 and 7 respectively. Four main peaks are identified, which reflect four different temperature ranges, as follows:

- 40-120°C, most likely referring to partial decomposition of pyroaurite (belonging to hydrotalcite group);
- 170-230°C, where a second split of pyroaurite occurs;
- 370-420°C, with the decomposition probably of chrysotile (kaolinite-serpentine group); and
- 650-720°C, with partial cleavage of clinohlore (chlorite group).

The products of the above decomposition processes might likely correspond at low temperatures to volatile matter, and as temperature increases, several oxides and silicate phases are formed. The pattern for both TG and DTG curves are more or less the same for all samples examined. Specifically, the % weight loss, for all samples, is varying between 4.4 and 14.36%, in the temperature range 600 to 750°C. In this temperature range, the decomposition of some hydrated siliceous minerals (e.g. serpentinite, chlorite) towards the formation of metal oxides is probably taking place. These results are relevant to LOI data mentioned above.

Results from SEM-EDS mapping of A1 sample are indicated in Figure 8. As it can be observed from the individual elemental maps in Figure 8c, there are two distinct microphase types: one with the major elements being Cr, Fe and Al, and a second one where the major elements are Si and Mg. In order to shed light into the precise composition of each microphase type, several points in each distinct area were examined.

### Table 3. Phase analysis results from the XRD

<table>
<thead>
<tr>
<th>(wt %)</th>
<th>Sample A1</th>
<th>Sample A2</th>
<th>Sample B1</th>
<th>Sample B2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Magnesiochromite (Mg, Fe)(\text{Cr},\text{Al})\text{O}_4)</td>
<td>23.99</td>
<td>22.17</td>
<td>50.57</td>
<td>50.53</td>
</tr>
<tr>
<td>Aluminian chromite (\text{FeAl}_2\text{O}_4)</td>
<td>25.71</td>
<td>23.77</td>
<td>24.89</td>
<td>24.88</td>
</tr>
<tr>
<td>Forsterite, Syn (Mg\text{Si}_2\text{O}_5)</td>
<td>5.06</td>
<td>4.68</td>
<td>11.43</td>
<td>11.43</td>
</tr>
<tr>
<td>Clinochrysolite (\text{Mg}_2\text{Si}_5\text{O}_10)</td>
<td>45.24</td>
<td>49.37</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td>Pyroaurite (\text{Mg}_2\text{Fe}_2\text{O}_7\cdot4\text{H}_2\text{O})</td>
<td>0</td>
<td>0</td>
<td>10.37</td>
<td>10.42</td>
</tr>
<tr>
<td>Clinochlore (\text{Mg}_2\text{Al}_2\text{Si}<em>5\text{O}</em>{10}\cdot\text{H}_2\text{O})</td>
<td>0</td>
<td>2.74</td>
<td>2.74</td>
<td>2.74</td>
</tr>
</tbody>
</table>

### Table 4. Moisture and LOI measurements

<table>
<thead>
<tr>
<th>Sample ID</th>
<th>Moisture (%)</th>
<th>LOI (%)</th>
<th>LOI (dry basis) (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sample A1</td>
<td>1.10</td>
<td>10.18</td>
<td>9.18</td>
</tr>
<tr>
<td>Sample A2</td>
<td>1.56</td>
<td>12.43</td>
<td>11.04</td>
</tr>
<tr>
<td>Sample B1</td>
<td>0.52</td>
<td>4.36</td>
<td>3.86</td>
</tr>
<tr>
<td>Sample B2</td>
<td>1.63</td>
<td>14.38</td>
<td>12.96</td>
</tr>
<tr>
<td>Sample A1 + B1</td>
<td>0.44</td>
<td>4.65</td>
<td>4.23</td>
</tr>
</tbody>
</table>
In Figure 9, the point-by-point identification SEM-EDS image is presented, while Table 5 summarizes the elemental compositions of all samples and the individual points marked in Figure 9, expressed in both wt % and at %. Rather similar results were obtained from the corresponding SEM-EDS analysis conducted for B1 sample, as shown in Figures 10 and 11 and Table 6.

As indicated from the SEM-EDS maps above, the main elements Mg and Al that are included in lattice are present in relatively high but varying amounts. However, basic ophiolitic constituents of a peridotite/dunite complex, such as magnesium olivine, serpentinite, ortho-pyroxenes and chlorites should be also present based on the elemental compositions recorded. In that sense, the SEM-EDS results shown above are in good accordance with literature findings [13], [14] and the XRD and TGA results presented here.

According to Grivas et al. [9] all exploitable chromian spinel deposits mined from the ‘50s until the early ‘90s are developed within a characteristic zone named as “metalliferous zone”. Analytical results of this study (Tables 5 and 6) for all samples investigated indicate that the average ratio of Cr/Cr + Al varies between 0.77 and 0.78, and that of Mg/Mg + Fe ranges from 0.56 to 0.59.
These figures are very close to those reported by Kapso-
tis [13] from the Voidolakos and Xerolivado mines, Vouri-
nos ophiolite complex. Thus, these chromites could be classi-
fied as magnesium chromites in the solid solubility system,
shown in the form of a simplified quadratic solid solutions
chart in Figure 12.

