GRANITIC MAGMATISM IN SULAWESI ISLAND, INDONESIA; IMPLICATION FOR METALLOGENIC PROVINCE

Adi Maulana¹, Koichiro Watanabe², Kotaro Yonezu², Akira Imai³

¹ Department of Geology Engineering, Faculty of Engineering, Hasanuddin University, Makassar 90245, Indonesia
² Department of Earth Resources Engineering, Kyushu University, Fukuoka 819-0395, Japan
³ Department of Earth Science and Technology, Akita University, Akita, Japan

Received Date: Month Date, Year

Abstract

In Sulawesi Island, located in the central part of the Indonesian Archipelagoes, Late Cenozoic Granitoid and their related mineral deposit show typical pattern that can be interpreted based on their petrochemical characteristic and distribution. Three distinctive type broad-scale granitic suites formed. The first type is high-K (HK) or shoshonitic suites which are concentrated in the southern and central-western (CW) part of the Western Sulawesi Province. The second suite consists of high-K calc-alkaline (CAK) which are found in the central and northwestern part of the province and the third suite is low-K to tholeiitic suites which are found in the central part of the Northern Sulawesi Province. Most of the granitic rocks are metaluminous and show a typical of I-type granitic rocks. With an exception of tonalitic rocks in Gorontalo area in the northern part of the island which show a MORB pattern, all granitic samples resemble the upper continental crust pattern in their trace and rare earth element pattern. Enrichment of large ion lithophile elements (Rb and Sr) and depletion of high field strength elements (especially Nb and Ta) suggests an arc magmatic affinity. Negative Eu anomaly in most of the samples shows plagioclase fractionation during magmatic differentiation. Granitic magmatism-related mineralization is ubiquitous in these granitic series. Mineralization includes porphyry and epithermal deposit. Ore element suites vary from Cu-Au-Fe associated with HK and CK in the south and CW of Western Sulawesi Province through Pb-Cu-Au-Mo associated with HK in the NW of Western Sulawesi Province and finally to Cu-Au-Ag associated with low-K to tholeiitic group in the Northern Sulawesi Province.

Keywords: Granite, Indonesia, Metallogeny, Sulawesi,

Introduction

One of the most problematic features in Sulawesi is the occurrence of various contrasting igneous rocks in space and time [1,2,3,4]. For example, whereas HK (high-K or shoshonitic series) and CAK (high-K calc-alkaline series) igneous rocks are only restricted in the younger (less than 14 Ma) rocks from the southern part of the Western Sulawesi Province, the CA (calc-alkaline) to low-K series igneous rocks are widely distributed in the central and northwestern part of the province which yielded a relatively older magmatic series (more than 16 Ma) [2,4,5].

Despite intensive scientific research, there is an ongoing controversy about the source of these magmatisms and the processes responsible for their petrogenesis as well as the related ore mineralization. One of main components of the magmatic products in this island is the Late Cenozoic granitoids which extend from the Western to the Northern part of the island [6]. It is reported that the granitic magmatism are associated with some mineralization [7,8].
However, study on the relationship between the granitic magmatism and the regional metallogeny in this island has never been done despite its significance values. This study is to report the granitic magmatism product in Sulawesi and aimed to constrain the implication to the metallogenic province in this island.

Regional geology

Sulawesi can be divided into four tectonic provinces (Fig. 1), namely (1) the Western Sulawesi Province, (2) the Eastern Sulawesi Province, (3) the Northern Sulawesi province and (4) the Banggai-Sula and Tukang Besi Continental Fragments (Fig.1). The detailed description can be found in [9].

