International Symposium on Earth Science and Technology, CINEST 2012

Origin of magnetite- and ilmenite-series granitic rocks in Sulawesi, Indonesia: magma genesis and regional metallogenic constraint

Adi Maulana\textsuperscript{a,c}, Koichiro Watanabe\textsuperscript{a}, Akira Imai\textsuperscript{b}, Kotaro Yonezu\textsuperscript{a}

\textsuperscript{a} Department of Earth Resources Engineering, Faculty of Engineering, Kyushu University, Fukuoka 819-0395, Japan
\textsuperscript{b} Department of Earth Science and Technology, Akita University, Akita, Japan
\textsuperscript{c} Department of Geology, Hasanuddin University, Makassar 90245, Indonesia

Abstract

Lateral and spatial variations magnetic susceptibilities of the granitic rocks from Sulawesi, Indonesia were studied to constrain its implication for their magma genesis and regional metallogenic. The magnetic susceptibility of the granitic rocks varies between 0.08 x 10^{-3} SI to 18.58 x 10^{-3} SI, corresponding respectively to ilmenite series (< 3 x 10^{-3} SI; oxidized type) and magnetite series (> 3 x 10^{-3} SI; reduced type) granite. This wide range result is due to large variation of rock types within one suite which cause a variety of magnetic minerals content in the rocks. Although regionally, Sulawesi granitic rocks are dominated by ilmenite series granites, the ratio of ilmenite/magnetite series granites decreases substantially from the southern part to the northern part of the island. The occurrence of the ilmenite-series with I-type characteristic granitic rocks in Sulawesi Island may be explained by assimilation process between magma and crustal material that containing a various quantity of reduced C- and S-bearing sediments. The ilmenite series granitic rocks are characterised by the occurrences of ilmenite and hematite, higher Sn-W, U-Th, V and total REE+Y, whereas the magnetite series are characterized by abundance of hematite and sulphide minerals but lower Sn-W, U-Th, V and total REE+Y. The absence of Sn and W mineralization in ilmenite-series granitic rocks could be explained by the high oxidation state of the granitic magma.

Keywords: granitic rocks, magnetite susceptibility, Sulawesi, Indonesia, metallogenic

* Corresponding author. Tel.: +81-80-3998-2804; fax: +81-92-802-3368
E-mail address: adi-m@mine.kyushu-u.ac.jp.
1. **Introduction**

The magnetite- and ilmenite series granite classification is based on magnetite content of granitic rocks which can be simply identified by their magnetic susceptibility (MS) value [1-3]. This MS reflects the oxygen fugacity of the granitic magma which is of paramount importance in controlling the compatible/incompatible nature of many ore elements. Hence, this redox state is very useful to provide an insight to the genesis of mineralization associated with the granitic rock and can be used as an invaluable tool in mineral exploration within granitic terranes [4-5]. Granitic rocks are widely distributed in Sulawesi Island, Indonesia, covering approximately 20% of the island. Series of mineralization has been reported from these granitic rocks [e.g 6-8]. Petrologic and geochemical studies on these granitic rocks have been conducted by some previous workers such as [9] and [10]. Nevertheless, study on magnetic susceptibility of these rocks has not been carried out yet despite its importance in elucidating the redox state of magma which controls the mineralization process. This paper is to summarize data on magnetic susceptibility of the granitic rocks in Sulawesi and discuss their implication on magma genesis and regional metallogenic.

