

Article

Chromite Composition and Accessory Minerals in Chromitites from Sulawesi, Indonesia: Their Genetic Significance

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Abstract: Several chromite deposits located in the in the South and Southeast Arms of Sulawesi, Indonesia, have been investigated by electron microprobe. According to the variation of the $Cr\# = Cr/(Cr + Fe^{3+})$, the chromite composition varies from Cr-rich to Al-rich. Small platinum-group minerals (PGM), 1–10 μm in size, occur in the chromitites. The most abundant PGM is laurite, which has been found included in fresh chromite or in contact with chlorite along cracks in the chromite. Laurite forms polygonal crystals, and it occurs as a single phase or in association with amphibole, chlorite, Co-pentlandite and apatite. Small blebs of irarsite (less than 2 μm across) have been found associated with grains of awaruite and Co-pentlandite in the chlorite gangue of the chromitites. Grains of olivine, occurring in the silicate matrix or included in fresh chromite, have been analyzed. They show a composition typical of mantle-hosted olivine. The bimodal composition and the slight enrichment in TiO_2 observed in some chromitites suggest a vertical zonation due to the fractionation of a single batch magma with an initial boninitic composition during its ascent, in a supra-subduction zone. This observation implies the accumulation of Cr-rich chromitites at deep mantle levels and the formation of the Al-rich chromitites close or above the Moho-transition zone. All of the laurites are considered to be magmatic in origin, *i.e.*, entrapped as solid phases during the crystallization of chromite at temperature of around 1200 °C and a sulfur fugacity below the sulfur saturation. Irarsite possibly represents a low temperature, less than 400 °C, exsolution product.

Keywords: chromitites; platinum-group minerals; olivine; ophiolite; Sulawesi; Indonesia

1. Introduction

The presence of platinum-group minerals (PGM) in the Indonesian Archipelago has been previously documented only from Borneo. In this area, the PGM have been described from placers deposits [1], which are considered to have derived from the erosion of podiform (ophiolite)-type chromitites [2–4] and of Alaskan-type complexes [5], as well as skarn deposits [6]. Borneo is also the type locality of two PGM, the rare vincentite, ideally $(Pd,Pt)_3(As,Sb,Te)$ [7], and the most common Ru-bearing mineral, laurite, ideally $(Ru,Os)S_2$ ([8] and the references therein). However, mineralogical data on PGM found in lode deposits of the Indonesian Archipelago are limited [2,3,5], and information about the presence of PGM on Sulawesi Island is not available. Generally, chromitites host a number of PGM representing pristine magmatic phases, trapped into crystallizing chromite at high temperatures. Their composition and mineral assemblage can be used to model specific physical-chemical conditions, such as the sulfur fugacity and the temperature of the magmatic system during the formation of the

host chromite [9–11]. The magmatic PGM associated with chromitites can be altered and reworked at low-temperature to form the secondary PGM [12–16], and their presence can be used to evaluate the mobility of platinum-group elements (PGE) and their redistribution on a small scale. Chromite composition helps to distinguish podiform chromitite associated with residual mantle in ophiolite belts from stratiform chromitite in continental layered intrusions and also from chromitite segregations in Alaskan-type complexes [17–19]. As a consequence, chromitite has become a reliable indicator of the geodynamic setting in which it and the host rock has formed [20–27]. In particular, the composition of chromite from podiform chromitites depends on the type of parental magma (e.g., MORB (mid-ocean ridge basalt), OIB (oceanic island basalt), boninite), the degree of depletion of its mantle source and the environment in which the chromitites were formed.

In this contribution, we present, for the first time, a detailed mineralogical investigation of primary chromite deposits and associated PGM from the Sulawesi ophiolite belt. The main goal of this paper is to establish, on the basis of the chromite composition and the associated silicates, the tectonic setting in which the Sulawesi chromitites formed. Mineral assemblage, textural relations and the composition of the PGM are used to discuss the evolution of the PGM from the magmatic stage to lower temperatures.

2. General Geology of the Sulawesi and Associated Ophiolite

The island of Sulawesi lies on the triple junctions between the Eurasian, Indo-Australian and Pacific mega-plates ([28] and the references therein), and it is a geologically and tectonically complex area. According to [29], the following four main geological provinces have been identified in Sulawesi (Figure 1): (1) the West and North Sulawesi Volcano-Plutonic Arc that consists of Cenozoic volcanic and plutonic rocks and a basement complex that is Mesozoic or younger in age formed of metamorphic and ultramafic rocks; Tertiary and Quaternary sediments have been also described; (2) the Central Sulawesi metamorphic belt composed of high pressure metamorphic rocks, the Pompangoe schists and an ophiolite mélangé; (3) the East Sulawesi ophiolite complex; (4) the Banggai Sula and Tukang Besi continental basement.

Although tectonically disrupted and affected by serpentinization, the East Sulawesi ophiolite complex contains the full suite of ophiolite lithology [30]. The ultramafic rocks consist, in decreasing order of abundance, of interlayered harzburgite, lherzolite and dunite. Cumulate, coarse-grained and pegmatitic gabbroic rocks have been also recognized. A small dolerite dyke complex occurs in a restricted area of the ophiolite complex, and it is tectonically in contact with a coarse-grained gabbro [25]. On the basis of their major element distribution, lavas with a MORB signature have been found in the East Sulawesi ophiolite belt [31,32]. However, incompatible trace elements data indicate a back-arc or supra-subduction zone (SSZ) origin [32,33]. Pelagic sedimentary limestone and cherts, which are from Early Cretaceous to Paleocene in age, perhaps constitute the sedimentary cover of at least part of the Sulawesi ophiolite [30].

The biggest ophiolite outcrop is located in the Southeastern Arm of Sulawesi. However, smaller occurrences of the ophiolite complex have been also described in the South Arm (Figure 1). The presence of serpentinized ultramafic rocks in the Bantimala and Barru Block, located in the South Arm of Sulawesi, has been described by [34], who used geochemical and mineralogical data to conclude that both of these blocks formed in an SSZ environment. Furthermore, they recognized that the harzburgite of the Barru Blocks is hosted in the mantle sequence of the ophiolite. In contrast, the dunite, harzburgite and clinopyroxenite of the Bantimala block are cumulates.

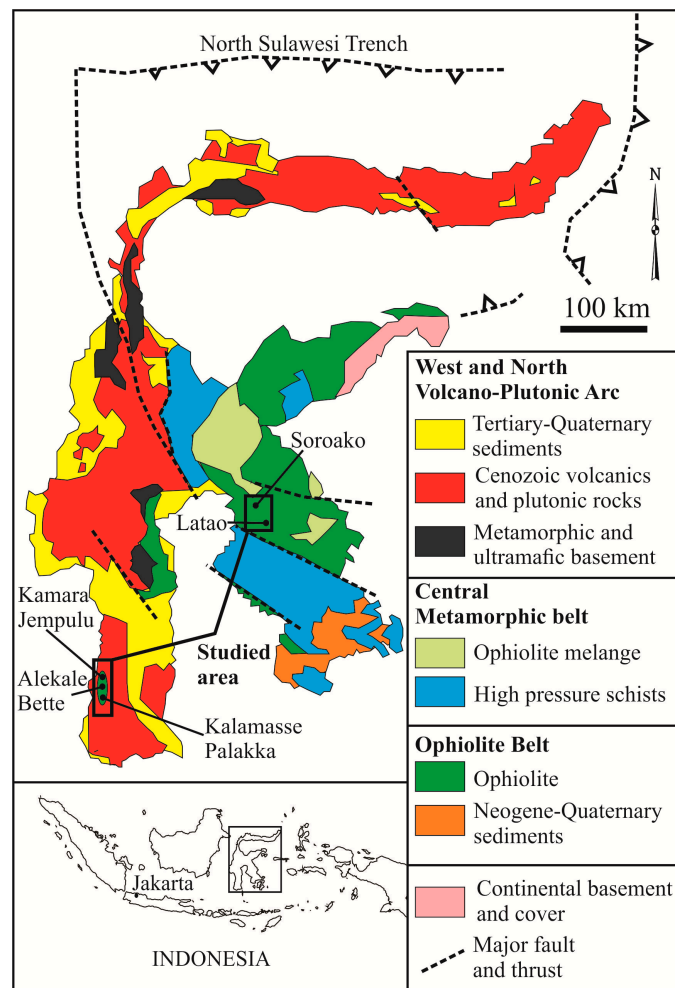


Figure 1. Geological map of Sulawesi (simplified after [28,29]), showing the location of the two chromitite areas and of the studied deposits.

3. Sample Provenance and Methodology

The Sulawesi chromitites occur in remote areas locally covered by vegetation (Figure 2A), and they have only been exploited by local surface workings. They form small and irregular pods (Figure 2B) or a dense dissemination of nodules (Figure 2C) within serpentinized peridotites.

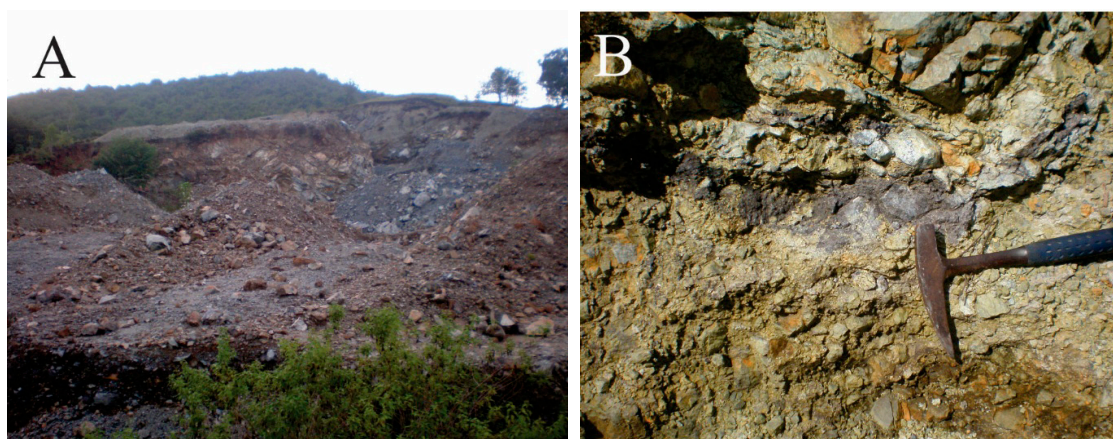


Figure 2. Cont.