The western Sulawesi Province consists of a continental margin segment with pre-Tertiary metamorphic basement rocks, originating from Sundaland overlain by Upper Cretaceous and Tertiary volcanic-sedimentary sequences, which are intruded by volcanic and plutonic rocks with various ages. The basement rocks were found in the southern, central and north western part of the province. The basement rocks in the southern part of the province consist of pre-Tertiary metamorphic basement rocks which can be divided into two different blocks; Bantimala Block and Barru Block [10,11]. The basement rocks in the central and northern part of the province form a belt called Central Sulawesi Metamorphic Belt. They consist of the Palu, Karossa and Malino Metamorphic Complex, which are composed of continental fragments derived from the Australian-New Guinea margin [7]. Tertiary sediments are found in the western part of the Walanae Graben in the southern part of the island as the Mallawa Formation, and in the western part near Latimojong Mountain as the Toraja Formation [12]. At the beginning of the Middle Miocene a major orogenic event took place, accompanied by andesitic volcanism and granitic intrusion spanning from the southern tip to the northern tip of the province to form Late Cenozoic volcanic and plutonic rocks. Quaternary sediments in this province are found in the Walanae Graben [6] and Palu area as Sulawesi Mollase.

The Eastern Sulawesi Province extends from the Central Sulawesi Trough across to the East and Southeast Arms, including Buton and Muna Islands. It consists of tectonically dismembered and highly faulted ophiolite associated with Mesozoic metamorphic rocks, ophiolitic mélangé and sedimentary rocks [13,14]. These form the basement of this region, which is overlain by Neogene to Quaternary sediments [15,16]. Large masses of ultramafic and mafic rocks forming ophiolite complex are distributed over most of the Eastern arm and the northwest part of the Southeast arm and also found are Buton and Kabaena Island. Neogene and Quaternary sediments, known as Celebes Molasse are found in the southern part of the province which consists of coarse- to fine-grained clastic sequences with shallow marine carbonate sequences [17].

The Northern Sulawesi Province consists of a Late Miocene to Recent subduction-related volcanic arc built on an oceanic substrate [7,18]. The oldest formation comprises a thick sequence of basaltic rocks (pillow lava, spilite, etc.) with interlayered deep-sea sediments, locally intruded by swarms of basalt dyke. Volcanism which occurred just after erosion of the plutonic rocks, produced andesitic and acid tuff with minor lava during Pliocene to Recent, forming what is referred to as the Pani Volcanic and Pinogu Volcanic Formation [19].

The Bangai-Sula microcontinent is represented above sea level by a group of islands, including Peleng, Banggai, Taliabu and Mangole Islands [20] whereas the Tukang Besi microcontinent comprises Buton, Muna and surrounding smaller islands.
Figure 1. Tectonic province of Sulawesi Island [10].

Method
Petrography, whole-rock major and trace element geochemistry, and Sr, Nd and Pb isotope analyses were carried out in order to examine the tectonic setting and origin of the granitic rocks. Granitic rocks samples including some enclaves were systematically collected from various localities in eleven areas covering the entire granitic rock distribution in Sulawesi Island. Thin sections were prepared and studied petrographically to determine the rock types, mineral assemblages, fabric and textural relations.

Concentration of major and trace elements including rare earth elements of 84 fresh samples were analyzed. Approximately 1 kg of each sample was crushed and milled to 200 mesh and then thoroughly mixed using a pulverizer. Major element compositions were determined on fused disc and pressed powder using an X-ray fluorescence spectrometer Rigaku RINT-300 at Department of Earth Resources Engineering, Kyushu University whereas rare earth elements and trace elements were determined by the ICP-MS method following a lithium metaborate/tetraborate fusion and nitric acid total digestion at ALS Chemex, Vancouver, Canada.
Trace and rare earth elements shown in the spider diagram were normalized to primitive mantle and to chondrite of [21], respectively. Loss on ignitions values were calculated after heating the sample powder to 100 °C for 2 hours and weighed and reheated to 500 °C for 1 hour and finally to 900 °C for 1.5 hours.

**Result and discussion**

**Whole-rock major and trace elements geochemistry**

To constrain the geochemical characteristics, we used K$_2$O-SiO$_2$ diagram of [22] to classify the studied samples for the granitic province in this island. Based on this classification, the studied samples can be grouped into three distinct series; HK, CAK and low-K to tholeiitic series. Combination of more than one granitic rock series in one pluton is common as seen in Mamasa, Masamba, Lalos-Toli, suggesting the multiphase intrusion within one pluton. The Total Alkali (Na$_2$O+K$_2$O) vs SiO$_2$ diagram of [23], A/NCNK (molar ratio of Al$_2$O$_3$/[(CaO+Na$_2$O+K$_2$O)]) versus A/NK (molar ratio of Al$_2$O$_3$/[(Na$_2$O+K$_2$O)]) and K$_2$O-SiO$_2$ diagram of [22] as well as trace and rare earth element normalized diagrams of the granitic rocks are also shown in Fig. 3 to 5. Most of the granitic rocks are plotted in the field of quartz diorite, granite, syenite, syenodiorite and gabbro whereas the enclave in Parigi is plotted in the syeno-diorite field (Fig. 3).

