

Mineral Chemistry and The Stability Temperature of Nickel-Iron Sulfide from Kolaka Ultramafic Rocks, Southeast Sulawesi

Rio Irhan Mais Cendra Jaya^{1✉}, Syahrul², Masri¹

¹Geological Engineering Department, Universitas Halu Oleo, Kendari, Indonesia

²Mining Engineering Department, Universitas Sembilanbelas November, Kolaka, Indonesia

ARTICLE INFO

Article history:

Received: March 8, 2025

Accepted: June 18, 2025

Published: June 22, 2025

Keywords:

ultramafic rocks
mineral chemistry
pentlandite
nickel
stability diagram

Corresponding author:

Rio Irhan Mais Cendra Jaya

Email: riocj@uho.ac.id

Read online:



Scan this QR code with your smartphone or mobile device to read online.

Copyright © 2025 Authors



This work is licensed under a Creative Commons Attribution-ShareAlike 4.0 International License.

ABSTRACT

This study investigates nickel-iron sulfide mineral chemistry and stability from ultramafic rocks in the Kolaka region, Southeast Sulawesi, Indonesia. Sampling was conducted at two Kolaka ultramafic rock outcrop sites in Baula and Wolo sub-districts. The Kolaka Ultramafic Rocks, part of the Kolaka Ophiolite Complex, are primarily composed of lherzolite, harzburgite, olivine websterite, and serpentinites. Sulfide minerals, including pentlandite, pyrite, and chalcopyrite, were observed in these rocks, along with Ni-Fe-rich minerals interpreted as awaruite. Pentlandite, the dominant sulfide mineral, occurs within olivine and chromite replacements, mainly at their rims and serpentine veins. Eight polished sections of ultramafic rocks from both sites were analyzed using EDS SEM to determine the chemical composition of pentlandite. This analysis reveals a variable composition of Ni and Fe, with Ni-rich members more prevalent. Pentlandites from the Baula district have Fe contents of 18.22–27.34 wt%, Ni contents of 32.59–39.10 wt%, and Co contents of 1.24–2.76 wt%, while those from the Wolo district have significantly higher Ni (46.19–53.79 wt%) and Co (2.79–4.18 wt%) contents but lower Fe (8.50–15.18 wt%). Based on the ternary diagram, pentlandites show various formation temperatures (200 to above 600°C). They are separated into two stability groups: Baula's pentlandite (Ni < 40%, Fe > 18%) with stability temperatures between 200 and 500°C, and Wolo's Ni-rich pentlandite (Ni > 46%, Fe < 16%) with stability temperatures above 600°C. The formation of Ni-rich pentlandite is attributed to Ni-rich ultramafic rocks reacting with seawater at high temperatures, facilitating efficient Ni scavenging during serpentinization.

ABSTRAK

Penelitian ini menginvestigasi kimia mineral dan stabilitas sulfida nikel-besi batuan ultramafik di wilayah Kolaka, Sulawesi Tenggara, Indonesia. Pengambilan sampel dilakukan pada singkapan batuan ultramafik di Kecamatan Baula dan Wolo. Batuan ultramafik Kolaka terdiri dari lherzolit, harzburgit, olivin websterit, dan serpentinit. Mineral sulfida, seperti pentlandit, pirit, dan kalkopirit, teramati pada batuan ini, bersama dengan mineral kaya Ni-Fe yakni awaruite. Pentlandite, mineral sulfida yang dominan, menggantikan olivin dan kromit, terutama pada bagian tepi dan urat-urat serpentin. Delapan sayatan poles batuan ultramafik dari kedua lokasi dianalisis dengan menggunakan SEM-EDS untuk mengetahui komposisi kimia pentlandit. Analisis ini menunjukkan komposisi Ni dan Fe yang bervariasi, dengan kandungan Ni yang lebih banyak. Pentlandit Daerah Baula memiliki kandungan Fe sebesar 18,22–27,34 wt%, Ni sebesar 32,59–39,10 wt%, dan Co sebesar 1,24–2,76 wt%, sedangkan yang berasal dari Wolo memiliki kandungan Ni yang jauh lebih tinggi (46,19–53,79 wt%) dan Co (2,79–4,18 wt%), namun memiliki kandungan Fe yang lebih rendah (8,50–15,18 wt%). Berdasarkan diagram terner, pentlandit menunjukkan kisaran temperatur pembentukan yang bervariasi (200 hingga lebih dari 600°C). Pentlandit dipisahkan menjadi dua kelompok: pentlandit Baula (Ni < 40%, Fe > 18%), dengan temperatur stabilitas antara 200 dan 500°C, serta pentlandit Wolo kaya Ni (Ni > 46%, Fe < 16%) dengan temperatur stabilitas di atas 600°C. Pembentukan pentlandit kaya Ni disebabkan oleh batuan ultramafik kaya Ni bereaksi dengan air laut pada temperatur tinggi, sehingga memudahkan proses pemurnian Ni secara efisien selama proses serpentinisasi.