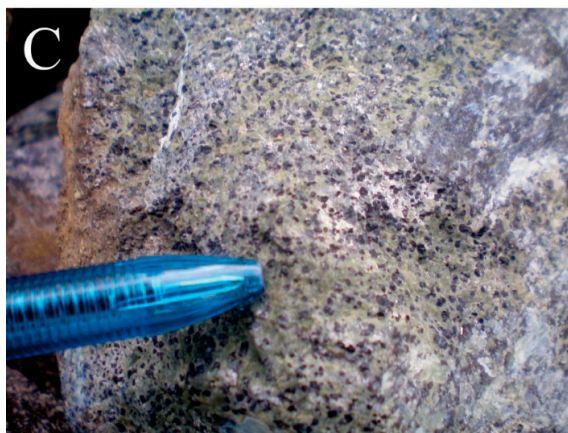


Figure 2. General view of selected outcrops of the chromitites in Barru block, Southern Arm of Sulawesi. Field image of the altered host peridotite in Kalamasse (A); a small massive chromitite and the altered host peridotite, Jempulu deposit (B); disseminated chromite crystals (black) in a peridotite (green) in Alekale (C).

The chromitites investigated were sampled in the South and Southeast Arm (Figure 1). Chromitites from the South Arm were collected from the following deposits located in the Barru Block: Alekale (Samples 3a, 11a), Bette (Samples 6a, 6b), Jempulu (Sample 1a), Kalamasse (Samples 2a, 2b, 7a, 7b, 9b), Kamara (Sample 13a) and Palakka (Sample 12b). In the Southeast Arm, the lode deposits of Latao (Samples 10a, 14a, 15b) and Soroako (Samples 5a, 5b) were sampled. All of the samples investigated represent massive chromitite with the exception of two samples, one from Soroako and one from Latao, that display a nodular texture.

A total of 17 polished sections representing an area of about 5 cm² were studied by reflected-light microscopy to locate the minerals of interest. PGM, chromite, silicates and sulfides were analyzed by electron microprobe using a Superprobe Jeol JXA 8200 (JEOL, Tokyo, Japan) installed at the Eugen F. Stumpfl Laboratory at the University of Leoben, Austria, using both energy dispersive (EDS) and wavelength dispersive (WDS) systems. Back-scattered electron (BSE) images were obtained using the same instrument. Selected PGM grains were also investigated using an environmental scanning electron microscope (ESEM) (Zeiss, Oberkochen, Germany) at the Chair of Ceramics, University of Leoben, Austria. During the analyses of chromite and silicates, the electron microprobe was operated in the WDS mode, with an accelerating voltage of 15 kV and a beam current of 10 nA. The analyses of Na, Mg, K, Al, Si, Ca, Ti, V, Cr, Zn, Mn, Fe and Ni were obtained using the K α lines and were calibrated on natural chromite, rhodonite, ilmenite, albite, pentlandite, wollastonite, kaersutite, sphalerite and metallic vanadium. The following diffracting crystals were used: TAP for Na, Mg, Al; PETJ for K, Si, Ca; and LIFH for Ti, V, Cr, Zn, Mn, Fe, Ni. The peak and background counting times were 20 and 10 s, respectively, for the major elements. They were increased to 40 and 20 s for the trace elements, such as Ca, Ni and Mn in olivine. The detection limits were automatically calculated by the microprobe software, and they are as follows: Na (140), Mg (100), K (70), Al (130), Si (250), Ca (50), Ti (270), V (150), Cr (180), Zn (170), Mn (100) and Ni (120) (ppm). The amount of Fe³⁺ in chromite was calculated assuming the spinel stoichiometry $R^{2+}O R^{3+}_2O_3$. More than 400 electron microprobe analyses were performed on the 17 samples from the eight chromite deposits. Representative analyses of chromite and silicates are listed in Tables A1–A3 (see Appendixes).

PGM were located by scanning polished sections under a reflected light microscope at 250–800 magnification. The PGM with a size less than 5 microns were only qualitatively analyzed by EDS. The larger PGM were quantitatively analyzed in the WDS mode, at a 20-kV accelerating voltage and a 10-nA beam current, with a beam diameter of about 1 micron. The peak and background counting times were 15 and 5 s, respectively. The K α lines were used for S, As, Fe and Ni, L α for Ir, Ru, Rh, Pd and Pt and M α for Os. The reference materials were pure metals for the six PGE (Ru, Rh, Pd, Os,

Ir, Pt), synthetic NiS, natural pyrite and niccolite for Ni, Fe S and As. The following diffracting crystals were selected: PETJ for S; PETH for Ru, Os, Rh; LIFH for Fe, Ni, Ir, Pt; and TAP for As. Automatic corrections were performed for interferences involving Ru-Rh and Rh-Pd. The detection limits (ppm) are 80 for S, 120 for As, 800 for Os, Ir and Pt, 200 for Ru, Rh and Pd, 150 for Fe, Ni and Cu. Selected analyses of the PGM are reported in Table A4 (see Appendixes).

4. Results

4.1. Chromite Texture and Composition

Under the microscope, most of the chromitites studied display the uniform texture typical of chromitite with <10% interstitial silicate, interrupted by cracks, brecciation and pull-a-part fractures (Figure 3A–C). In a few samples from Kalamasse and Alekale and those characterized by nodular texture, the modal proportion of the interstitial silicates increases up to 40% (Figure 3D–F). Chromite is usually fresh (Figure 3A), showing a narrow ferrian-chromite alteration rim only along grain boundaries and cracks (Figure 3B–E). One sample from Alekale is characterized by a strong alteration, and the chromite grains are almost totally replaced by spongy chromite intimately intermixed with Cr-chlorite (Figure 3F).

The space between the chromite grains in the samples investigated is almost totally composed of altered silicates, such as serpentine, talc and chlorite. Rare fresh olivine (Figure 3A) has been found in the matrix of the chromitites from Soroako (Figure 3A), Kalamasse and Latao. Small grains (up to 20 μm) of heazlewoodite and pentlandite have been found as accessory minerals in the matrix of the chromitites from Palakka, Kalamasse and Latao.

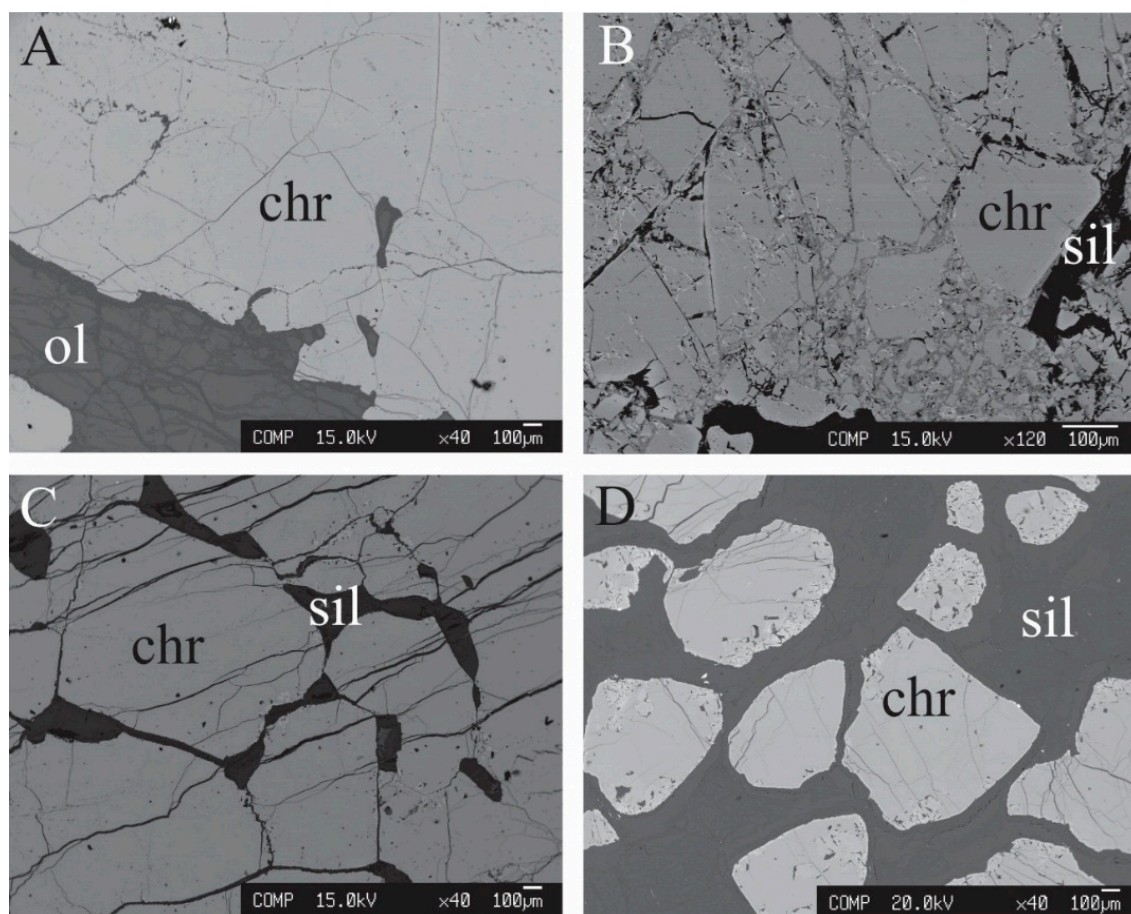


Figure 3. *Cont.*

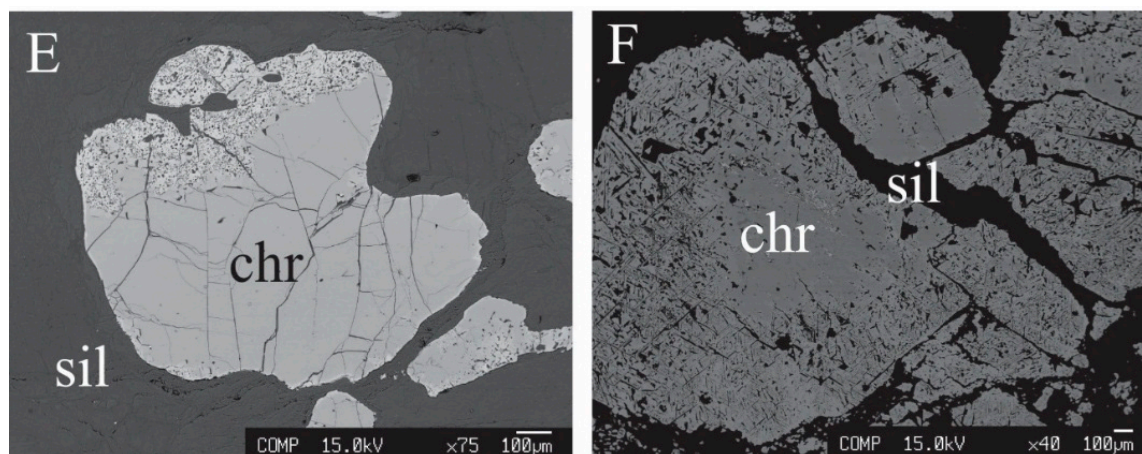


Figure 3. Back-scattered electron images of polished sections from the Sulawesi chromitites. (A) Massive and unaltered chromite in contact with olivine partially transformed in serpentine from Soroako; (B) massive chromite showing strong brecciation and ferrian chromite alteration (light grey) developed along cracks and fissures from Jempulu; (C) massive chromite from Latao with pull-a-part texture; (D) massive chromite with about 40% of altered silicates from Kalamasse; (E) ferrian chromite alteration (light grey) developed in the rim of a chromite crystal from Kalamasse; (F) altered chromite grains from Alekale. Abbreviations: chr = chromite; ol = olivine; sil = altered silicates.