2. **Regional Geology and Tectonic Setting**

Sulawesi can be divided into four (4) tectonic provinces [11] namely (1) the Western and North Sulawesi Pluto-Volcanic Arc, (2) the Central Sulawesi Metamorphic Belt, (3) the East Sulawesi Ophiolite Belt and (4) the Banggai-Sula and Tukang Besi continental fragments (Fig.1). The outline of tectonic division of this island is as follows:

2.1. **West and North Sulawesi Pluto-Volcanic Arc**

This province occupies North Arm to South Arm of Sulawesi and can be subdivided into two segments: (i) the West region, which consists of a continental margin segment with metamorphic basement rocks of pre-Tertiary Sundaland origin (including Bantimala and Barru Complex) and overlain by Upper Cretaceous and Cenozoic volcanic-sedimentary sequences. (ii) the North region, which consists of a Late Miocene to Recent subduction-related volcanic arc, resulting from the west-dipping subduction of the Molucca Sea Plate. This region is built on an oceanic substrate in most of the north, and a Paleozoic microcontinental block, the Malino Metamorphic Complex which was derived from the New Guinea-Australian margin of Gondwanaland.

2.2 **Central Sulawesi Metamorphic Belt**

This belt is confined to the center and part of the Eastern Arm of the island, and is assumed to have resulted from collision between fragments of Gondwana and the active Asian margin in the late Oligocene or early Miocene. It consists of sheared metamorphic rocks including the Pompaneo Schist Complex and a mélangé complex, as well as a Miocene Ophiolite (Lamasi Complex). This region has been assumed to be an accretionary complex formed during Cretaceous and Paleogene or a suture between western and eastern part of Sulawesi; the two are not conclusive.

2.3 **Eastern Sulawesi Ophiolite Belt**

This belt extends from the central Sulawesi trough across the East and Southeast Arms, including Buton and Muna Islands. It consists of tectonically dismembered and highly faulted ophiolite associated with Mesozoic metamorphic rocks and sediments. These form a basement for this region, which is overlain by Cenozoic sediments. The ophiolite series comprises residual mantle peridotite, mafic-ultramafic cumulate and gabbro, sheeted dolerites and basaltic volcanic rocks. The oceanic plateau
component of the ophiolite has been interpreted as a product of the Southwest Pacific Superplume.

2.4. Banggai-Sula and Tukang Besi continental fragments

These continental fragments are located in the eastern and southeastern parts of Sulawesi, respectively. The Banggai-Sula microcontinent is represented above sea level by a group of islands, including Peleng, Banggai, Taliabu and Mangole Islands whereas the Tukang Besi microcontinent is comprised of Buton, Muna and smaller surrounding islands. Banggai–Sula has a metamorphic basement which was intruded by Late Paleozoic granitoids and overlain by Triassic felsic to intermediate volcanic products. The region is interpreted to have originated from New Guinea in the late Cenozoic and to have transported by extension on the Sorong Fault during the Neogene. Like other microcontinents in the region, Buton and the rest of the Tukang Besi platform are interpreted as an Australian continental fragment. However, it was suggested that Buton Island and the Tukang Besi Archipelago represent different continental fragments which were formerly separated from each other by oceanic crust.

Fig. 1. Tectonic Setting of Sulawesi Island (modified from[11]).
3. Analytical Method and Samples

Magnetic susceptibility values of the rocks were measured in the field with a portable device of KT-10 Magnetic Susceptibility Meter from Terraplus. The units of measurement in volume susceptibility are the commonly used dimensionless SI units (International Standard units) and the $10^{-3}$ units is used as measured values.

The study focused on nine (9) different granitic bodies in Sulawesi Island. The sites were chosen because of the accessibility and the abundance of outcrop of fresh rocks for both geochemical sampling and the collection of measurements. Several (5 to 10 times) measurement were normally taken from each sample at different orientations and an average reading is recorded.

Petrographic features and geochemical composition of the granitic rocks in Sulawesi have been reported by [10]. The analyzed granitic rocks are medium- to coarse-grained biotite-hornblende-quartz diorite to biotite granite and hornblende-biotite quartz monzonite. Geochemically, the granitic rocks exhibit a wide range of composition from granite to monzodiorite through quartz monzonite, granodiorite and diorite with silica average contents ranging from 60.9 to 73.4 wt%. However, most of the samples were classified as quartz monzonite and granodiorite.