1 Introduction

Nickel-iron sulfide (Ni-Fe-S) phases are a critical subject of study in geology, as they are key components of sulfide-rich ore deposits and play a vital role in understanding geological processes like magmatic differentiation, ore formation, and mantle differentiation. These sulfides are typically found in ultramafic and mafic igneous rocks and are closely associated with economic deposits of nickel, copper, and platinum-group elements (PGE) (Naldrett, 2013).

Nickel-iron sulfides occur naturally as minerals such as pentlandite ((Ni,Fe)₉S₈), pyrrhotite (Fe_{1-x}S), and troilite (FeS) (Barnes et al., 2020, Alksnis et al., 2018). They are formed primarily through magmatic processes, particularly in sulfide immiscibility during the cooling and crystallization of magma (Barnes and Lightfoot, 2005). As sulfide-rich melts segregate from silicate magmas, they concentrate chalcophile (sulfur-rich) elements, such as nickel (Ni), copper (Cu), and cobalt (Co). This mechanism is fundamental to the genesis of many nickel sulfide deposits.

The Kolaka Region is in Southeast Sulawesi, known worldwide for its lateritic nickel deposits. Laterite nickel deposits mainly originate from ultramafic rock weathering, such as harzburgite and dunite (Hasria et al., 2024). Some research reports that Ni-bearing minerals in laterite in this area are mostly garnierite and goethite (Ito et al., 2021).

Although nickel (Ni) and iron (Fe) from this area are primarily laterite-derived deposits, some studies have also found nickel sulfide-bearing minerals. Idrus et al. (2022) and Yao et al. (2023) report that pentlandite ((Ni, Fe)₉S₈) and millerite (NiS) are found on chromite from Kabaena Island, Southeast Sulawesi. Despite the discovery of the sulfides, these reports didn't discuss nickel-iron sulfide specifically. We present nickel-iron sulfide's composition and mineral chemistry from Kolaka, Southeast Sulawesi ultramafic rocks. This research mainly describes the nickel-iron sulfide mineral chemistry and its stability during its formation based on Kaneda et al. (1986) ternary diagram.

2 Geology

The Kolaka Ultramafic Rocks, part of the Kolaka Ophiolite Complex, are in the Kolaka region, Southeast Sulawesi, Indonesia (Figure 1). The ultramafic rocks widely stretch on the western side of Sulawesi's southeast arm. The northern part of the ultramafic rocks is found in the Wolo District, and the southern part is found in the Baula, Pomalaa, and Sopura

Districts. The ultramafic rocks also form the island cluster in the Gulf of Bone, known as Padamarang Island. Northeast-southeast-oriented faults dominate the structural style bordering the ultramafic rocks.

The Kolaka Ultramafic rocks are surrounded by Carbonaceous metamorphic rock basement and Neogene sediments known as Sulawesi Molasse (Surono, 2013a). The basement, known as the Mekongga and Pompangoe Complex, consists of schist, gneiss, chert, and meta-limestone (Rusmana et al., 1993, Simandjuntak et al., 1993). The basement forms the highest mountain range in the Sulawesi southeast arm, known as Mt. Mekongga. Sulawesi Molasse consists of Langkowala Fm., Boepinang Fm., and Alangga Fm. (Simandjuntak et al., 1993). These rocks are Neogene sediments, forming post-collision of metamorphic basement and ophiolite complex (Nugraha and Hall, 2022, Surono, 2013b).