Selected chromite analyses are listed in Tables A1 and A2 (Appendixes) and plotted in the binary and ternary diagrams of Figure 4.

The overall variation ranges of major oxides (wt %) in the unaltered cores of chromite grains are: Cr_2O_3 (39.76–64.14), Al_2O_3 (7.01–24.36), Fe_2O_3 (0–8.32) MgO (8.02–12.8) and FeO (13.45–21.78). The amounts (wt %) of trace elements are within the following ranges: TiO_2 0.07–0.56, ZnO 0–0.26, V_2O_5 0–0.3 and NiO 0–0.51. The Mn content is always below the detection limit (100 ppm). The Sulawesi chromitites are plotted in the podiform field on the $\text{Cr\#}$ versus $\text{Fe}^{2+\#}$ binary diagram (Figure 4A). The compositions from the various localities form an almost continuous trend from Cr-rich ($\text{Cr\#}$ up to 0.85), to intermediate and Al-rich (minimum $\text{Cr\#}$ = 0.54), in a relatively narrow variation range in $\text{Fe}^{2+\#}$ (0.34–0.58). A good negative correlation is observed between Cr_2O_3 and Al_2O_3 (Figure 4B,C), consistently with the Al-Cr substitution predominant in podiform chromitites compared to the stratiform type [19,35,36]. However, the Cr_2O_3 versus Al_2O_3 diagram (Figure 4B) shows that the samples from the Bette deposit and a few from the Kalamasse deposit are plotted in the field of the stratiform chromitite. According to the same diagram, the chromitites from Kamara, Palakka, Jempulu, located in the South Arm, and Latao and Soroako, located in the Southeast Arm, are Cr-rich having a Cr_2O_3 content higher than 50 wt % and Al_2O_3 below 15 wt %. Al-rich chromitites with Cr_2O_3 content lower than 50 wt % and Al_2O_3 higher than 15 wt % have been found in the Bette and Kalamasse deposits, both cropping out in the South Arm. The Alekale deposit (South Arm) is the only one in which both Cr-rich and Al-rich chromitites have been located (Figure 4B). The distance between the two chromitites is about 1 km. TiO_2 is generally lower than 0.3 wt % in most of the analyzed samples, as is typical for podiform chromitites (Figure 4C). Only the sample from the Bette deposit in the Southern Arm contains up to 0.55 wt % of TiO_2 (Figure 4C).

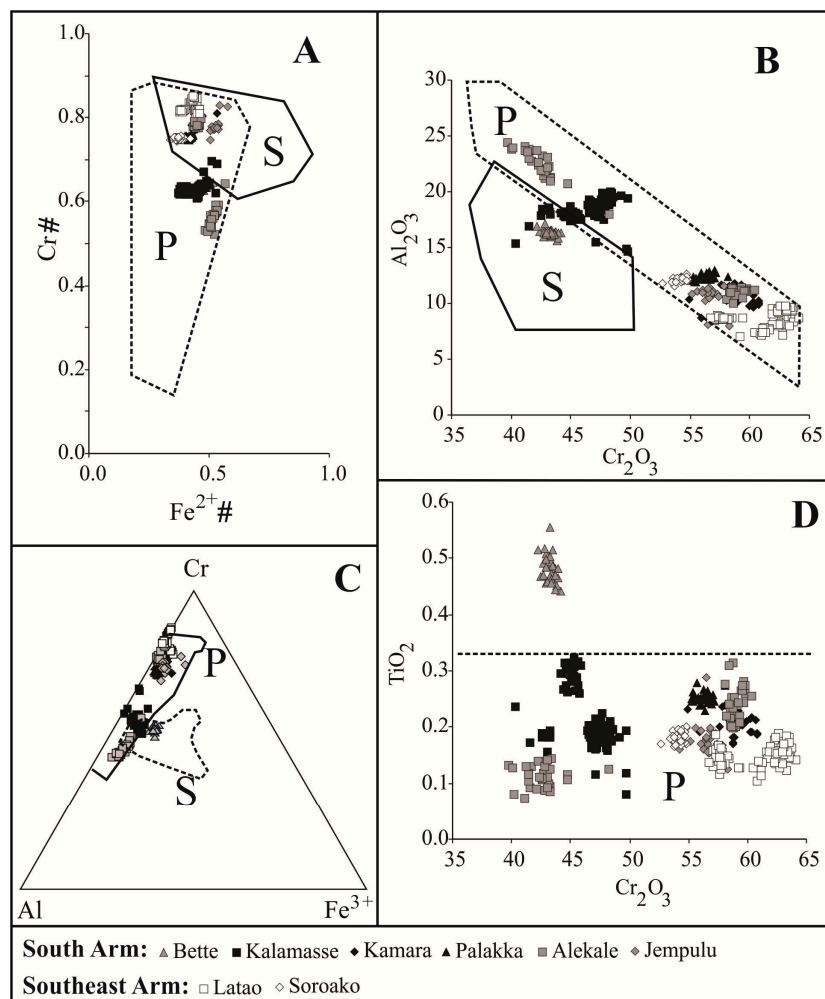


Figure 4. Composition of unaltered chromite from the studied chromitite from Sulawesi. (A) Variation of the chromium number, $Cr\# = Cr/(Cr + Al)$, and bivalent iron number, $Fe^{2+\#} = Fe^{2+}/(Fe^{2+} + Mg)$; (B) negative correlation of Al_2O_3 versus Cr_2O_3 ; (C) Cr–Al–Fe³⁺ atomic ratios; (D) variation of Cr_2O_3 and TiO_2 . P = field of podiform chromitites; S = field of stratiform chromitites [19,35,36].

4.2. Olivine

Although most of the silicate matrix in the Sulawesi chromitite has been totally altered, a few relicts of fresh olivine have been analyzed in the chromitites from Soroako (Figure 5A), Kalamasse and Latao. Polygonal crystals of olivine (up to about 200 μm) have been found included in the fresh chromite from Soroako, Latao and Palakka chromitites (Figure 5B–D).

Olivine displays a narrow range of the forsterite end member (Figure 6). The Ni, Mn and Ca contents vary significantly between interstitial olivine and olivine included in chromite.

In particular, in the interstitial olivine, the forsterite varies from 94.4% to 96.6%, whereas in the olivine included in chromite, the variation is very limited, being between 96.99% and 97.41% (Figure 6). The NiO wt % content is generally higher in the inclusion, and it defines a slightly positive trend with the forsterite (Figure 6A). The highest values of MnO wt % have been detected in the interstitial olivine, and MnO shows a negative correlation with the forsterite content (Figure 6B). In most of the olivine, Ca is below 500 ppm, except in the interstitial olivine from Kalamasse, where Ca lies between about 600 and 800 ppm. The values of Ca versus forsterite in the analyzed olivine are plotted in the field of the mantle olivine proposed by [37] having Ca below 1000 ppm and high forsterite contents (Figure 6C and Table A3). The Cr_2O_3 content (wt %) is between 0.3% and 0.44% and 0.02% and 0.96% in the included and interstitial olivine, respectively (Table A3).

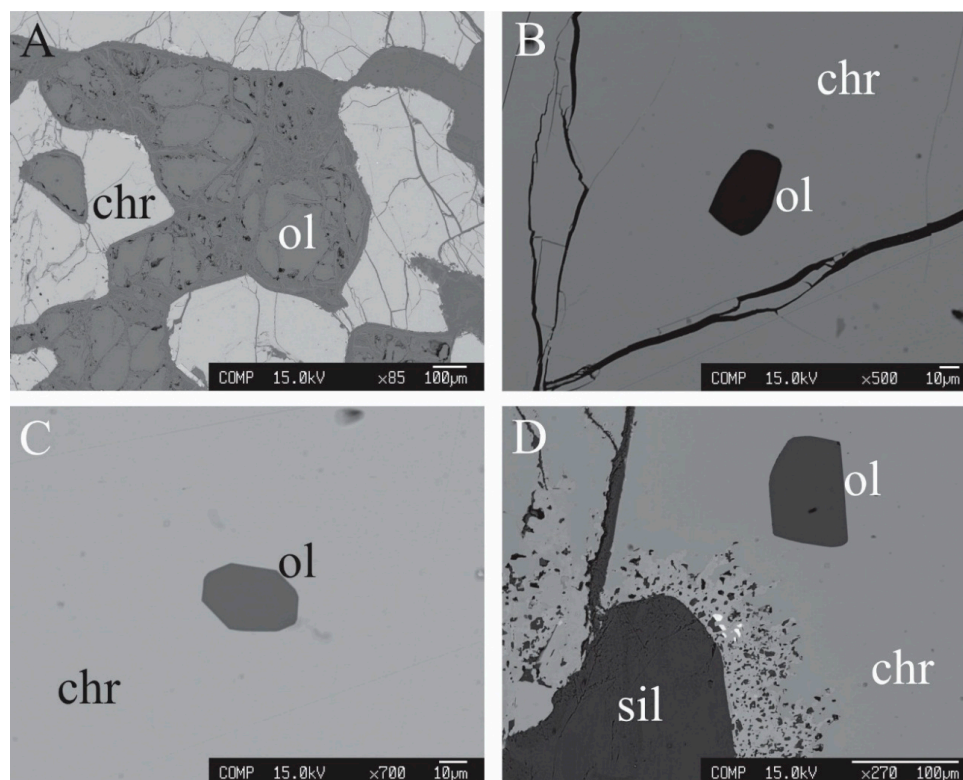


Figure 5. Back-scattered electron images of olivine found in the matrix of the Soroako chromitite (A) and included in fresh chromite from Palakka chromitite (B–D). Abbreviation: ol = olivine; chr = chromite; sil = altered silicates.