- **HK (high-K or shoshonitic series)**
  HK rocks were restricted in the central and southwestern part of the Western Sulawesi Province (Mamasa, Polewali, Masamba and Barru Plutons), consistent with proposed regional magmatic suite features of the island. However, the granitic rocks in the Sony Pluton, which is located in the NW part of the Western Sulawesi Province, also show HK affinity (Fig. 3). In the Polewali Pluton, all rocks were plotted in the HK series (K$_2$O content range from 3.9 to 4.9 wt%) with only a quartz monzonite (POL-13) straddle between HK and CAK border. The SiO$_2$ content is broadly similar (64.3 to 65.4 wt%) except for granodiorite (POL-ST3) which contains lower SiO$_2$ content (56.6 wt%). Most of granitic rocks from the Mamasa Pluton (except sample MA45 and MA41BA) show a strong shoshonitic character with K$_2$O range from 4.2 to 6.6 wt% and SiO$_2$ range from 51.6 to 67.6 wt%. Two syenite samples (MA-38 and MA-38B) show an extreme of K$_2$O (up to 10.4 wt%). Barru quartz monzonite (DIO BR) contains 60.7 wt% SiO$_2$ and 4.1 wt% K$_2$O, which are also plotted in the HK field. The granitic rocks in Sony Pluton are characterized by high K$_2$O (range from 3.7 to 5.5 wt%) and SiO$_2$ which is only restricted between 62 to 65 wt% except quartz syenite (SO-21) which show a relatively lower SiO$_2$ content but extremely high total FeO content. The K$_2$O and SiO$_2$ contents of the granodiorite (LA-18C and LA-18D) from the Lalos-Toli Pluton are relatively similar.

  ASI (Alumina Saturation Index = A/NCNK) of granitic rocks from this series range from 0.6 to 1.1. The A/NK versus A/NCNK diagram (Fig. 3) shows that the granitic rocks mainly belong to metaluminous (A/NCNK<1.1) and therefore plotted as I-type granitic rocks.

  Trace and rare earth elements were normalized to primitive and chondrite values of [21] (Fig. 4). Primitive-mantle normalized trace element patterns of the HK series rocks generally show a regular trend. They show enrichment of large ion lithopile elements (LILE) and depletion of high field strength elements (HFSE) including Nb, Ta and Ti which resemble upper continental crust pattern. They are further characterized by the negative anomaly of Sr, suggesting plagioclase fractionation during crystallization. However, Barru quartz monzonite (DIO-BR) and a dioritic enclave (67-C2) show a positive Sr anomaly, suggesting plagioclase accumulation.
Chondrite normalized REE patterns of most of the HK granitic rocks series show relative enrichment of light rare earth elements ($\text{La}_N/\text{Yb}_N = 1.8 \text{ to } 52$) and negative Eu anomalies [$\text{Eu}_N/\left(\text{Sm}_N \times \text{Gd}_N\right)^{0.5}$] ($\text{Eu}^* = 0.4 \text{ to } 0.8$) with flat heavy rare earth elements (HREE) patterns. An extreme enrichment of LREE was shown by the high $\text{La}_N/\text{Yb}_N$ ratio up to 94 with a relatively flat HREE pattern from Masamba granitic rocks (67C-2). An enclave (67C-2) presents a contrasting signature with low LREE enrichment (Fig. 4).

**High-K calc-alkaline series (CAK)**
The CAK granitic rocks series are mostly restricted in the central part until the northwestern part of the Western Sulawesi Province. They are found in West Palu, Emu- Lab Lalos-Toli, Parigi and Latuppa. SiO$_2$ contents of the granitic rocks from this series range from 55 to 69 wt% whereas SiO$_2$ contents of enclaves are lower (<55 wt%).