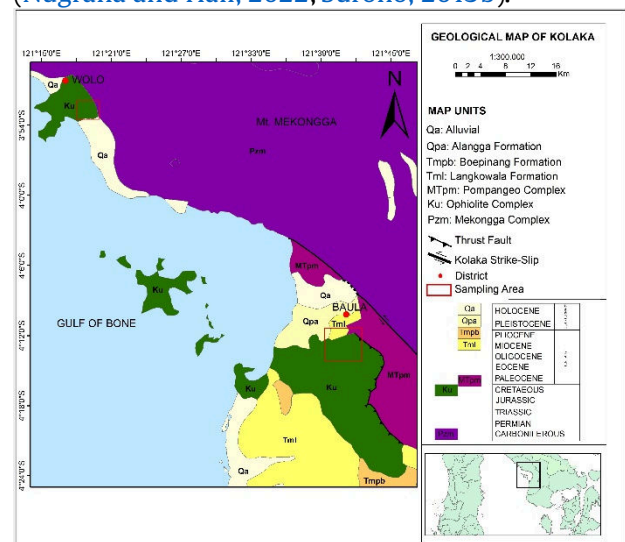


Figure 1 Geological map of Kolaka Region (modified after (Rusmana et al., 1993, Simandjuntak et al., 1993))

The ultramafic rocks we sampled are from the Wolo and Baula Districts, shown in Figure 1. The samples show a moderate to high degree of serpentinization, as shown by an extensive network of serpentine veins reflecting several generations of vein formation. Some quartz and magnesite veins in the outcrop indicate the carbonation process.

3 Method

The work stage comprises field rock sampling, polished section analysis, and Scanning Electron Microscopy (SEM) analysis using Energy Dispersive X-ray spectroscopy (EDS), focusing on nickel-iron sulfide-bearing minerals. Eight ultramafic rock samples were taken from two ultramafic outcrops in

the Kolaka Region, Wolo and Baula District. Reflected-light microscopy from the Geology Laboratory at the University of Halu Oleo was prepared, and eight polished sections were examined to find and study the nickel-iron sulfide-bearing minerals. Afterward, these minerals were analyzed by electron microprobe using Tabletop SEM EM-30AXN installed in the Integrated Laboratory at the University of Halu Oleo. During the EDS quantitative analyses of nickel-iron sulfide-bearing minerals, the electron microprobe was operated with an accelerating voltage of 10 kV and a beam current of 10 nA in the WD mode. The larger minerals were analyzed with a higher voltage of 15 kV. The value of S, Ni, Fe, Mg, Co, Cu, and Cd was acquired using the $K\alpha$ lines and then calibrated based on their respective minerals.

4 Results

4.1 Mineralogy and Sulfide Assemblages

The mineralogy of ultramafic rocks from the Kolaka Ophiolite Complex is reported in detail in an accompanying study (Jaya et al., 2024a, Jaya et al., 2024b) and is only summarized here. The ultramafic rocks consist of lherzolite, harzburgite, olivine websterite, and serpentinite. Harzburgite shows partial serpentinization of olivine and enstatite altered to tremolite and talc. Most enstatites are kink-banded and show undulate extinction, indicating a deformation during crystallization. Some clinopyroxene (augite and diopside) are lamellar exsolution alongside enstatite. Cr-spinel mainly preserved intergrowth with olivine. Brucite and magnesite are also present as the continuation of the carbonation process of serpentinization.

Serpentinization of olivine and pyroxene resulted in the development of mesh and hourglass textures alongside magnetite grains inside the veins. Samples with a higher degree of serpentinization show multiple generations of serpentine. The abundant lizardite and brucite without magnetite inside thin fractures show an early stage of serpentinization, while magnetite abundance in thicker fractures indicates the late stage of serpentinization.