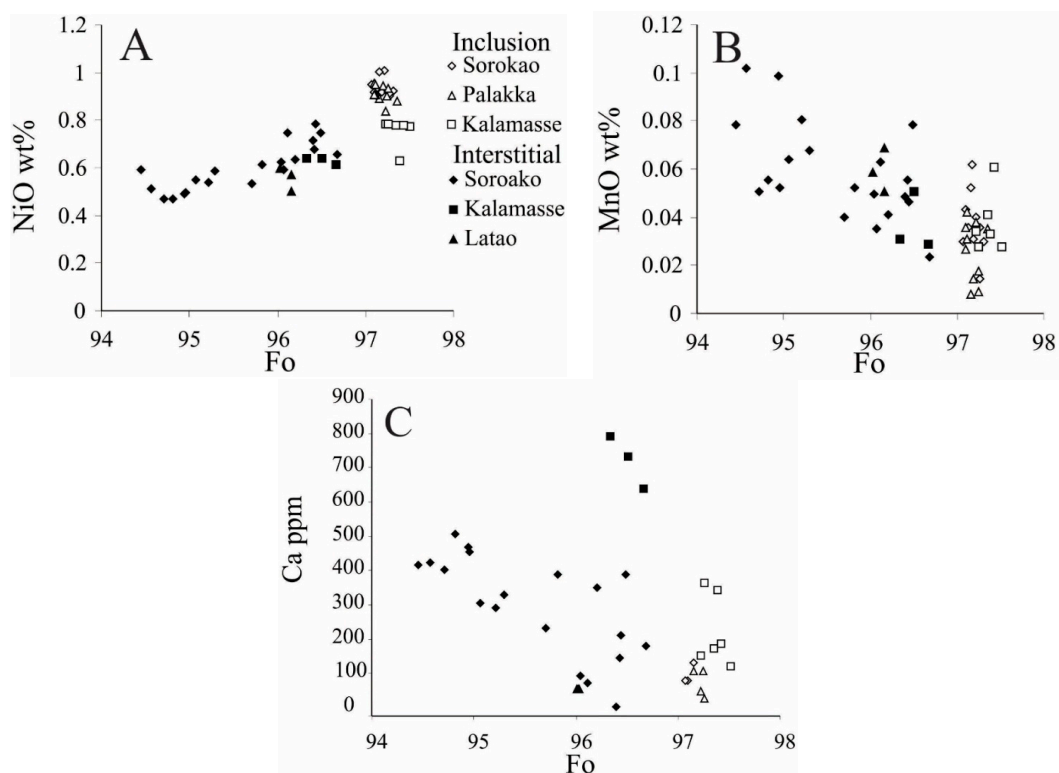


Figure 6. Variation of NiO (A), MnO (B) and CaO (C) as a function of forsterite molar % in the olivine from chromitites of Sulawesi.

4.3. The Platinum-Group Minerals

Platinum-group minerals have been found in the chromitites from the South Arm and Southeast Arm of Sulawesi. In particular, PGM have been analyzed in the deposits of Alekale, Kalamasse, Kamara, Palakka and Soroako. The most abundant PGM is laurite (RuS_2), accompanied by minor irarsite (IrAsS). The PGM are between 1 and 10 μm . Laurite is euhedral and occurs as inclusions either in fresh chromite (Figure 7A–C) or in contact with fractures (Figure 7D–F). Most of the laurite grains form a single phase (Figure 7A,B,F); however, some occur with a Ni sulfide (Figure 7C), with a Co-rich pentlandite (Figure 7D) and with an apatite (Figure 7E). Small blebs of irarsite were found in (1) a grain composed of awaruite and pentlandite that occurs in the altered silicate matrix (Figure 8A,B) and (2) associated with a Co-rich pentlandite in the ferrian chromite (Figure 8C,D). Selected microprobe analyses of the Sulawesi laurite are listed in Table A4. The laurite contains appreciable amounts of Rh and Pd (2.57 and 2.64 wt %, respectively), and variable amounts of Ni, Fe and Cu are carried in laurite. Arsenic is less variable, and 1.01–2.02 wt % is present. Iridium varies between 0 and 12.68 wt %, and Pt is absent. Grains of irarsite were identified, but could not be quantitatively analyzed because of their small size. Laurite does not show significant compositional variations in relation to its textural position, such as being included in chromite or in contact with fractures, as is typical, for example, of altered laurite [14]. On the contrary, they have similar Ru–Os–Ir relationships regardless of their paragenetic association (Figure 9).

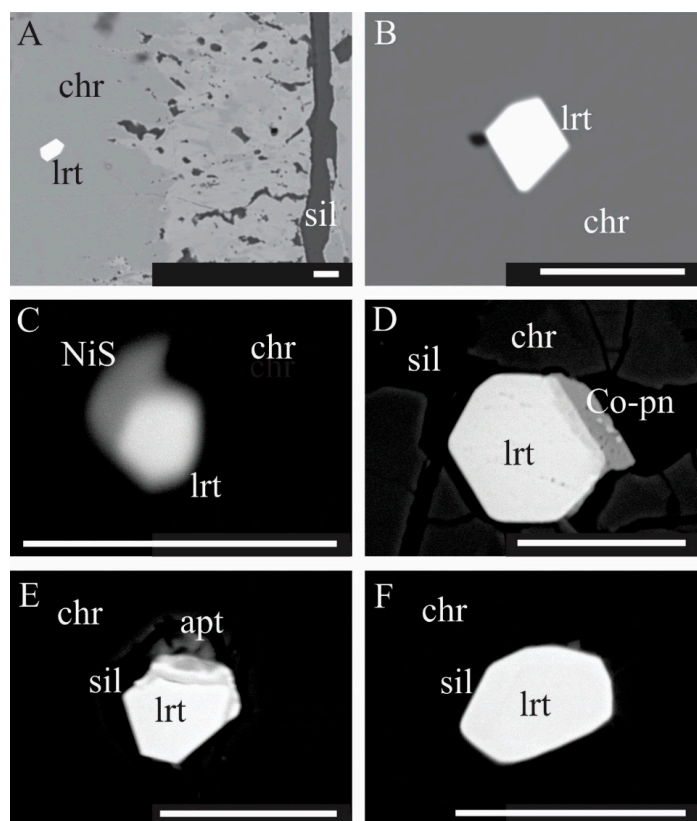


Figure 7. Back-scattered electron (BSE) images of platinum-group minerals (PGM) associated with the chromitites of Sulawesi. A polygonal crystal of laurite included in fresh chromite from Palakka (A,B); laurite associated with a Ni-sulfide, included in fresh chromite from Kalamasse (C); zoned laurite in contact with Co-pentlandite in cracks in the chromite (Kalamasse); the white spots in the Co-pentlandite are laurite (D); laurite showing an altered rim in contact with apatite in cracks in the chromite (Kalamasse); single phase laurite in cracks in the chromite (Kalamasse). Scale bar = 10 μm . Abbreviations: chr = chromite; lrt = laurite; sil = altered silicates; NiS = Ni-sulfide; Co-pn = Co-pentlandite; apt = apatite.

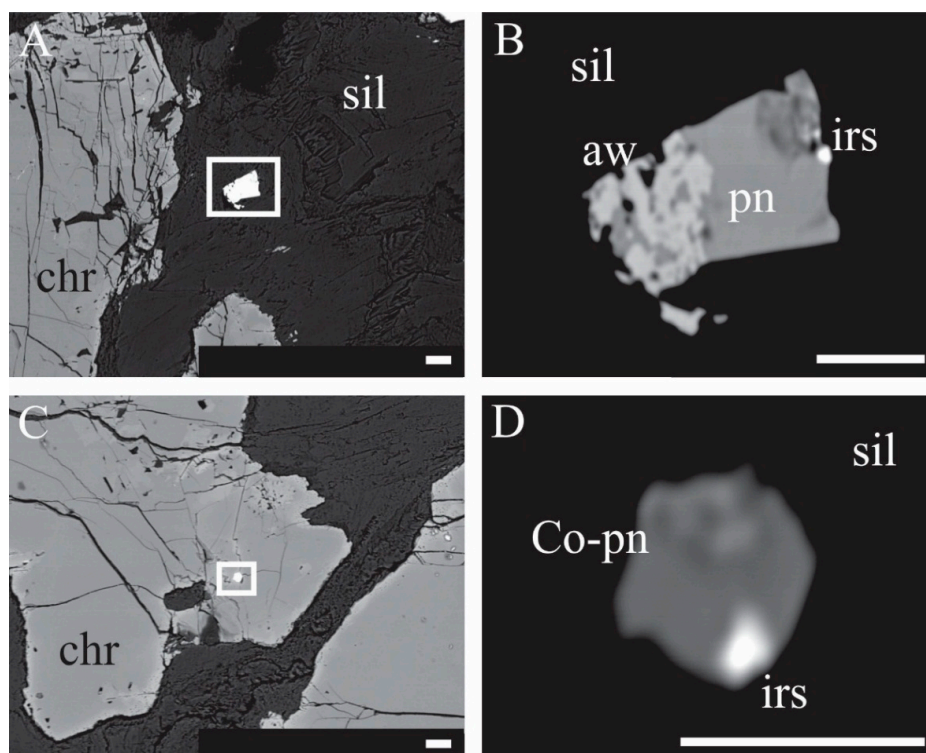


Figure 8. BSE images of PGM associated with the chromitites of Kalamasse. A grain composed of awaruite, pentlandite and irarsite in the silicate matrix (A); enlargement of (A) (B); a grain composed of Co-pentlandite and irarsite in the silicate matrix (C); enlargement of (C) (D). Scale bar = 10 μm . Abbreviations: chr = chromite; sil = altered silicates; aw = awaruite; pn = pentlandite; irs = irarsite; Co-pn = Co-pentlandite.