A/NK values of the granitic rocks are > 1 while the A/CNK ranges from 0.86 to 1, implying that all granitic rocks are also metaluminous and has an I-type character. The granitic rocks in this suite are relatively enriched in LILE such as Rb, Ba, Th, U but depleted in HFSE (e.g. Zr, Nb, Ta, Ti, Hf) and REE as shown in the primitive mantle normalized trace element pattern (Fig 4). Most of the rocks show negative anomalies Sr, except granodiorite (PA-27E) and the enclave (PA-28E) from Parigi which displays a positive anomaly of Sr. The positive Sr anomaly can be explained by the high CaO and Na$_2$O content manifested by plagioclase abundances, concordant with its petrographic analysis.

Chondrite normalized rare earth element patterns show enrichment of LREE with $\text{La}_N/\text{Yb}_N$ values up to 32 and relatively flat HREE (Fig. 4). Two groups of Eu anomaly were found, the negative anomalies with $\text{Eu}^*$ range from 0.5 to 0.9 and the positive anomalies with $\text{Eu}^*$ ranges from 1.1 to 1.3. Monzogranite (PA-27E) and the enclave (PA-28ENC) show a slightly depleted LREE and positive Eu anomaly compared to other granitic rocks.

**Low-K to tholeiitic series**
The low-K to tholeiitic series granitic rocks are mostly found in Gorontalo area in the Northern Sulawesi Province. However, some granitic rock from Mamasa Pluton (MA-45 and MA41-BA) and Masamba Pluton (MST-3B, MRF-4B and MST-3A) also show relatively low content of K$_2$O which led them to be classified as low-K to tholeiitic field in SiO$_2$ vs K$_2$O diagram (Fig. 3). Compared to the other suites, the SiO$_2$ contents of granitic rocks from these units are relatively high. The A/CNK vs A/NK diagram (Fig. 3) shows that most of the granitic rocks were plotted in the metaluminous field, while monzogranite (MAL 61) was plotted in the transition between meta- and peraluminous field.

Enrichment of LILE, Th and U and depletion of HFSE are displayed in primitive mantle normalized trace element diagram (Fig. 4) except for a tonalite (GR-1) and a granodiorite (MA-41BA), which show depletion of these elements. Most of the granitic rocks also show negative Nb, Ta and Ti anomalies, suggesting an arc-related geochemical signature. Some of them also show negative Sr anomaly (MA41-BA and MST-3B).

Chondrite normalized rare earth element patterns (Fig. 4) display four distinctive groups; the first (including MA-45, MST-3A, 61 MAL, 60 GTL, GR-3) with enrichment of LREE ($\text{La}_N/\text{Yb}_N = 2.9 \text{ to } 8.3$) and slightly negative Eu anomaly ($\text{Eu}^* = 0.66 \text{ to } 0.76$), the second (MA-41BA and MST-3B) shows lower LREE but positive Eu anomaly ($\text{Eu}^* = 1.3 \text{ to } 2.1$) and very low HREE, the third (62 GTL and 55- GTL) with lower LREE ($\text{La}_N/\text{Yb}_N = 1.7 \text{ to } 2.7$) and small negative Eu anomaly ($\text{Eu}^* = 0.72 \text{ to } 0.82$) which resembles enriched-MORB and the last (GR-1) with depletion of LREE ($\text{La}_N/\text{Yb}_N = 0.46$) and positive of Eu anomaly ($\text{Eu}^* = 0.96$) which resembles the normal-MORB trend of [21].
Figure 2. Sample location map showing the distribution and classification of granitic rocks according to their geochemical character in Sulawesi Island.

Figure 3. Silica vs Total alkali diagram (right) and alumina saturation index of the granitic rocks.
Regional Metallogeny Province

The different partitioning of Fe among silicates and oxides in granitic rocks is controlled by oxygen fugacity or $f(O_2)$ and explain the ilmenite- and magnetite-series [24]. In addition, $f(O_2)$ also plays an important role in ore mineralization process within granitic rocks since it controls redox state of magma [25].