Assuming the ideal magnesium chromite stoichiometry
(MgCr$_2$O$_4$), the divalent magnesium ion (Mg$^{2+}$), according to
the SEM-EDS results (Tables 5 and 6) is partially replaced by
the divalent ferrous ion (Fe$^{2+}$) by more than 40 at% in the
solid solution series chromite–magnesium chromite
(Fe$_{0.5}$Mg$_{0.5}$O$_4$). Simultaneously, a partial replacement of the triva-
 lent chromium ion (Cr$^{3+}$) by the trivalent aluminum ion (Al$^{3+}$)
by more than 20 at% also occurs. These chemical processes
are indicative of a geochemical environment rich in magnes-
ium and aluminum, possibly in aluminosilicates, such as ser-
pentine, chlorite and tremolite. Apparently, there are several
natural solubility solid-state geochemical systems with up to
100% substitution of chromite by magnesium chromite and
vice versa (Fe$^{2+}$ ↔ Mg$^{2+}$) in tetrahedral positions of the lattice,
magnesium chromite by spinel (Cr$^{3+}$ ↔ Al$^{3+}$) in octahedral
positions, spinel by hercynite and hercynite by chromite.
These successive substitutions are mainly due to the similari-
ty of the ionic radii of the divalent and trivalent cations in-

### Table 5. Point & ID results based on the SEM image of Figure 9

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Spectrum No.</th>
<th>Elemental composition in wt %</th>
<th>Elemental composition in at %</th>
</tr>
</thead>
<tbody>
<tr>
<td>A1</td>
<td>37</td>
<td>Cr 43.0 Fe 14.7 Al 6.6 Mg 8.1 Si 27.5 O 7.3 Ni 9.9 Mn 50.7</td>
<td>Cr 7.8 Fe 7.3 Mg 9.9 O 50.7</td>
</tr>
<tr>
<td>A1</td>
<td>38</td>
<td>Cr 3.1 Fe 28.6 Al 21.5 Mg 46.7 O 7.3 Ni 9.9 Mn 50.7</td>
<td>Cr 1.1 Fe 7.3 Mg 9.9 O 50.7</td>
</tr>
<tr>
<td>A1</td>
<td>39</td>
<td>Cr 43.8 Fe 14.4 Al 6.5 Mg 7.9 Si 27.4 O 7.3 Ni 9.9 Mn 50.7</td>
<td>Cr 24.4 Fe 49.9 Mg 9.9 O 50.7</td>
</tr>
<tr>
<td>A1</td>
<td>41</td>
<td>Cr 0.4 Fe 16.5 Al 28.5 Mg 6.4 Si 48.1 O 7.3 Ni 9.9 Mn 50.7</td>
<td>Cr 0.2 Fe 6.3 Mg 9.9 O 50.7</td>
</tr>
</tbody>
</table>

### Table 6. Point & ID results based on the SEM image of Figure 11

<table>
<thead>
<tr>
<th>Sample name</th>
<th>Spectrum No.</th>
<th>Elemental composition in wt %</th>
<th>Elemental composition in at %</th>
</tr>
</thead>
<tbody>
<tr>
<td>B1</td>
<td>32</td>
<td>Cr 44.8 Fe 12.5 Al 6.8 Mg 7.9 Si 27.9 O 7.3 Ni 9.9 Mn 50.7</td>
<td>Cr 25.3 Fe 6.6 Mg 9.9 O 50.7</td>
</tr>
<tr>
<td>B1</td>
<td>33</td>
<td>Cr 2.5 Fe 28.6 Al 23.4 Mg 45.4 O 9.9 Ni 9.9 Mn 50.7</td>
<td>Cr 0.9 Fe 24.0 Mg 9.9 O 50.7</td>
</tr>
<tr>
<td>B1</td>
<td>34</td>
<td>Cr 44.6 Fe 13.3 Al 6.6 Mg 8.0 Si 27.5 O 9.9 Ni 9.9 Mn 50.7</td>
<td>Cr 25.3 Fe 7.0 Mg 9.7 O 50.7</td>
</tr>
<tr>
<td>B1</td>
<td>35</td>
<td>Cr 6.7 Fe 28.0 Al 17.8 Mg 47.1 O 9.9 Ni 9.9 Mn 50.7</td>
<td>Cr 2.5 Fe 23.7 Mg 60.6 O 0.1</td>
</tr>
</tbody>
</table>

Figure 10. SEM-EDS maps from sample B1

Figure 11. SEM image related to Point & ID analysis from sample B1

Figure 12. Quadratic Solid Solutions Series of chromite with the indication of computed average chemical formula of the magnesium chromite examined according to SEM-EDS results
volved, in the tetrahedral and octahedral crystallographic sites respectively, but also to the actual formation conditions of temperature and pressure. It is worth noting that the average stoichiometric chromite formula for the SEM-EDS analysis result is (Fe₉₀₋₂Mg₂₋₅)(Cr₁₋₆Al₃₋₅)O₄ (Fig. 12). Moreover, according to the SEM-EDS Point & ID analysis results of the A1 and B1 chromite samples (Tables 5 and 6), Cr/Fe ratios reveal mean values 3.18 and 3.73 for sample A1 and sample B1 respectively. In accordance with relevant literature findings [6], [12], these values underline the considerable presence of metallurgical type of chromite.