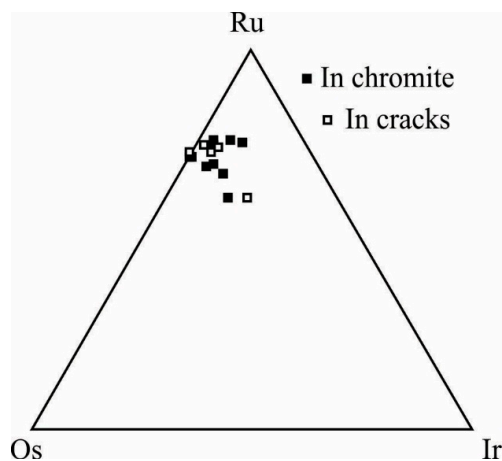


Figure 9. Plots (atom %) of the compositions of laurite from chromitites of Sulawesi.

5. Discussion

5.1. Parental Melt and Chromite Composition: Tectonic Implications

The Sulawesi chromitites studied here are generally massive with a weak alteration overprint (Figure 3). Therefore, their chromite composition can be successfully used so as to recover the composition of the parent magma, the degree of partial melting of the mantle source and the geodynamic environment, as proposed in the pioneer papers of [17,18] and later by several

authors [20,21,24]. According to the theoretical assumption and the formula proposed by [38], the Al_2O_3 content of the spinel is controlled by the Al_2O_3 content of the parental melt, and it is now widely accepted that high-Cr chromites crystallize from melts less aluminous (picritic or boninitic basalts) than those that are parent to high-Al chromites (normal MORB). In particular, Al-rich chromites are generally believed to have formed at the mid-ocean ridge [39–42] or in the back-arc basin ([41] and the references therein), whereas Cr-rich chromites are typically hosted in the mantle sequence of ophiolites related to the SSZ geodynamic setting ([27] and the references therein).

However, the presence of both Al-rich and Cr-rich chromites within one single ophiolite complex has been documented worldwide [26,27,39–56]. This coexistence can be explained with the following models as summarized in [52]: (1) intrusions of different melts derived from differently depleted mantle sources (*i.e.*: MORB *versus* boninite), during the geodynamic evolution of the oceanic lithosphere from the MOR towards the SSZ; (2) mixing of several magmas produced by multi-stage melting of a partially re-fertilized and fluid-metasomatized residual source, in the SSZ; (3) the reaction of a single intrusion of a boninitic parental melt with country-rock peridotites characterized by variable residual composition; (4) fractional precipitation during differentiation of a single batch of magma with initial high-Cr boninitic composition, in the SSZ; and (5) bimodal distribution and vertical zoning with the Cr-rich chromite located in the deep mantle section and the Al-rich chromite occurring higher in the succession, close or above the Moho transition.

Recently, Llanes Castro *et al.* [43] explained the bimodal (Al-rich *versus* Cr-rich) composition of the chromites from Havana-Matanzas, Cuba, as having been caused by the degree of melt–rock interaction. This is related to the percolation of melts produced in the subduction environment through variably depleted peridotites in the mantle wedge. According to [55,56], based on their relationships with the host peridotite, concordant and discordant chromites have been identified in the Oman ophiolite. However, due to the strong alteration that affects the Sulawesi chromites, it was not possible to recognize in the field their relation with the host serpentinized peridotite.

The composition of the Sulawesi chromite indicates the coexistence of the Al-rich and Cr-rich chromites (Figure 4), and in the case of the Alekale deposit, they occur in close vicinity (Figure 4). To better understand the origin of these chromites, their chromite composition has been data plotted in the binary diagrams of Figure 10. In the diagram of TiO_2 *versus* Al_2O_3 (Figure 10A), all of the analyzed samples fall in the field of the SSZ chromite, with the exception of a group of samples from the Alekale deposit that are plotted in the overlapping field of SSZ and MORB chromites. The chromites from Bette are slightly enriched in TiO_2 (Figure 10A). The diagram of Figure 10B shows that the chromites from Kamara, Palakka, Jempulu, Latao, Soroako and one group from Alekale fall in the field of low-Ti Island Arc Basalts (IAB). Only the chromite from the Bette deposit is plotted in the overlapping field of the high-Ti IAB and MORB. The chromites from Kalamasse and one group from Alekale display compositional similarity with those reported from chromites in supra-Moho cumulate sequences of the Urals (data from [27]). According to the diagrams presented in Figure 10, we can argue that the Sulawesi chromites formed in an SSZ from a single batch of magma with an initial high-Cr boninitic composition, which was undergoing differentiation in the deep mantle section and above to the Moho transition zone. This observation is in agreement with the conclusions reported by [34] that investigated serpentinized ultramafic rocks in the South Arm of Sulawesi. These authors, on the basis of whole-rock trace element analyses and spinel compositions, suggested that dunite, harzburgite and clinopyroxenite located in the Bantimala Block in the South Arm of Sulawesi are cumulates.

The parental melt composition from which ophiolitic chromites precipitate can be calculated using the equation proposed by [38], the approach of [26,27] and data from [25]. The diagrams of Figure 11, based on the chromite–melt relationships, show that most of the analyzed chromites from Sulawesi were derived from Island Arc-related melts. Furthermore, they define a continuous trend from Al_2O_3 -poor to relatively Al_2O_3 -rich compositions, supporting an origin by differentiation of a single melt whose composition was initially well inside the Island Arc field.

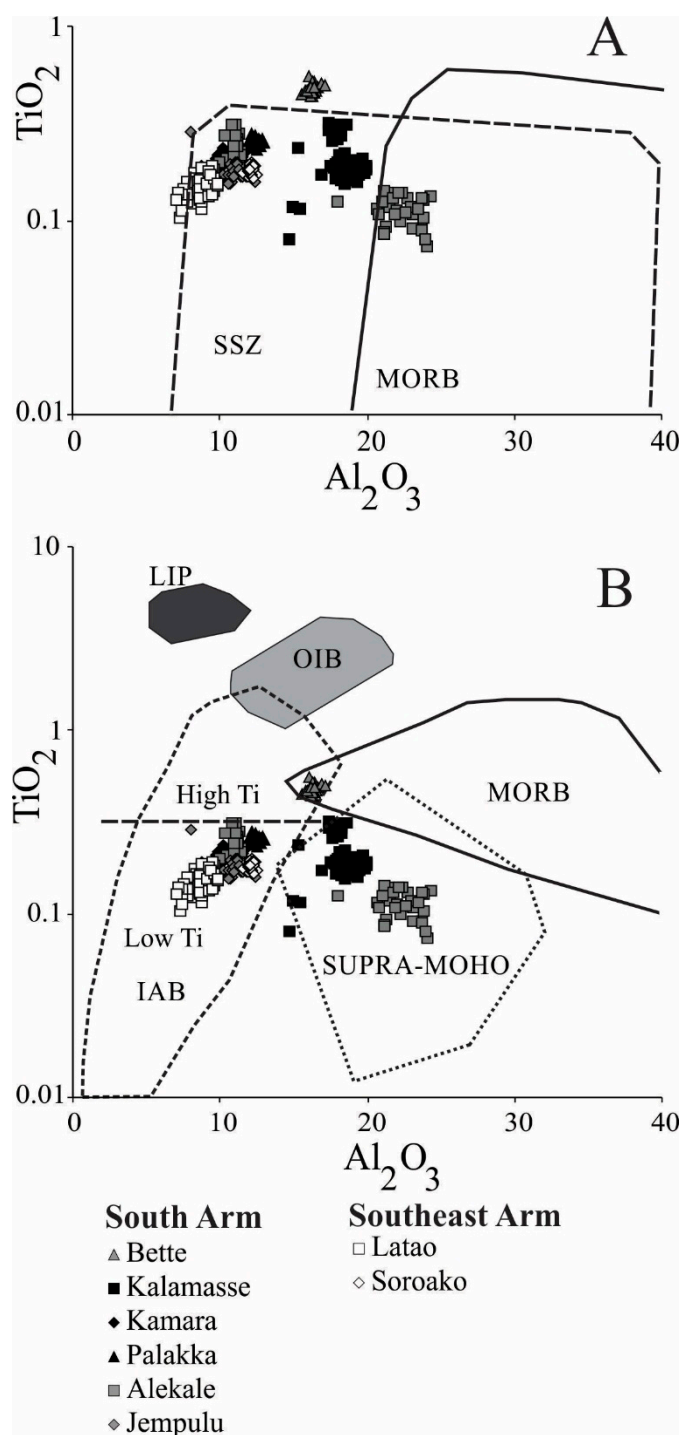


Figure 10. TiO_2 - Al_2O_3 relationships in chromitites of Sulawesi. (A) Composition of the chromitites from Sulawesi, compared to the field of spinels from the supra-subduction zone (SSZ) and mid-ocean ridge (MORB) mantle peridotites (compositional fields from [25]); (B) the fields for IAB (island arc basalt), OIB (oceanic island basalt), MORB (mid-ocean ridge basalt), LIP (large igneous province) basalt and supra-Moho (SUPRA-MOHO) chromitite from the Urals are from [25,27]. The horizontal dashed line at $\text{TiO}_2 = 0.30$ wt % separates the high-Ti IAB (high-K calc-alkaline suite) from the low-Ti IAB (boninitic, tholeiitic).

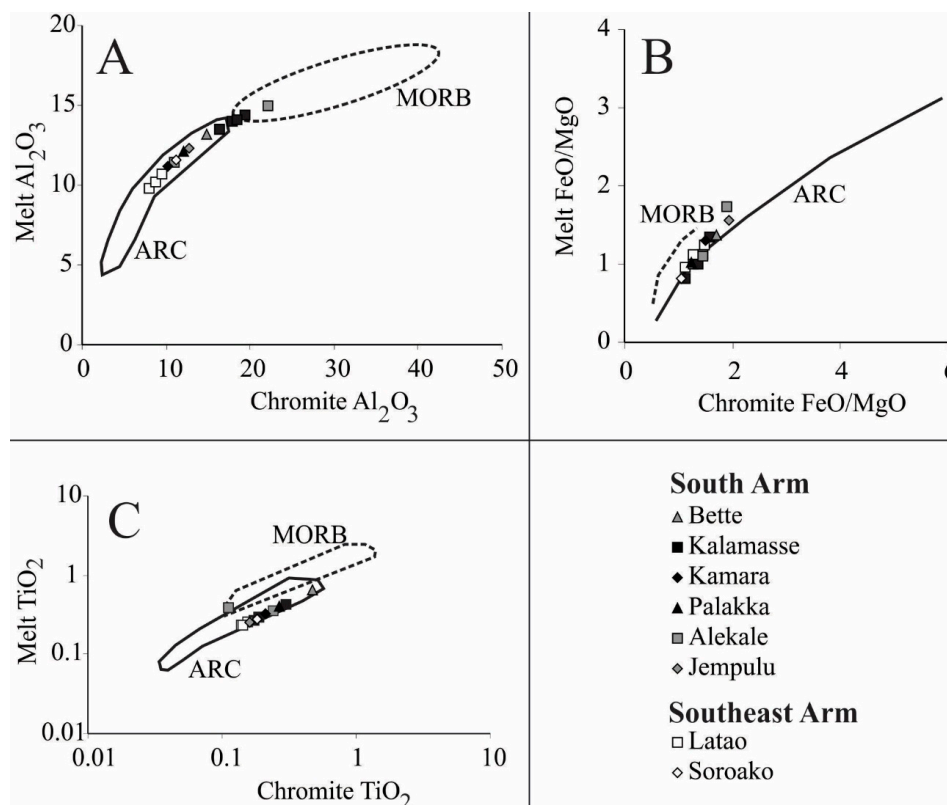


Figure 11. Chromite-melt relationships for (A) Al_2O_3 , (B) FeO/MgO and (C) TiO_2 , in the chromitites from Sulawesi (modified after [22]).