Some sulfide minerals, pentlandite, pyrite, and chalcopyrite (Figure 2), are observed in the Kolaka ultramafic rocks. Ni-Fe-rich minerals were also found and interpreted as awaruite. The presence of sulfide minerals also shows the hydrothermal alteration process (Pirajno, 2009).

Some intensely serpentine veins and chromite contain pyrite, pentlandite, magnetite, chalcopyrite, and ultramylonitic Ni-Fe crystals interpreted as awaruite. Magnetite and flame-textured pentlandite grow along the rim of chromite (Figure 2a).

Pentlandite is also found as aggregates in serpentine veins. Sometimes intergrown with chalcopyrite (Figure 2c). Chalcopyrite, which usually forms at higher temperatures in hydrothermal systems, is shown to be replaced by pyrite (Figure 2b). This indicates a decreasing temperature in the system, as pyrite is more stable at lower temperatures, such as during oxidation (Amcoff, 1988). Ultramylonitic Ni-Fe crystals are coarsely disseminated on most samples. These crystals are awaruite, which is characterized by higher reflectance and tiny size (Figure 2d).

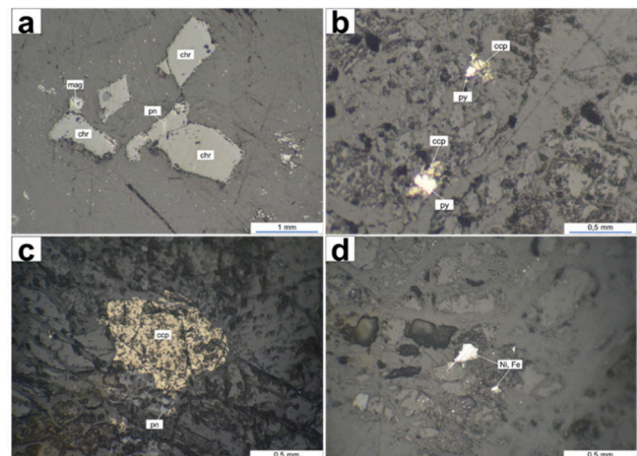


Figure 2 Polished section image of sulfide minerals from Kolaka ultramafic rocks: (a) Chromite grains rimmed with magnetite and pentlandite, (b) Pyrite replaces chalcopyrite, indicating a decreasing temperature in the system, (c) Chalcopyrite intergrown with pentlandite within serpentinized olivine, and (d) Dissemination of ultramylonitic Ni-Fe crystals (awaruite) on serpentinized ultramafic rock indicating redox conditions (Frost, 1985). Awaruite represents a promising source of nickel (Seiler et al., 2023). Mineral abbreviations based on (Whitney and Evans, 2010)

4.2 Chemical Composition of Pentlandite

Sulfides from Kolaka Ultramafic Rocks occur within olivine and chromite replacement. The replacements are mostly found at their rim and serpentine veins, mainly in the center of the mesh texture. The dominant sulfide mineral is pentlandite.

Pentlandite has a relatively variable composition of Ni and Fe but mostly tends to Ni-rich members (Figure 3). Fe contents in Baula are 18.22–27.34 wt%, Ni contents are 32.59–39.10 wt%, and Co contents are 1.24–2.76 wt% (Table 1). In some polished sections (Ewo-041 and Ewo-044), chalcopyrite crystal is intergrown with pentlandite and has lower Co contents (1.24 wt%) but medium Cu contents (2.10 – 3.49 wt%). In contrast with Baula, Wolo pentlandite has a significantly higher content of Ni and Co but lower Fe. Fe contents in Wolo are 8.50–15.18 wt%, Ni contents are 46.19–53.79 wt%, and Co contents are 2.79–4.18 wt% (Table 2).