The reduced-I type (ilmenite-series) granitic rocks in Sulawesi which are located in the CW of the Western Sulawesi Province are associated generally with Au and base metal (Pb-Zn-Cu) mineralization in Sassak, north of Toraja district [19], Mangakaluku, Latuppa, and south Palopo. Recently, preliminary study on the occurrence of Au-Cu mineralization was reported from granodiorite stock in Mallawa area south Sulawesi [26]. It is interesting to note that potential Sn and W occurrence associated with this reduced I-type and ilmenite-series granitic rocks in Sulawesi have not been reported yet. This is in contrast with the occurrence of Sn and W mineralization which associated with ilmenite-series granitic rocks in Sumatera and Tin Island as reported by some previous workers [27]. The absence of the Sn and W in the ilmenite-series mineralization could be explained by the oxidation state of the magma. [28] reported the low oxygen fugacity values of the Sn-W related granitic rocks. The reduced-I type and ilmenite-series granitic rocks in the Western Sulawesi Province show a relatively high oxygen fugacity. The reduced I-type (ilmenite-series) and normal- I type
magnetite-series granitic magmas in Sulawesi Island contain relatively high FeO and Rb/Sr content and were mainly plotted in the increasing oxidation trend which corresponds to Cu-Mo related magma in diagram of [29]. Alternatively, the absence of Sn-W mineralization is due to the low Al content of biotite. [30] reported Sn and W mineralization in Japan and Korea are associated with the reduced granitic rocks which contain high total Al content of biotite.

The normal- I type, magnetite-series granitic rocks which are distributed mainly in the Northern Sulawesi Province (but also in the NW part of the Western Sulawesi Province; i.e. Sony Pluton), are associated with various deposit types, including porphyry Cu-Au mineralization associated with tourmaline in Bulagidun [31], porphyry Cu-Au and epithermal Cu-Au-Ag mineralization in Tumbalalito [8], high sulfidation mineralization in Motomboto [32] and fracture disseminated Au mineralization at Gunung Pani [18]. In addition, the granitic rocks are also related with porphyry Mo mineralization in Malala [7]. The close relation between the granitic rocks in these areas and the porphyry Cu-Au is shown in the oxygen fugacity and temperature diagram [9]. In this figure, granitic rocks from the Sony Pluton were plotted in the field of Mo deposit whereas the granitic rocks from the Gorontalo Pluton were plotted close to the field of porphyry Cu-Au deposit. The close relation with the Cu-Mo mineralization of the normal I-type magnetite-series granitic rocks in this island is also shown in diagram of Fe2O3 vs. Rb/Sr [9].

Conclusion
The geochemical series pattern of the granitic rocks seems to be consistent with the regional geochemical pattern of the igneous rocks in the island. The HK are concentrated in the south (Barru Pluton) and central-west (Polewali, Mamasa and Masamba Pluton) of the Western Sulawesi Province whereas the CAK are more confined to the central (West Palu, Emu-Lab, Parigi and Lutuppa Pluton) north-western part (Lalos-Toli and Sony Plutons) of the province. The low-K to tholeiitic series granitic rocks were found in the Gorontalo Pluton, in the central part of the Northern Province. Some of the plutons (Mamasa, Masamba, Lalos-Toli) show a composite pattern (combination of HK, CAK and low-K to tholeiitic), suggesting that multiple granitic magmatism occurred in these areas.

Both reduced- I type ilmenite- and normal-I type magnetite-series granitic rocks in Sulawesi are associated with ore mineralization (e.g. Cu, Au, Ag, sulfide, base metal, and Mo). The normal-I type magnetite-series rocks distributed in the Northern Sulawesi Province show more intense ore mineralization than the reduced-I type ilmenite-series rocks in the Western Sulawesi Province. The absence of Sn-W mineralization in the reduced-I type ilmenite-series is due to the high oxygen fugacity or low total Al content in biotite which correspond to shallow solidification depth. It is suggested from this study that redox condition play an important role in regional metallogeny systems in Sulawesi.

Acknowledgment
We would like to extend our gratitude to GCOE program of Kyushu University and MEXT scholarship for the financial support.

References