5.2. Origin of the PGM in the Sulawesi Chromitites

As is typical for most of the chromitites hosted in the mantle sequence of ophiolite complexes, the PGM discovered in the Sulawesi chromitites consist of Os-, Ir- and Ru-rich phases. Based on their mode of occurrence, such as included in fresh chromite crystal or associated with altered minerals, two distinct PGM populations have been recognized in the Sulawesi chromitite: (1) PGM that formed in the high-temperature magmatic stages, as part of the chromite precipitation event (primary PGM) and (2) PGM that originated during low-temperature processes (secondary PGM).

The primary PGM assemblage found in the Sulawesi chromitites consists of laurite that is characterized by a narrow variation of Os and Ru (Figure 9). Its composition suggests that the Sulawesi laurites, even the crystals found in contact with secondary silicates, were not affected by post-magmatic alteration, as observed in laurites associated with other ophiolitic chromitites [12,14,57–65]. During the alteration processes, laurite released S that was replaced by Fe and O to form a fine intergrowth of native ruthenium and magnetite [61] or it has lost part of the Os and Ir to form Ru-rich laurite [14]. Therefore, we can use the analyzed laurite to model the mechanism of its crystallization at high temperature. It is now widely understood that the most important parameters that control the precipitation of magmatic Os-, Ir- and Ru-bearing PGM are temperature and sulfur fugacity. Experimental work [11,66] confirmed by several natural observations [9,10,39,50,67,68] indicates that laurite is in equilibrium with Os–Ir–(Ru) alloys at a temperature of 1300 °C and relatively low sulfur fugacity. Laurite becomes progressively enriched in Os with decreasing temperature and increasing sulfur fugacity, up to the stability field of erlichmanite. At Sulawesi, the primary mineral assemblage is exclusively composed of laurite that is not particularly enriched in Os, suggesting that the sulfur fugacity, although well below the Os–OsS₂ buffer, was high enough to prevent crystallization of Os–Ir–(Ru) alloys during the magmatic stage.

The secondary PGM assemblage consists of very tiny grains of irarsite of about 1 µm in size that occur associated with Co-pentlandite, pentlandite and awaruite (Figure 8). Their mode of

occurrence as small blebs located at the border of the host pentlandite, partially transformed to awaruite (Figure 8), suggests that this ore assemblage formed by desulfurization of Fe–Ni sulfides during the early hydrothermal alteration caused by the interaction between abyssal peridotite and seawater at temperatures below ~ 400 °C [69]. The most important implication of this assumption is that some of the Ir was originally incorporated in solid solution within base metal (BM) sulfides. During serpentinization, the BM sulfides underwent partial alteration to generate the irarsite droplets (Figure 8). This observation suggests an origin by exsolution during alteration and partial desulfurization of a magmatic iridium-rich pentlandite.

5.3. Olivine Composition and Its Significance

Olivine is one of the most important minerals in the upper mantle, as well as in crustal ultramafic rocks [37,70]. Its composition in terms of major and minor elements can be used, with caution, to distinguish olivine formed deep in the mantle from olivine crystallized in the crust by mafic and ultramafic magmas. Olivine is a common accessory mineral in most of chromitites, including those of Sulawesi. Due to the serpentinization that often affected the ophiolitic chromitites and their host peridotite, olivine rarely survives the alteration process. Therefore, few grains of fresh olivine generally occur in the silicate matrix of the chromitites. Fresh olivine may also occur as inclusions in unaltered chromites, reflecting its magmatic origin. In the Sulawesi chromitite both types of olivine, *i.e.*, interstitial and included, have been analyzed. The composition of olivine in chromitite depends on element partitioning with chromitite. On the basis of several examples from the Urals, [27] have shown that olivine displays a wide range of forsterite molar % with peculiar Ni, Mn and Ca contents according to the type of host chromitite. In particular, most of the olivine associated with ophiolitic mantle chromitites is characterized by high forsterite contents, from 94–98 mol%, and NiO contents of between 0.35 and 1.15 wt %. MnO wt % and Ca (ppm) are very low. All of the analyzed olivine grains, interstitial and included, from Sulawesi chromitites display values of forsterite, NiO, MnO and Ca consistent with those reported from the ophiolitic mantle-hosted chromitites from the Urals (Figure 6). This observation suggests that the studied olivine and its host chromitites were generated in the mantle section of the Sulawesi ophiolite. However, according to [37] (and the references therein), olivine with a low Ca content can also crystallize from a mantle-derived magma to form cumulate rocks.

6. Summary and Concluding Remarks

According to the content of TiO_2 and Al_2O_3 in the analyzed chromite, the Sulawesi chromitites were generated in an SSZ from a single batch of magma with initial high-Cr boninitic composition (Figure 10). This conclusion is also supported by the calculated composition of the melts in equilibrium with the Sulawesi chromitites that have an Island Arc signature (Figure 11).

Although the chromite composition of some samples from Alekale and Kalamasse plotted in the field of chromitites formed in the supra-Moho cumulate sequences of the Urals (data from [27]), the composition of the accessory olivine suggests that most of the studied chromitites of Sulawesi are part of an ophiolite mantle sequence. However, as documented by [37], low-Ca content is not unique to mantle olivine. Since the presence of cumulate ultramafics rocks has been reported in the Bantimala Block located in the South Arm of Sulawesi [34], we cannot exclude the possibility that the Alekale and Kalamasse chromitites formed above the Moho-transition zone.

The PGM discovered during this investigation are very similar to those reported from ophiolitic mantle-hosted chromitites. The magmatic composition registered in the laurite grains that were not affected by later alteration processes suggests that the primary PGM associated with the Sulawesi chromitites crystallized at a temperature around 1200 °C and sulfur fugacity well below the S-saturation. A few grains of irarsite have been also found. They have been classified as secondary PGM, *i.e.*, formed at relatively low temperature, below 400 °C, by exsolution of Ir during alteration of a precursor iridium-rich pentlandite.

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Author Contributions: Federica Zaccarini wrote the paper and analyzed the minerals by electron microprobe. Arifudin Idrus collected the samples and provided the geological and field information. Giorgio Garuti contributed the elaboration and the interpretation of the data.

Conflicts of Interest: The authors declare no conflict of interest.

Appendixes

Table A1. Representative electron microprobe analyses (wt %) of chromite from chromitites of Sulawesi, South Arm.

Sample	Cr ₂ O ₃	Al ₂ O ₃	Fe ₂ O ₃	MgO	FeO	TiO ₂	V ₂ O ₃	NiO	ZnO	Total
<i>Alekale (Cr-rich)</i>										
3a.1	58.53	11.35	1.35	11.53	16.30	0.22	0.09	0.15	0.11	99.64
3a.2	58.64	10.90	1.84	11.40	16.29	0.23	0.07	0.04	0.03	99.43
3a.3	58.74	11.04	1.37	11.30	16.61	0.32	0.13	0.02	0.03	99.55
3a.4	58.79	11.32	1.39	11.47	16.50	0.20	0.07	0.10	0.12	99.95
3a.5	58.99	10.78	1.56	11.28	16.44	0.20	0.11	0.06	0.00	99.41
3a.6	59.06	11.30	1.41	11.67	16.23	0.22	0.14	0.10	0.09	100.22
3a.7	59.55	11.11	0.88	11.29	16.69	0.28	0.15	0.08	0.19	100.21
3a.8	59.64	11.20	0.27	11.49	17.07	0.24	0.05	0.17	0.14	100.27
3a.9	59.82	11.06	0.73	11.35	17.04	0.26	0.02	0.14	0.05	100.46
3a.10	60.39	11.14	1.00	11.61	16.18	0.25	0.10	0.08	0.15	100.90
<i>Alekale (Al-rich)</i>										
11a.1	41.12	24.04	3.48	10.76	19.24	0.07	0.30	0.09	0.11	99.22
11a.2	48.21	17.96	4.07	9.22	21.43	0.13	0.18	0.03	0.17	101.39
11a.3	43.33	21.16	5.26	10.00	20.02	0.14	0.14	0.06	0.19	100.30
11a.4	44.76	20.72	4.48	9.87	20.43	0.12	0.21	0.07	0.16	100.81
11a.5	42.63	23.16	4.08	10.66	19.30	0.11	0.19	0.08	0.23	100.44
11a.6	44.76	20.76	4.30	10.03	20.07	0.11	0.23	0.09	0.22	100.55
11a.7	42.74	21.48	5.12	10.05	20.01	0.12	0.22	0.11	0.09	99.94
11a.8	41.68	22.74	5.09	10.55	19.35	0.13	0.17	0.12	0.19	100.03
11a.9	42.25	22.37	4.91	10.30	19.67	0.14	0.22	0.13	0.17	100.14
11a.10	42.82	21.80	4.81	10.28	19.57	0.13	0.18	0.20	0.13	99.92
<i>Bette</i>										
6a.1	43.69	17.47	8.61	11.09	17.90	0.53	0.23	0.14	0.11	99.77
6a.2	44.25	16.91	7.67	10.80	17.95	0.54	0.11	0.07	0.06	98.33
6a.3	44.95	16.81	7.21	10.70	18.44	0.48	0.23	0.09	0.14	99.05
6a.4	44.93	17.10	7.50	10.70	18.53	0.51	0.28	0.14	0.11	99.79
6a.5	45.20	16.85	6.94	10.50	19.24	0.49	0.27	0.19	0.17	99.84
6a.6	45.76	16.91	7.46	10.94	18.59	0.46	0.19	0.10	0.07	100.40
6a.7	44.24	17.20	7.28	10.86	18.30	0.51	0.29	0.22	0.09	98.98
6a.8	45.50	16.85	6.94	10.15	19.33	0.50	0.25	0.11	0.15	99.78
6a.9	44.39	17.72	6.91	11.55	18.87	0.52	0.11	0.05	0.83	100.82
6a.10	44.46	16.87	7.83	10.84	18.36	0.53	0.26	0.10	0.19	99.45
6b.1	44.79	17.14	7.81	11.07	18.09	0.48	0.21	0.12	0.25	99.96
6b.2	44.82	16.55	8.15	10.71	18.10	0.57	0.12	0.18	0.26	99.47
6b.3	44.83	16.96	7.64	10.73	18.17	0.52	0.19	0.17	0.16	99.37
6b.4	44.93	16.92	7.30	10.39	18.96	0.47	0.27	0.09	0.12	99.46
6b.5	44.96	16.68	7.68	10.81	18.24	0.50	0.26	0.09	0.10	99.32
6b.6	44.96	17.05	7.56	10.71	18.73	0.53	0.24	0.05	0.12	99.95
6b.7	45.20	16.70	7.40	10.47	18.29	0.46	0.16	0.28	0.16	99.12
6b.8	45.20	16.95	7.24	10.79	18.91	0.50	0.22	0.08	0.05	99.95
6b.9	45.36	16.11	8.20	10.58	18.21	0.47	0.22	0.24	0.15	99.53
6b.10	45.52	16.35	7.31	10.59	18.59	0.48	0.26	0.18	0.10	99.39