Table 1 Chemical composition of pentlandite from ultramafic rocks at Baula District

Sample	BAULA			
	Ewo-041	Ewo-042	Ewo-043	Ewo-044
S	39.59	36.04	38.23	40,01
Ni	33.23	32.59	39.10	35.26
Fe	21.17	27.34	18, 22	18.48
Co	1.24	1.95	2.76	2.20
Cu	3.49	0.00	0.00	2.10
Cd	0.06	0.00	0.00	0.00
Total	98.78	97.92	98.31	98.05

Table 2 Chemical composition of pentlandite from ultramafic rocks at Wolo District

Sample	WOLO			
	Wol-021	Wol-022	Wol-023	Wol-024
S	33.08	30.51	35.90	34.44
Ni	53.79	50.63	46.19	47.79
Fe	8.50	15, 18	14.63	14, 15
Co	4.18	3.71	3.41	2.79
Cu	0.36	0.00	0.00	0.00
Cd	0.05	0.00	0.00	0.00
Total	99.96	100.03	100.13	99.17

The chemical data of pentlandites from the Baula and Wolo Districts are analyzed with mineral stoichiometry to find their composition. The chemical data of pentlandite is normalized (8 sulfur). Pentlandite composition in the Baula district is $\text{Fe}_{2,121-3,484}\text{Ni}_{3,668-4,470}\text{Co}_{0,136-0,314}\text{S}_8$, while pentlandite from Wolo is $\text{Fe}_{1,181-2,285}\text{Ni}_{5,623-7,106}\text{Co}_{0,352-0,549}\text{S}_8$.

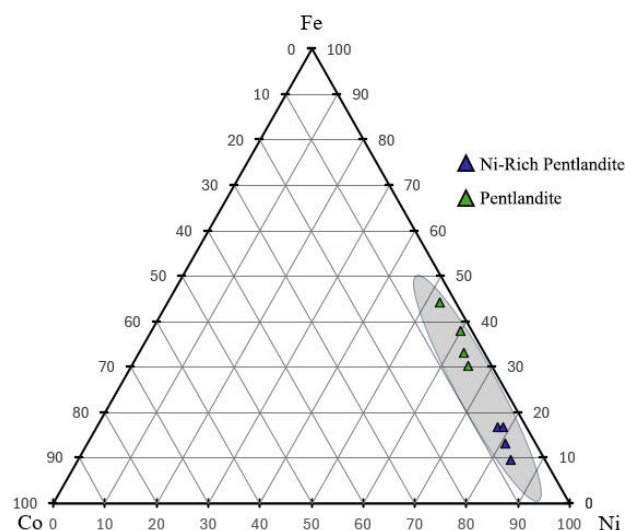


Figure 3 Fe-Ni-Co ternary diagram from Kaneda et al. (1986) shows the chemical composition of pentlandite from Kolaka Ultramafic Rocks

4.3 Serpentinization and The Stability of Pentlandite During Its Formation

Serpentinization of ultramafic rocks occurs when hydrothermal waters react with olivine and pyroxene to form serpentine, magnetite, brucite, hydrogen, and other secondary minerals. During the early stages of serpentinization, the fluid's reaction with olivine produces a large amount of H_2 , resulting in redox conditions (Schwarzenbach et al., 2012). Serpentinization and hydrogen (H_2) lead to a gain in sulfur in the rock and the formation of native metals (Ni, Fe, and Co) and their sulfide-bearing minerals (pentlandite) and metal alloys (awaruite) (Klein et al., 2009). Sulfur within ultramafic rocks represents a net sink of seawater sulfur (Alt et al., 2007).

Pentlandite from Kolaka Ultramafic Rocks mainly occurs in the center of mesh serpentine, replacing olivine (Figure 2c). Ni and Fe rarely migrate further outside of olivine grain, and pentlandite in the mesh centers is formed by the interaction between sulfur-rich fluid and Ni-Fe from altered olivine (Eckstrand, 1975). Kaneda et al. (1986) Fe-Ni-Co-S system and the Fe-Ni-S system show that pentlandite composition is temperature-dependent, and this temperature is genetically related to pentlandite stability during its formation.

Based on Figure 4, pentlandites show a wide range of temperatures, between 200 and 500°C, and are separated into two stability groups: pentlandite and Ni-rich pentlandite. Ni-rich pentlandites are characterized by high Ni content (>46%) and low Fe content (<16%), all found in the Wolo District. These minerals show stability fields at formation temperatures above 600°C, contrasting with pentlandites (Ni < 40% and Fe > 18%) from the Baula District, which show stability temperature ranges between 200 and 500°C. Even though pentlandite from Baula is not grouped as Ni-rich in this paper, it still has high Ni content. High Ni content in pentlandite from Kolaka Ultramafic Rocks is considered normal and thus differentiates it from non-ultramafic rocks pentlandite. Ni-rich pentlandite forms due to the geochemical exchange between Ni-rich ultramafic rocks and seawater (Schwarzenbach et al., 2012).

