Ore mineralogy of podiform-type chromite deposit in Tedubara area and its vicinity, Kabaena Island, Indonesia

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Abstract: Kabaena Island is one of the areas in Southeast Sulawesi that has the potential for chromite deposits. This paper is aimed to provide information on the mineralogical aspects of chromitite from the research area. Back-scattered electron (BSE) imaging and chemical analysis of chromite were performed using an electron microprobe. Chromite deposits in the study area are of podiform-type. Chromite is massive and brecciated. Based on the content of Cr # = Cr / (Cr + Fe³⁺) of the chromite, comprised between 0.61 and 0.74, the studied chromitite can be classified as Cr-rich. The only PGM (Platinum Group Minerals) found in several chromitite samples is laurite (RuS₂). PGM occurs enclosed in chromite crystals and in the contact with microfractures of chromite crystals.

1. Introduction
Chromite is one of the most important minerals as a source of metalliferous ore for industrial world such as stainless steel, gray cast iron, iron free high temperature alloys, and chromium plating to protect the iron surface [6]. The use of chromium in various industries has resulted in high demand for chromitites.

Chromitites can be found in several areas in Indonesia such as Sulawesi, Kalimantan, and Papua [4,10,11]. The chromite minerals found in this area are formed in ophiolite complexes with ultramafic rocks as host rocks. The chromite in ophiolite is usually enriched by Platinum Group Elements (PGE) [7]. Platinum Group minerals generally are formed in the chromite crystals, at the periphery of the crystal, or in the interstitial silicate gangue in chromite [12]. Information on the occurrence of PGM especially regarding the chromite deposits is still lacking. In Sulawesi Island, a research conducted by [11] indicated that PGM generally occur as inclusions in chromite or areas in contact with cracks. The most common PGM is laurite (RuS₂) along with minor irarsite (IrAsS) [11]. The PGM found included in chromite crystallize during the chromite precipitation at magmatic stage. In some cases, they can be modified during the post-magmatic at low temperature conditions. The PGM that contains the high melting and refractory platinum group elements (PGE) formed during the partial melting process in the mantle and then trapped as solid particles into chromite [12]. Chromite is more resistant to an alteration than silicates and sulfides, so the PGMs formed as inclusions in chromite are protected from serpentinization and alteration processes. Conversely, PGM that forms on the edge of chromite crystals or in the silicate gangue is easily altered and formed a secondary PGM [1]. This paper aims to provide information about ore mineralogy and chemical composition of chromite and to document the
presence of PGM in chromite deposits located in the Tedubara area of the Kabaena Island, which is part of the Ophiolite Belt of East Sulawesi.

2. Geological Setting of Kabaena Island

The East Sulawesi Ophiolite Belt has a wide distribution, from the upper end of the East Arm to the lower end of the Southeast Sulawesi Arm (figure 1). Ultramafic rocks are dominant in the Southeast Arm, while mafic rocks are more dominant in the north. Kabaena Island is part of the East Ophiolite Sulawesi Belt, and is mostly composed of ultramafic rocks, Cretaceous in age [9] (figure 2).

Figure 1. Map of Sulawesi Island lithotectonic units (modified from [5]), showing the distribution of the East Sulawesi Ophiolite (ESO) from the South Arm, through the East Arm to the Southeast Arm of Sulawesi Island.
Although data available on the tectonic setting of Kabaena Island are scarce, based on the reconstruction from [3], the age of Kabaena Island and the surrounding varies from the Cretaceous the Middle Miocene (± 15 Ma). Kabaena Island is located in the southern part of the forerunner to the Southeast Sulawesi Arm along with Muna Island which is separated by a subduction zone from the Banda Peninsula at that time. Kabaena Island is also being pushed closer to the Southeast Sulawesi Arm due to the division of the South Banda Sea that occurred during the Pleistocene (± 5 Ma). The ultramafic rocks exposed in Kabaena Island and other parts of Sulawesi are estimated to have originated from spreading between the Indian and Australian plates. This is supported by research [5] on several ultramafic rock samples taken from the northern and southern parts of Kabaena Island which indicates a MOR affinity.