Table A1. Cont.

Sample	Cr ₂ O ₃	Al ₂ O ₃	Fe ₂ O ₃	MgO	FeO	TiO ₂	V ₂ O ₃	NiO	ZnO	Total
<i>Jempulu</i>										
1a.1	56.88	10.67	3.07	9.68	19.38	0.19	0.14	0.06	0.12	100.19
1a.2	58.30	8.02	4.86	9.14	19.53	0.13	0.18	0.02	0.11	100.29
1a.3	56.47	8.06	6.33	8.52	20.87	0.29	0.20	0.06	0.09	100.89
1a.4	57.39	10.63	1.95	9.44	19.44	0.17	0.14	0.04	0.13	99.33
1a.5	56.53	10.96	3.81	9.82	19.03	0.18	0.09	0.03	0.06	100.49
1a.6	56.04	10.99	2.90	9.40	19.03	0.17	0.14	0.09	0.20	98.94
1a.7	56.80	11.20	2.63	9.81	19.03	0.20	0.15	0.10	0.11	100.03
1a.8	56.07	11.20	3.54	9.99	18.33	0.19	0.10	0.19	0.07	99.69
1a.9	56.58	11.47	3.04	10.11	18.39	0.17	0.11	0.12	0.04	100.03
1a.10	54.26	12.36	3.64	9.99	18.37	0.16	0.09	0.04	0.12	99.03
<i>Kalamasse</i>										
7a.1	47.07	18.99	4.93	13.28	14.67	0.28	0.13	0.15	0.08	99.59
7a.2	47.25	19.34	4.87	13.51	14.43	0.29	0.19	0.16	0.12	100.15
7a.3	47.43	19.02	4.70	13.14	14.81	0.31	0.08	0.13	0.20	99.82
7a.4	47.47	19.13	4.56	13.38	14.42	0.28	0.17	0.23	0.06	99.71
7a.5	47.63	18.87	4.89	13.41	14.59	0.32	0.17	0.14	0.05	100.07
7a.6	47.69	18.38	5.51	13.25	14.97	0.31	0.08	0.11	0.06	100.35
7a.7	48.03	18.83	4.45	13.24	15.34	0.33	0.15	0.12	0.12	100.60
7a.8	48.09	18.96	3.74	13.24	15.45	0.28	0.11	0.14	0.18	100.20
7a.9	48.23	18.67	4.64	13.16	15.17	0.31	0.22	0.08	0.00	100.47
7a.10	48.61	18.57	3.95	12.97	15.59	0.33	0.17	0.19	0.18	100.57
2b.1	47.63	19.90	3.58	12.72	15.55	0.19	0.14	0.24	0.12	100.06
2b.2	47.67	19.48	3.57	12.73	15.63	0.18	0.14	0.03	0.07	99.48
2b.3	47.88	19.46	3.10	12.46	15.73	0.19	0.18	0.15	0.10	99.24
2b.4	48.01	19.55	3.13	12.36	15.97	0.18	0.16	0.24	0.06	99.66
2b.5	48.02	19.26	3.67	12.44	16.00	0.16	0.16	0.03	0.11	99.85
2b.6	48.14	19.14	3.03	12.49	15.77	0.17	0.17	0.08	0.02	99.00
2b.7	48.16	19.31	2.33	12.12	16.73	0.16	0.18	0.05	0.03	99.06
2b.8	48.30	19.97	2.33	12.60	16.04	0.19	0.13	0.09	0.18	99.84
2b.9	48.39	19.72	2.65	12.46	15.89	0.21	0.14	0.18	0.16	99.80
2b.10	49.17	19.62	2.28	12.67	16.24	0.18	0.15	0.11	0.06	100.48
9b.1	48.08	19.43	2.83	11.85	17.95	0.20	0.16	0.15	0.12	100.78
9b.2	47.51	19.70	3.58	12.00	17.13	0.21	0.16	0.21	0.13	100.64
9b.3	48.04	18.73	3.81	11.64	17.06	0.17	0.10	0.07	0.13	99.76
9b.4	48.28	18.57	3.78	11.76	17.41	0.20	0.14	0.14	0.19	100.47
9b.5	48.28	18.65	3.82	11.57	17.39	0.18	0.10	0.09	0.10	100.19
9b.6	49.02	18.37	3.63	11.32	17.71	0.19	0.12	0.19	0.10	100.65
9b.7	48.77	18.76	3.45	11.66	17.39	0.22	0.11	0.17	0.14	100.66
9b.8	48.86	18.88	3.08	11.74	17.54	0.23	0.15	0.14	0.06	100.69
9b.9	49.40	19.32	3.01	11.91	17.46	0.20	0.12	0.14	0.10	101.66
9b.10	49.76	18.66	3.02	10.63	18.10	0.08	0.11	0.06	0.19	100.60
<i>Kamara</i>										
13a.1	59.08	10.90	1.48	11.37	16.47	0.20	0.08	0.14	0.05	99.77
13a.2	60.77	9.90	1.29	11.10	16.90	0.19	0.09	0.20	0.14	100.59
13a.3	58.91	11.27	1.31	11.53	16.40	0.21	0.10	0.24	0.06	100.03
13a.4	60.21	9.84	1.84	11.22	16.54	0.22	0.13	0.09	0.06	100.14
13a.5	60.76	10.00	0.54	10.86	17.18	0.19	0.04	0.01	0.06	99.64
13a.6	57.59	11.68	1.75	11.53	15.98	0.20	0.12	0.13	0.07	99.04
13a.7	58.33	11.51	1.81	11.58	16.06	0.22	0.14	0.16	0.12	99.92
13a.8	57.86	11.56	1.26	11.59	16.31	0.24	0.06	0.16	0.04	99.07
13a.9	58.32	11.58	1.36	11.27	16.48	0.22	0.11	0.15	0.08	99.56
13a.10	59.95	9.74	1.35	10.69	17.07	0.21	0.09	0.08	0.19	99.38

Table A1. Cont.

Sample	Cr ₂ O ₃	Al ₂ O ₃	Fe ₂ O ₃	MgO	FeO	TiO ₂	V ₂ O ₃	NiO	ZnO	Total
<i>Palakka</i>										
12b.1	57.11	12.35	1.73	11.89	15.51	0.24	0.09	0.20	0.06	99.19
12b.2	57.46	12.57	1.97	12.19	15.52	0.26	0.17	0.16	0.05	100.35
12b.3	57.84	12.44	1.61	12.17	15.69	0.26	0.06	0.20	0.08	100.37
12b.4	57.15	12.57	2.50	12.26	15.39	0.25	0.08	0.11	0.16	100.47
12b.5	57.65	12.40	2.46	12.44	15.14	0.25	0.04	0.18	0.08	100.64
12b.6	56.48	12.41	1.83	11.85	15.68	0.25	0.08	0.15	0.21	98.93
12b.7	56.36	12.58	2.32	12.30	15.03	0.23	0.03	0.23	0.12	99.19
12b.8	56.33	12.58	2.68	12.46	14.98	0.27	0.04	0.18	0.17	99.69
12b.9	57.18	12.69	2.08	12.17	15.51	0.25	0.08	0.17	0.05	100.16
12b.10	58.14	12.43	1.38	11.95	16.13	0.28	0.11	0.19	0.17	100.77

Table A2. Representative electron microprobe analyses (wt %) of chromite from chromitites of Sulawesi, Southeast Arm.