High-temperature serpentinization (above 600°C) can facilitate the efficient scavenging of Ni or other metals from Ni-rich ultramafic rocks during serpentinization to form Ni-rich pentlandite. The Ni:Fe ratio in the parent rock also determines whether the resulting pentlandite will be Ni-rich or Fe-rich (Li, 2014). Schwarzenbach et al. (2012) point out that redox conditions with low oxygen and high sulfur activity are needed to effectively scavenge metals, including Ni, from parental rock or magma. Future

research about oxygen and sulfur fugacity fluctuations during serpentinization of Kolaka Ultramafic Rocks is essential to support this research.

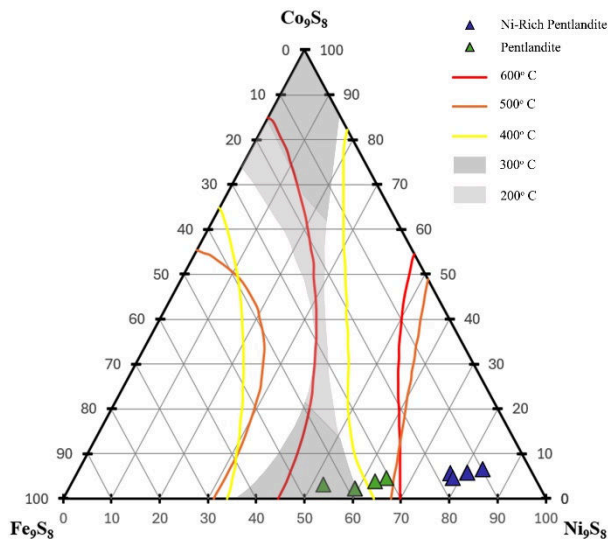


Figure 4 Stability of pentlandite in the Fe_9S_8 – Co_9S_8 – Ni_9S_8 diagram from Kaneda et al. (1986). Pentlandite separates into two stability formations: temperatures of 200–500°C characterized by higher Fe content and above 600°C characterized by higher Ni content

5 Conclusion

Pentlandite occurs as sulfide alteration in Kolaka Ultramafic Rocks. This nickel-iron-bearing mineral replaces olivine and chromite during the serpentinization process. Pentlandites from the Baula district have a relatively variable composition of Ni and Fe, with Fe contents ranging from 18.22 to 27.34 wt%, Ni contents from 32.59 to 39.10 wt%, and Co contents from 1.24 to 2.76 wt%. In contrast, pentlandites from the Wolo district have significantly higher Ni (46.19 to 53.79 wt%) and Co (2.79 to 4.18 wt%) contents but lower Fe (8.50 to 15.18 wt%). Based on the stability diagram, pentlandites from the Baula district show their formation stability temperatures between 200 and 500°C, while those from the Wolo district indicate temperatures above 600°C. The higher temperatures of Ni-rich pentlandites suggest more effective Ni scavenging during serpentinization.