3. Sampling and Research Methods
The studied chromitites are mostly located in remote areas with difficult access because of the relatively dense vegetation and high hilly morphology as the dominant morphology. Chromite deposits have been exposed to the surface as a result of existing local community mining activities and now abandoned. Chromitite occur as lens-shaped deposits on the walls of outcrops rock as well as nodule-shaped minerals, associated with ultramafic rocks (figure 3). Based on field observation and shape of the mineralized body, the chromite deposits in the research area correspond to the podiform type [7].

Figure 2. Regional geology of the study area (Modified from [8]).
Figure 3. Chromite deposits associated with ultramafic rock in the research area: (a) Outcrop showing the old mining activity; (b) Close-up view of ultramafic rock outcrop in the presence of a podiform chromite pod; (c) Massive and nodular chromitite.

Chromite samples were collected in 8 areas of Tedubara. They were previously studied by reflected-light microscope. Chemical analysis of minerals was carried out in all the collected samples by means of an electron microprobe using a JEOL JX A 8200 Superprobe (JEOL, Tokyo, Japan), installed in Eugen F. Stumpfl Laboratory, Leoben University in Austria. Chromite was quantitatively analysed using wave-light dispersive system (WDS) and PGM using energy dispersive system (EDS). The same instrument was used to obtain back-scattered electron (BSE) images of chromite and of PGM.
4. Results and Discussion

4.1. Chromite textures and composition

The studied samples represent massive chromitite, containing 60 to 90 volume % of chromite. They display the following textures: 1) massive and fractured, 2) lobate and 3) brecciated (figure 4). The silicates of the gangue mainly consist of serpentine, talc and chlorite. Few preserved crystals of olivine have been also recognized (figure 4c).

![Figure 4](image_url)

Figure 4. Back-scattered electron images showing the texture of the studied samples. (a) massive and fractured; (b) lobate; (c) brecciated. Abbreviation: Chr = chromite; Sil = silicate; Ol = olivine; Mgs = magnesite; Mag = magnetite.

Based on the electron microprobe analyses presented in Table 1, the Cr₂O₃ exhibits a spread in concentrations, varying from 48.65-56.04 wt % (average 51.59 wt %). The value variations (in wt %) of other major oxides are: Al₂O₃ (13.18-20.83), Fe₂O₃ (1.89-3.21), MgO (11.16-14.42), and FeO (12.8 -17.59). The amount of the trace elements that are comprised in the following range (wt%): TiO₂ (0.18-0.29), ZnO (0.01), V₂O₅ (0.07-0.19), and NiO (0.07-0.14). The SiO₂ content in all the analyzed samples is lower than 0.03 wt %.

The calculated atomic per formula unit (apfu) show that the values of Zn, Si, V, Ni and Mn are <0.002. The average values are the following: Cr (1.28), Al (0.65), Mg (0.62), Fe²⁺ (0.38), Fe³⁺ (0.06), and Ti (0.001). The Cr # = [Cr / (Cr + Al)] in the analyzed chromitites are comprised between 0.61-0.74 and the Fe²⁺# = [Fe²⁺ / (Fe²⁺ + Mg)] between 0.33-0.47. The high Cr # value (> 0.6) indicates that the chromitite in the research area can be classified as Cr-rich type [2].
Table 1. Average values (in wt %) of microprobe analysis data of chromite from Tedubara area, Kabaena Island.