5. Conclusions

XRD results indicate that all the samples in the research area (Aetorachi, South Vourinos) contain magnesium and aluminum-chromite (“aluminum-picrochromite”) along with forsterite (magnesian olivine), serpentine and chlorite occurrences; also, occurrences of the hydrotalcite group (pyroaurite/stichtite). These minerals appear in the dunite/diorite/harzburgite/ peridotite association as the main components of the ophiolitic complex that host the chromite ore.

The above results are also confirmed by semi-quantitative elemental analyses using SEM-EDS: from the chemical elements that are present in chromite, chromium is present in all samples in relatively high amounts, along with variable magnesium, aluminum and iron amounts. The indicative average chemical formula of this specific chromite type is calculated to be: (Feₓ₀₋₂Mgₓ₋₅)(Cr₁₋₆Al₃₋₅)O₄. It is worth noting that, since the Cr/Fe ratio is higher than 2.8/1, the chromite of the Aetorache sampling area can be classified as metallurgical chromite.

The LOI of the samples with higher content of chlorite/serpentine/tremolite/pyroxaurites paragenetic accessory minerals in the chromite deposits is comparatively much higher at relatively low temperatures (11.04 and 12.96%) than the samples where the chromite predominates quantitatively (3.86 and 4.23%) with lower volatile phase contents (hydrates and carbonates).

The TG/DTG results indicated weight losses in the range of 4.4 to 14.36%, at temperatures between 600 and 750°C, where the decomposition of some hydroxyl-rich silicate minerals (serpentinite, chlorite) occurs, followed by formation of metal oxides. These findings are quite comparable to LOI (%) results.

The results of the current research can be useful for the ongoing and future exploitation of chromite ore in the Vourinos complex, which is situated in Region of Western Macedonia, Greece, an area with high unemployment and rather slow economic growth.

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References


Мінералогічна характеристика та оцінка хромітової руди в масиві Греєна та Козани Вурінос, Західна Македонія, Греція

А. Баклаварідіс, К. Ваталіс, В. Караянніс, П.-Н. Бенетіс, Г. Харалампідес

Мета. Дослідження зразків хромітової руди з рудника “Етораче” в південної частині масиву Вурінос у Західній Македонії, Греція, з мінералого-геохімічної точки зору для оцінки можливості його промислової розробки.

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Meta. Dosiadjenije zrazkov kromitovyh rud z rudnika “Etorache” v p'evdenni chastini massiva Wuriunos u Zakhidnoj Makedonii, Greciya, z mineralogo-geokhimichnoj tochki zoru dlia otsenki mogilivos'j yego promyslovoj rozrobki.

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Методика. Были проведены рентгеноструктурный анализ минеральной фазы (РФА), элементная сканирующая электронная микроскопия в сочетании с анализом энергодисперсионной спектроскопии (СЭМ-ЭДС) и термогравиметрия/дифференциальная термогравиметрия (ТГ/ДТГ).

Результаты. Результаты РФА показали, что все образцы содержат в основном фазы хромита и алюминия ("пикрохромит алюминий"), а также проявляют для его присутствия термической точки зрения для оценки возможности его промышленной разработки. Получена средняя химическая формула, основанная на основе результатов РФА-ЭДС, устанавливающаяся на конкретный тип хромита: Fe3O4.MgO.Cr2O3.Al2O3.O. Установлено, что потери массы термическим анализом в диапазоне от 4.4 до 14.36%, при температурах от 600 до 750 °С, указывают на присутствие силикатных минералов, богатых гидроксидом, серпентинита и хлорита. Минеральные фазы, проявленные в данном анализе, присутствуют в основных породах дунит/диорит/гранит/перидотит олимонитового комплекса, что влечет за собой хромитовые руды.

Научная новизна. Дана оценка хромитовых аспектов хромитового массива Вуринос, регион Западной Македонии, Греция, особенно в южной части массива Вуринос в Западной Македонии, Греция, с минералого-геохимической точки зрения для оценки возможности его промышленной разработки.

Минералогическая характеристика и оценка хромитовой руды в массиве Гревена и Козани Вуринос, Западная Македония, Греция

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Цель. Исследование образцов хромитовой руды из рудника “Эторачес” в южной части массива Вуринос в Западной Македонии, Греция, с минералого-геохимической точки зрения для оценки возможности его промышленной разработки.

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Ключевые слова: хромитовая руда, массив Вуринос, рудник Эторачес, минералогическая характеристика, геохимия, РФА, СЭМ-ЭДС, ТГ/ДТГ