References

- ALKSNIS, A., LI, B., ELLIOTT, R. & BARATI, M. KINETICS OF OXIDATION OF PYRRHOTITE. *IN*: DAVIS, B. R., MOATS, M. S., WANG, S., GREGUREK, D., KAPUSTA, J., BATTLE, T. P., SCHLESINGER, M. E., ALVEAR FLORES, G. R., JAK, E., GOODALL, G., FREE, M. L., ASSELIN, E., CHAGNES, A., DREISINGER, D., JEFFREY, M., LEE, J., MILLER, G., PETERSEN, J., CIMINELLI, V. S. T., XU, Q., MOLNAR, R., ADAMS, J., LIU, W., VERBAAN, N., GOODE, J., LONDON, I. M., AZIMI, G., FORSTNER, A., KAPPES, R. & BHAMBHANI, T., EDS. EXTRACTION 2018, 2018 CHAM. SPRINGER INTERNATIONAL PUBLISHING, 403-413. https://doi.org/https://doi.org/10.1007/978-3-319-95022-8_32
- Alt, J. C., Shanks, W. C., Bach, W., Paulick, H., Garrido, C. J. & Beaudoin, G. 2007. Hydrothermal alteration & microbial sulfate reduction in peridotite and gabbro exposed by detachment faulting at the Mid-Atlantic Ridge, 15°20'N (ODP Leg 209): A sulfur & oxygen isotope study. *Geochemistry, Geophysics, Geosystems*, 8(8). <https://doi.org/10.1029/2007gc001617>
- Amcoff, Ö. 1988. Experimental replacement of chalcopyrite by bornite: Textural and chemical changes during a solid-state process. *Mineralium Deposita*, 23(4). 286-292. <https://doi.org/10.1007/BF00206409>
- Barnes, S.-J. & Lightfoot, P. C. 2005. Formation of Magmatic Nickel Sulfide Deposits and Processes Affecting Their Copper and Platinum Group Element Contents. *IN*: HEDENQUIST, J. W., THOMPSON, J. F. H., GOLDFARB, R. J. & RICHARDS, J. P. (eds.) One Hundredth Anniversary Volume. Society of Economic Geologists. <https://doi.org/10.5382/av100.08>
- Barnes, S. J., Taranovic, V., Schoneveld, L. E., Mansur, E. T., Le Vaillant, M., Dare, S., Staude, S., Evans, N. J. & Blanks, D. 2020. The Occurrence and Origin of Pentlandite-Chalcopyrite-Pyrrhotite Loop Textures in Magmatic Ni-Cu Sulfide Ores. *Economic Geology*, 115(8). 1777-1798. <https://doi.org/10.5382/econgeo.4757>
- Eckstrand, O. R. 1975. The Dumont serpentinite; a model for control of nickeliferous opaque mineral assemblages by alteration reactions in ultramafic rocks. *Economic Geology*, 70(1). 183-201. <https://doi.org/10.2113/gsecongeo.70.1.183>
- Frost, B. R. 1985. On the Stability of Sulfides, Oxides, and Native Metals in Serpentinite. *Journal of Petrology*, 26(1). 31-63. <https://doi.org/10.1093/petrology/26.1.31>
- Hasria, H., Jaya, R. I. M. C., Awadh, S., Riskiyanti, R., Deniyatno, D., Syahrul, S. & Septiana, S. 2024. Mineralogy and Geochemical Characteristics of Lateritic Nickel Deposit in Wiwirano District, North Konawe,