| Elements   | Sample Codes |        |        |        |        |        |        |        |
|------------|--------------|--------|--------|--------|--------|--------|--------|--------|
|            | TBR01 (N = 15) | TBR03 (N = 15) | TBR04 (N = 15) | TBR17 (N = 15) | TBR30 (N = 15) | TBR32 (N = 15) | TBR33 (N = 15) | TBR36 (N = 15) |
| SiO₂       | 0.03          | 0.03   | 0.04   | 0.02   | 0.03   | 0.04   | 0.03   | 0.03   |
| TiO₂       | 0.29          | 0.22   | 0.23   | 0.18   | 0.19   | 0.24   | 0.24   | 0.22   |
| Al₂O₃      | 20.08         | 14.72  | 14.43  | 20.83  | 13.18  | 18.74  | 17.96  | 20.65  |
| FeO⁺       | 14.05         | 14.06  | 13.51  | 15.23  | 17.59  | 16.11  | 12.80  | 13.97  |
| Fe₂O₃⁺     | 2.51          | 2.26   | 2.12   | 1.89   | 2.78   | 2.24   | 3.08   | 3.21   |
| MgO        | 13.88         | 13.22  | 13.65  | 13.12  | 11.16  | 12.32  | 14.42  | 13.86  |
| MnO        | 0.23          | 0.26   | 0.23   | 0.25   | 0.28   | 0.26   | 0.26   | 0.26   |
| Cr₂O₃      | 49.09         | 55.23  | 56.04  | 48.65  | 54.80  | 49.95  | 51.35  | 47.62  |
| NiO        | 0.09          | 0.10   | 0.09   | 0.07   | 0.07   | 0.07   | 0.09   | 0.07   |
| ZnO        | 0.01          | 0.01   | 0.01   | 0.01   | 0.01   | 0.01   | 0.00   | 0.01   |
| V₂O₅       | 0.08          | 0.07   | 0.09   | 0.10   | 0.14   | 0.11   | 0.10   | 0.10   |
| Total      | 100.36        | 100.16 | 100.43 | 100.36 | 100.23 | 100.09 | 100.33 | 100.00 |

| Elements   |        |        |        |        |        |        |
|------------|--------|--------|--------|--------|--------|--------|
| Fe(²⁺)     | 0.06   | 0.05   | 0.05   | 0.04   | 0.07   | 0.05   |
| Fe(³⁺)     | 0.36   | 0.37   | 0.36   | 0.39   | 0.48   | 0.42   |
| Mg         | 0.64   | 0.62   | 0.64   | 0.60   | 0.54   | 0.58   |
| Mn         | 0.006  | 0.007  | 0.006  | 0.007  | 0.008  | 0.007  |
| Cr         | 1.20   | 1.38   | 1.40   | 1.19   | 1.40   | 1.24   |
| Ni         | 0.002  | 0.002  | 0.002  | 0.002  | 0.002  | 0.002  |
| Zn         | 0.0002 | 0.0003 | 0.0001 | 0.0001 | 0.0003 | 0.0001 |
| V          | 0.001  | 0.001  | 0.001  | 0.001  | 0.002  | 0.001  |
| Cr#        | 0.62   | 0.72   | 0.72   | 0.61   | 0.74   | 0.64   |
| Fe²⁺#      | 0.36   | 0.37   | 0.36   | 0.39   | 0.47   | 0.42   |

4.2. Platinum Group Minerals (PGM)
Few PGM have been found in the studied chromites and, on the basis of preliminary EDS analyses, they are laurite ideally (Ru₂Os)S₂. Laurite forms very polygonal and tiny grains (about 5 microns in size) and occurs in two different textural positions: 1) enclosed in chromite crystals (figure 5a-b) and 2) in the contact with microfractures of the host chromite (figure 5c-d).
Figure 5. Reflected light microscope images showing the presence of PGM (laurite) associated with the chromitite from study area: (a) and (b) PGM as an inclusion in the chromite crystal; (c) and (d) PGM in the contact with microfractures in chromite crystals. Abbreviation: Chr = chromite; Sil = silicate; Lrt = laurite.

5. Summary and Conclusions
The investigated chromites of Kabaena Island show a massive texture that during a post magmatic event had been fractured and brecciated. Most of the fractures are filled with secondary silicates which are interpreted to be the result of an alteration process. Few grains of olivine have been preserved in the silicate matrix. The electron microprobe analysis revealed that the chromitites can be classified as Cr-rich and the low TiO\textsubscript{2} content suggests that their composition is compatible with those of podiform chromitites. The only discovered PGM is laurite. Based on its morphology and composition, we can argue that it formed at high temperature, before or concomitantly with the host chromite.

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