Sample	Cr ₂ O ₃	Al ₂ O ₃	Fe ₂ O ₃	MgO	FeO	TiO ₂	V ₂ O ₃	NiO	ZnO	Total
<i>Latao</i>										
15b.1	63.52	9.30	0.00	10.67	15.85	0.14	0.16	0.09	0.05	99.78
15b.2	64.65	7.91	0.00	11.16	16.18	0.14	0.12	0.06	0.15	100.35
15b.3	61.54	9.05	2.39	12.57	14.57	0.15	0.21	0.06	0.04	100.57
15b.4	64.77	8.23	0.00	11.43	15.66	0.15	0.19	0.13	0.04	100.59
15b.5	65.29	8.25	0.00	11.59	15.97	0.17	0.12	0.06	0.19	101.64
15b.6	64.23	8.27	0.00	11.50	15.38	0.14	0.05	0.04	0.12	99.73
15b.7	64.54	8.19	0.00	11.38	15.44	0.13	0.10	0.01	0.08	99.87
15b.8	63.60	8.55	0.03	11.82	15.51	0.15	0.09	0.02	0.11	99.88
15b.9	63.82	8.73	0.00	11.79	15.12	0.15	0.14	0.10	0.08	99.91
15b.10	64.38	8.83	0.00	11.70	15.61	0.16	0.09	0.04	0.09	100.86
14a.1	60.17	9.21	3.12	12.80	13.86	0.14	0.09	0.16	0.08	99.63
14a.2	60.48	9.02	1.86	12.39	14.82	0.17	0.20	0.06	0.13	99.11
14a.3	60.73	9.43	2.42	12.75	13.82	0.15	0.09	0.13	0.20	99.73
14a.4	60.22	9.20	2.42	12.67	14.21	0.20	0.14	0.11	0.17	99.34
14a.5	60.30	9.12	2.49	12.60	14.03	0.14	0.12	0.25	0.17	99.23
14a.6	60.41	9.22	2.85	12.76	13.73	0.18	0.19	0.32	0.11	99.78
14a.7	60.55	9.13	2.31	12.70	14.12	0.16	0.11	0.11	0.09	99.29
14a.8	60.59	9.12	2.62	12.50	14.14	0.16	0.11	0.05	0.15	99.42
14a.9	60.81	9.09	2.57	12.50	14.15	0.16	0.10	0.17	0.07	99.62
14a.10	61.25	9.14	2.63	12.82	14.15	0.16	0.15	0.17	0.18	100.64
10a.1	62.81	9.36	0.29	11.30	16.94	0.15	0.22	0.03	0.05	101.15
10a.2	63.10	9.43	0.38	11.39	16.78	0.16	0.16	0.06	0.08	101.54
10a.3	62.92	9.28	0.67	11.40	16.46	0.14	0.17	0.11	0.06	101.20
10a.4	63.07	9.25	0.00	11.13	16.63	0.15	0.17	0.03	0.03	100.46
10a.5	62.63	9.53	0.43	11.38	16.49	0.19	0.11	0.18	0.09	101.02
10a.6	62.43	9.15	0.87	11.24	16.57	0.16	0.17	0.05	0.07	100.70
10a.7	62.28	9.46	0.34	11.22	17.00	0.14	0.14	0.12	0.03	100.71
10a.8	63.05	9.57	0.00	11.05	16.67	0.17	0.14	0.00	0.03	100.68
10a.9	62.34	9.29	0.00	11.06	16.97	0.18	0.13	0.16	0.06	100.20
10a.10	63.13	9.39	0.00	11.04	16.75	0.17	0.18	0.12	0.09	100.87
<i>Soroako</i>										
5b.1	56.17	12.53	3.09	12.11	15.80	0.19	0.08	0.11	0.04	100.11
5b.2	56.65	12.83	2.33	13.23	13.34	0.18	0.13	0.20	0.14	99.02
5b.3	56.81	12.93	2.13	13.00	13.92	0.20	0.16	0.13	0.18	99.47
5b.4	56.96	12.50	1.21	12.77	14.74	0.18	0.19	0.10	0.14	98.78
5b.5	56.98	12.84	1.85	13.23	14.20	0.19	0.24	0.18	0.11	99.83
5b.6	57.11	12.65	2.39	13.45	13.25	0.18	0.11	0.19	0.05	99.37
5b.7	57.13	12.87	2.48	13.14	13.95	0.20	0.13	0.10	0.16	100.17
5b.8	57.20	12.75	1.84	13.33	13.89	0.18	0.11	0.18	0.12	99.61
5b.9	57.42	13.19	1.66	13.30	13.60	0.18	0.07	0.12	0.13	99.67
5b.10	57.59	12.66	2.14	13.51	13.82	0.21	0.14	0.10	0.11	100.29

Table A3. Representative electron microprobe analyses (wt %) of olivine from chromitites of Sulawesi.

Sample	SiO ₂	MgO	FeO	Cr ₂ O ₃	MnO	NiO	Total	Fo (%)	Ca (ppm)
Included									
<i>Soroako</i>									
5a.3	41.58	52.91	2.90	0.34	0.05	0.92	98.69	97.01	100
5a.4	41.79	53.50	2.88	0.32	0.05	1.00	99.54	97.07	150
5a.9	41.74	52.63	2.91	0.42	0.03	0.95	98.69	96.99	100
<i>Palakka</i>									
12b.12	41.91	53.53	2.79	0.44	0.01	0.91	99.59	97.16	130
12b.13	42.26	53.84	2.90	0.28	0.01	0.90	100.19	97.07	130
12b.19	42.37	53.42	2.80	0.30	0.04	0.84	99.77	97.14	70
12b.20	42.27	53.36	2.77	0.34	0.02	0.93	99.70	97.17	50
Interstitial									
<i>Soroako</i>									
5a.2	42.33	53.23	3.32	0.21	0.03	0.67	99.78	96.62	200
5a.3	42.79	52.79	3.55	0.17	0.06	0.69	100.05	96.36	160
5a.5	42.64	53.11	3.95	0.07	0.05	0.64	100.45	96.00	110
5a.6	42.45	53.60	3.92	0.02	0.06	0.76	100.81	96.06	90
5a.7	42.56	52.68	3.48	0.09	0.08	0.75	99.64	96.43	400
5a.8	42.98	53.45	3.81	0.06	0.04	0.65	100.99	96.15	360
5a.9	42.12	52.31	4.11	0.05	0.05	0.63	99.27	95.78	400
5a.10	42.23	53.30	3.57	0.06	0.05	0.79	100.00	96.38	230
5a.12	41.85	52.99	4.69	0.02	0.07	0.60	100.22	95.27	340
5a.13	42.14	52.45	4.73	0.04	0.08	0.55	99.99	95.19	310
5a.16	41.95	52.39	5.49	0.03	0.08	0.60	100.54	94.45	430
5a.17	42.02	52.75	5.40	0.02	0.10	0.53	100.82	94.57	440
5a.18	42.61	52.39	4.99	0.04	0.10	0.51	100.64	94.93	480
5a.19	42.31	52.71	4.90	0.02	0.07	0.56	100.57	95.05	320
5a.20	42.28	52.51	4.99	0.02	0.05	0.51	100.37	94.94	460
<i>Kalamasse</i>									
2a.1	41.92	54.51	2.58	0.69	0.03	0.78	100.51	97.42	140
2a.2	42.04	52.84	3.65	0.27	0.03	0.65	99.48	96.27	790
2a.3	41.58	53.43	3.35	0.32	0.03	0.63	99.34	96.60	640
2a.4	42.08	53.26	3.50	0.28	0.05	0.65	99.82	96.45	740
2a.5	42.18	52.46	2.76	0.89	0.04	0.79	99.10	97.14	170
2a.6	42.05	53.18	2.67	0.95	0.04	0.78	99.67	97.26	190
2a.9	42.31	54.07	2.81	0.58	0.03	0.79	100.59	97.17	380
2a.10	42.37	53.38	2.64	0.50	0.04	0.64	99.58	97.30	360
2a.11	42.39	54.28	2.65	0.62	0.06	0.79	100.78	97.34	210
<i>Latao</i>									
15b.2	41.67	53.52	3.87	0.80	0.05	0.59	100.49	95.97	80
15b.3	42.32	54.05	4.04	0.96	0.06	0.61	102.04	95.98	80

Table A4. Representative electron microprobe analyses (wt % and at.%) of laurite from chromitites of Sulawesi.

Sample	S	As	Os	Ir	Ru	Rh	Pd	Pt	Fe	Ni	Cu	Total
<i>Palakka</i>												
12b.3	33.07	1.72	20.97	4.65	30.29	2.55	2.52	0.00	1.14	0.29	0.10	97.31
12b.4	33.21	1.77	20.27	5.84	31.67	2.57	2.64	0.00	0.94	0.19	0.06	99.17
<i>Kamara</i>												
13a.1	34.99	2.02	18.59	3.25	36.85	2.06	2.45	0.00	0.80	0.16	0.06	101.24
<i>Latao</i>												
14a.1	32.51	1.12	21.58	12.68	27.97	1.20	1.62	0.00	1.07	0.04	0.13	99.92
<i>Kalamasse</i>												
7a.3	34.18	1.26	20.62	2.18	35.13	1.36	2.04	0.00	1.42	0.26	0.02	98.47
7a.4	34.09	1.06	24.84	0.00	35.00	1.27	2.01	0.00	0.91	0.15	0.02	99.36
7a.5	34.16	1.01	24.37	0.48	33.26	1.29	1.88	0.00	1.36	0.17	0.01	97.99
7a.6	33.69	1.26	24.47	1.00	33.80	1.65	1.96	0.00	1.01	0.13	0.06	99.03
7a.6	34.14	1.46	21.30	1.78	35.83	1.42	2.09	0.00	0.93	0.27	0.04	99.26
7b.2	34.68	1.02	17.93	4.93	34.97	1.53	2.02	0.00	1.60	0.23	0.10	99.01
9a.1	34.99	1.43	19.48	5.28	31.47	2.22	2.26	0.00	2.11	0.42	0.14	99.81
Sample	S	As	Os	Ir	Ru	Rh	Pd	Pt	Fe	Ni	Cu	
<i>Palakka</i>												
12b.3	65.94	1.47	7.05	1.55	19.16	1.58	1.51	0.00	1.31	0.32	0.10	
12b.4	65.53	1.50	6.74	1.92	19.82	1.58	1.57	0.00	1.07	0.21	0.06	
<i>Kamara</i>												
13a.1	65.80	1.63	5.89	1.02	21.98	1.21	1.39	0.00	0.87	0.16	0.06	
<i>Latao</i>												
14a.1	66.10	0.98	7.40	4.30	18.05	0.76	0.99	0.00	1.25	0.05	0.13	
<i>Kalamasse</i>												
7a.3	66.10	1.04	6.72	0.70	21.55	0.82	1.19	0.00	1.58	0.28	0.02	
7a.4	66.25	0.88	8.14	0.00	21.58	0.77	1.18	0.00	1.02	0.16	0.02	
7a.5	66.74	0.84	8.03	0.16	20.62	0.79	1.11	0.00	1.53	0.18	0.01	
7a.6	66.02	1.06	8.08	0.33	21.01	1.01	1.16	0.00	1.14	0.14	0.06	
7a.6	65.92	1.21	6.93	0.57	21.95	0.85	1.22	0.00	1.03	0.29	0.04	
7b.2	66.39	0.84	5.79	1.57	21.24	0.91	1.17	0.00	1.76	0.24	0.10	
9a.1	66.47	1.16	6.24	1.67	18.97	1.31	1.29	0.00	2.30	0.44	0.14	

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