- SE Sulawesi, Indonesia. Iraqi Geological Journal, 57(2C). 171-183. <https://doi.org/10.46717/igj.57.2c.13ms-2024-9-21>
- Idrus, A., Septiana, S., Zaccarini, F., Garuti, G. & Hasria, H. 2022. Mineralogical, Textural and Chemical Characteristics of Ophiolitic Chromitite and Platinum Group Minerals from Kabaena Island (Indonesia): Their Petrogenetic Nature and Geodynamic Setting. Minerals, 12(5). <https://doi.org/10.3390/min12050516>
- Ito, A., Otake, T., Maulana, A., Sanematsu, K., Sufriadin & Sato, T. 2021. Geochemical constraints on the mobilization of Ni and critical metals in laterite deposits, Sulawesi, Indonesia: A mass-balance approach. Resource Geology, 71(3). 255-282. <https://doi.org/10.1111/rge.12266>
- Jaya, R. I. M. C., Juarsan, L. I., Masri, Rubaiyn, A., Syahrul, Neni, Ramadani, S. & Hasria 2024a. Petrochemistry of Ultramafic Rock in Baula-Pomalaa Ophiolite Complex, Southeast Sulawesi, Indonesia. Journal of Geoscience, Engineering, Environment, and Technology, 9(1). 44-51. <https://doi.org/10.25299/jgeet.2024.9.1.14491>
- Jaya, R. I. M. C., Masri, Juarsan, L. I., Haraty, S. R., Pramadana, R. & Hasria 2024b. Serpentine Paragenesis in Ultramafic Rocks of the Baula - Pomalaa Ophiolite Complex, SE Sulawesi, Indonesia. Journal of Geology and Mineral Resources, 25(2). 95-106. <https://doi.org/10.33332/jgsm.geologi.v25i2.761>
- Kaneda, H., Takenouchi, S. & Shoji, T. 1986. Stability of pentlandite in the Fe-Ni-Co-S system. Mineralium Deposita, 21(3). 169-180. <https://doi.org/10.1007/BF00199797>
- Klein, F., Bach, W., Jöns, N., McCollom, T., Moskowitz, B. & Berquó, T. 2009. Iron partitioning and hydrogen generation during serpentinization of abyssal peridotites from 15°N on the Mid-Atlantic Ridge. GEOCHIMICA ET COSMOCHIMICA ACTA, 73(22). 6868-6893. <https://doi.org/https://doi.org/10.1016/j.gca.2009.08.021>
- Li, Y. 2014. Chalcophile element partitioning between sulfide phases and hydrous mantle melt: Applications to mantle melting and the formation of ore deposits. Journal of Asian Earth Sciences, 94. 77-93. <https://doi.org/https://doi.org/10.1016/j.jseaes.2014.08.009>
- Naldrett, A. J. 2013. Magmatic sulfide deposits: geology, geochemistry and exploration, Springer. 728 p. <https://doi.org/10.1007/978-3-662-08444-1>
- Nugraha, A. M. S. & Hall, R. 2022. Neogene sediment provenance and paleogeography of SE Sulawesi, Indonesia. Basin Research, 34(5). 1714-1730. <https://doi.org/10.1111/bre.12682>
- Pirajno, F. 2009. Hydrothermal Processes and Mineral Systems, Springer Netherlands. 1250 p. <https://doi.org/10.1007/978-1-4020-8613-7>
- Rusmana, E., Sukido, Sukarna, D., Haryono, E. & Simandjuntak, T. 1993. *The Geological Map of Lasusua - Kendari, Sulawesi*. Bandung: Geological Research and Development Centre.
- Schwarzenbach, E., Frueh-Green, G., Bernasconi, S., Alt, J., Shanks, W., Gaggero, L. & Crispini, L. 2012. Sulfur geochemistry of peridotite-hosted hydrothermal systems: Comparing the Ligurian ophiolites with oceanic serpentinites. GEOCHIMICA ET COSMOCHIMICA ACTA, 91. 283-305. <https://doi.org/10.1016/j.gca.2012.05.021>
- Seiler, S., Sánchez, G., Pawlik, M., Bradshaw, P. & Klein, B. 2023. Awaruite, a New Large Nickel Resource: Flotation under Weakly Acidic Conditions. Minerals, 13(9). 1147. <https://doi.org/10.3390/min13091147>
- Simandjuntak, T. O., Surono & Sukido. 1993. *Peta Geologi Lembar Kolaka, Sulawesi*. Bandung: Pusat Penelitian dan Pengembangan Geologi.
- Surono 2013a. The Geology of The Southeastern Arm of Sulawesi, Bandung, Geological Agency, Ministry of Energy and Mineral Resources. 174 p.
- Surono 2013b. Quarternary and Neogen Sediment Rocks. *In: SURONO & HARTONO, U. (eds.) The Geology of Sulawesi*. Jakarta: LIPI Press. 225-257.
- Whitney, D. & Evans, B. 2010. Abbreviations for Names of Rock-Forming Minerals. American Mineralogist, 95. 185-187. <https://doi.org/10.2138/am.2010.3371>
- Yao, J., Xu, J., Wu, C., Zhang, Z., Rosana, M. F., Li, X. & Jin, Z. 2023. Origin of high-Cr podiform chromitites from Kabaena Island, Southeast Sulawesi, Indonesia: constraints from mineralogy and geochemistry. International Geology Review, 65(19). 2943-2960. <https://doi.org/10.1080/00206814.2023.2167130>