4. Results

Summary of magnetic susceptibility (MS) measurements of granitic rocks in Sulawesi is depicted in Fig. 2. The results have shown that the magnetic susceptibility of the granitic rocks varies between $0.081 \times 10^{-3}$ to $18.58 \times 10^{-3}$ SI units, showing a bi-modal pattern which correspond to both ilmenite-series ($< 3 \times 10^{-3}$ SI; reduced type) and magnetite-series ($> 3 \times 10^{-3}$ SI; oxidized type) granite (Fig. 3).

Magnetic susceptibility value of granitic rocks in Emu-Lab, in the central part of the island, ranges from 0.14 to $4.33 \times 10^{-3}$ SI units. This value correlates the ilmenite- and magnetite-series granitic rocks. In Lalos-Toli and Sony area, which are situated in the northern part of the island, MS ranges from 1.88 to $18.58 \times 10^{-3}$ SI units, showing a higher value of MS than Emu-Lab. Additionally, MS value in granitic rocks samples in Gorontalo area (also located in the Northern Arm of the island) show higher value, ranging from 3.78 to $5.33 \times 10^{-3}$ SI units which correspond to magnetic-series value.

Conversely, the MS values of the samples in Parigi and West Palu, which are located in south of Emu-Lab, range from 0.29 to $4.23 \times 10^{-3}$ SI units and from 0.10 to $0.24 \times 10^{-3}$ SI units, respectively. Similarly, MS values in Polewali, Mamasa, and Masamba, which are situated in the southernmost part of Emu-Lab area, have an average from 0.16 to $0.27 \times 10^{-3}$ SI units. However, some samples in Polewali show a bit higher value of MS ($2.35 \times 10^{-3}$ SI units).

![Fig.2 Distribution of magnetic susceptibility values of granitic rocks in Sulawesi.](image-url)
These features display that the granitic rocks are dominated by ilmenite-series granitic rocks since the MS value are generally lower than $3 \times 10^{-3}$ SI units. However, the MS values show a consistent increasing trend to the northern part of the island, suggesting different petrogenesis process. The MS value range of the granitic rock from Gorontalo in the northern part of the island are relatively higher ($> 3 \times 10^{-3}$ SI) compared to those from Mamasa ($< 0.36 \times 10^{-3}$ SI) in the southernmost part and hence classified as magnetite-series granitic rocks.

5. Discussion

5.1 Magma Genesis

The formation of magnetite-series granitic rocks required oxidized mafic source, whereas the ilmenite-series could have been formed by assimilation of organic carbon from the accreted sediments in lower-middle crust process [2] or through subduction process [12]. [13] classified the granitic rocks into I- and S- type based on their chemical characteristic. I-type granitic rocks derived from source of igneous rocks and containing moderate amount of $\text{Al}_2\text{O}_3$ and high amount of $\text{Na}_2\text{O}$. S-type results from the partial melting of metasedimentary source rocks and has high $\text{Al}_2\text{O}_3$ but low $\text{Na}_2\text{O}$. The I- and S-type granitic rocks can be determined from the alumina saturation index or ASI value (molar $\text{Al}_2\text{O}_3$/CaO + $\text{Na}_2\text{O}$ +
K$_2$O). Those with A/CNK less than 1.1 will be classified as I-type whereas those with A/CNK higher than 1.1 would be grouped as S-type granitic rocks. [14] reported that magnetite- and ilmenite-series granitic rocks in Japan are comparable to I- and S-type granitic rocks, respectively. The close relationships of these classifications were also reported from other areas such as Sierra Nevada Batholith [15].

The low Alumina Saturation Index (< 1.1.) of most samples [10] allow them to be classified as I-type granitic rocks and hence were grouped into metaluminous group. At the same time, the magnetic susceptibility value show two contrasting groups, in which the granitic rocks from the northern part (Gorontalo) of the island belong to magnetite-series and those from west and southern part of the island belong to ilmenite-series granitic rocks.

The occurrence of the ilmenite-series with I-type characteristic in Sulawesi Island may be explained by model that proposed by [15]. It is reported that the sedimentary layers contain much carbon as a redox agent. Interaction between magma and this redox agent eventually reducing the magma and hence produce I-type granitic rocks with ilmenite-series characteristic. It is very likely that the granitic magma in west and southern part of Sulawesi may have been modified while ascending to the surface through the continental crust by assimilation process with crustal material that containing a various quantity of reduced C- and S-bearing sediments.

This scenario is concordant with the radiogenic isotope composition of the granitic rocks. Isotopically, the granitic rocks in Sulawesi Island are mafic in the north and become felsic in the west and southern part of the island [16]. The $^{87}$Sr/$^{86}$Sr isotope ratio of the granitic rocks in the northern part is lower than those in the west and southern part. In contrast, Nd isotopes ratios of the granitic rocks in the northern part are higher than those in the west and southern part. This suggests that the granitic rocks in the west and southern part were continental derived whereas the granitic rocks in the northern part were originated from mafic source. Therefore, the crust generation model of granitic magma in Sulawesi Island is an ensimatic basement to the north but sialic crust to the west and southern part.

5.2 Regional Metallogenic

The different partitioning of Fe among silicates and oxides in granitic rocks is controlled by oxygen fugacity or $\phi$(O$_2$) and explain the ilmenite- and magnetite-series [1]. In addition, $\phi$(O$_2$) also plays an important role in ore mineralization process within granitic rocks since it controls redox state of magma [4]. The ilmenite-series granitic rocks in Sulawesi are associated generally with small porphyry copper and base metal mineralization in Sassak, north of Toraja district [17], Mangakaluku, Latuppa, and south Palopo. Recently, preliminary study on the occurrence of porphyry Cu minerals was reported from granodiorite stock in Mallawa area south Sulawesi [18]. On the other hand, potential Sn and W occurrence associated with ilmenite-series granitic rocks in Sulawesi has not been reported yet.

The magnetite-series granitic rocks which are distributed mainly in the northern part of the island, are associated with various deposit types, including porphyry Cu and Au mineralization associated with tourmaline in Bulagidun [7], porphyry Cu-Au and epithermal Cu-Au-Ag mineralization in Tumbalalito [6], high sulfidation mineralization in Motomobo [19] and fracture disseminated Au mineralization at Gunung Pani [20]. In addition, the granitic rocks are also related with porphyry Mo mineralization in Malala [8].
Fig. 4 Proposed metallogenic province associated with granitic rock map in Sulawesi.

6. Conclusions

This study shows that the granitic rocks in Sulawesi consist of ilmenite- and magnetite-series and show a space-dependant distribution. The granitic rocks in the northern part belong to magnetite-series whereas those in the southern part generally belong to ilmenite-series. These two magmatic series are considered to represent different redox condition, source rock composition, and crystallization and emplacement history. The differences of magnetic susceptibility within one suite are due to large variation of rock types which cause a variety of the abundance of magnetic minerals in the rocks.

Based on the whole-rock composition, both ilmenite- and magnetite series mostly resembles the I-type granitic rock showing metaluminous affinity. The occurrence of the ilmenite-series with I-type characteristic in west and southern part of Sulawesi may have been originated from modified magma by assimilation process with crustal material which eventually producing I-type with ilmenite-series character.

Both ilmenite- and magnetite-series granitic rocks in Sulawesi are associated with ore mineralization (e.g. Cu, Au, Ag, sulfide, base metal, and Mo). The magnetite-series rocks distributed in the northern part show more intense ore mineralization than the ilmenite-series rocks in the southern part of the island.

Cu-Au-Mo mineralization is associated with I-type and calc-alkaline magnetite-series granitic rocks in the northern part of the island.
Acknowledgements

GCOE program in Kyushu University is highly appreciated for field work budget support. MEXT program is highly acknowledged for PhD scholarship to the first author.

References