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Exhumation and Tectonomagmatic Processes of the Granitoid Rocks from Sulawesi, Indonesia: Constrain from Petrochemistry and Geothermobarometry Study

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Abstract - Exhumation and tectonomagmatic processes of the granitoid from Sulawesi were discussed using petrochemistry (*e.g.* petrographic and major element compositions) and geothermobarometry data (mineral chemistry data). Detailed petrographic observations were conducted to determine the mineral composition, texture, and structure of the granitoid rocks, whereas the whole rock composition were determined using XRF method, and the mineral chemistry was analyzed using Electron Microprobe Analyzer (EPMA). The granitoids are classified as calc-alkaline, metaluminous I-type. Pressures of 0.91 to 1.2 kbar and emplacement depths of 3.2 to 4.3 km at temperatures of 677 - 729°C were estimated for Mamasa Pluton. Whereas Masamba Pluton was emplaced at pressures of 2.3 to 2.8 kbar, temperatures of 756 - 774°C, and emplacement depths of 8.2 to 10 km. Moreover, Lalos-Toli and Sony Plutons were emplaced at temperatures of 731 to 736°C and 601 to 609°C, respectively. The pressures varying from 3.1 to 3.3 kbar and 3.2 to 3.4 kbar, equate to an emplacement depth of 11.3 and 11.6 km, respectively. Gorontalo Pluton emplaced at temperatures of 662 - 668°C with the pressure range from 2.6 to 2.7 kbar, is equivalent to 9.3 km deep. Varied oxidation state (ranging from -14 to 19) is inferred from the mineral assemblages, showing a strong association with highly oxidized I-type series granitic rocks. The exhumation rate estimation shows that Mamasa and Masamba Plutons were exhumed respectively at a rate of 0.37 and 1.6 mm/year, whereas Lalos-Toli and Sony Plutons at 1.4 and 2.7 mm/year, respectively. Gorontalo Pluton located in the Northern Sulawesi Province was exhumed at 0.42 mm/year. The rapid exhumation rate of Sony Pluton is attributed to the active vertical movement of Palu-Koro Fault Zone which has been active since Pliocene. It shows that faulting may play an important role in differential exhumation of intrusive bodies in the orogenic belt.

Keywords: exhumation, petrochemistry, geothermobarometry, granitoid rocks, Sulawesi, Indonesia

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Introduction

Late Cenozoic granitoid rocks (granodiorite to monzogranite in composition) are widely distributed from the southern to the central part of Sulawesi Island, whereas granodiorite to tonalitic rocks occur in the northern portion of the island (Maulana *et al.*, 2016). The occurrences of the granitoid rock exposures were resulted from deformation processes which brought the rocks to the surface, forming high mountain ranges. The presence of these relatively young granitoid rocks at a relatively high altitude (up to 2,000 m) are very astonishing and have attracted much attention (*e.g.* Hall, 2011). To understand the process which is responsible for the exhumation process investigation on the petrochemistry and geothermobarometry of the rocks is essential. Although many researches have been done on the petrology and geochemistry as well as on the geochronology of the granitoid rocks from this island (*e.g.* Bergman *et al*., 1996; Polve *et al.,* 1997; Elburg and Foden, 1999; Maulana *et al.,* 2016), investigations on the geothermobarometry as well as exhumation and tectonomagmatic processes of these rocks have not been reported yet.

Hornblende and biotite are the most abundant ferro-magnesian minerals in granitoid rocks. Geothermobarometric studies using hornblende are very useful to estimate the emplacement depth of intrusive rocks, especially for calc-alkaline intrusive rock where hornblende is abundant (Tulloch and Challis, 2000; Moazzen and Droop, 2005; Zhang *et al*., 2006). This mineral is stable over a wide range of pressure (1 - 23 kbar) and temperature (400 - 1150°C) (Blundy and Holland, 1996; Stein and Dietl, 2001) and hence very reliable for geothermobarometry estimation. Biotite composition has been used as a petrogenetic and tectonomagmatic indicator in granite (Albuquerque, 1973; Lalonde and Bernard, 1993; Abdel-Rahman, 1994). This mineral is the most important host of any excess of alumina in granites and hence the most available indicator of oxidation state.

In this study, the petrochemical characteristic and a data set of mineral chemistry of the granitoid rocks from Sulawesi are presented in order to estimate the geothermobarometric condition. The emplacement depth estimation coupled with previous and current geochronological data are discussed. The exhumation rate and process were calculated to shed a light in resolving the exhumation and tectonomagmatic process.

Geological Setting

Based on the overall geological framework that has emerged from previous studies (Hamilton, 1979) and partly from regional geological reviews of Maulana (2009), and van Leeuwen and Pieters (2011), Sulawesi can be divided into four tectonic provinces, 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 (Figure 1). The detailed description is as follows:

Western Sulawesi Province

This province consists of a continental margin segment with pre-Tertiary metamorphic basement rocks, originating from Sundaland overlain by Upper Cretaceous and Cenozoic volcanic-sedimentary sequences, intruded by various ages of volcanic and plutonic rocks. The basement rocks were found in the southern, central, and northwestern parts of the province. The basement rocks, in the southern part of the province, comprise pre-Tertiary metamorphics included into high-pressure types, namely glaucophane schist, albite-actinolite-chlorite schist, chlorite-mica schists, garnet-glaucophane rock, garnet-glaucophane-quartz schist, garnet-chloritoid-glaucophane-quartz schist, quartzites, graphite phyllites (Parkinson, 1998), and blocks of eclogite included in blueschist (Maulana, 2009; Maulana *et al*., 2013). The K/Ar ages on muscovite-garnet and quartz-muscovite schists from the Bantimala basement complex range from 124 - 112 Ma (Wakita *et al*., 1996). In the Middle Cretaceous (Late Albian - Early Cenomanian, *i.e.* about 105 - 95 Ma), the chert unconformably overlies the high-pressure metamorphic rocks (Wakita *et al*., 1996). The ultramafic rocks are dominated by serpentinized peridotite, which contains chromite lenses and are locally intruded by dacite and andesite (Maulana *et al.,* 2015).

The basement rocks in the central and northern parts of the province form a belt called Central Sulawesi Metamorphic Belt, confined to the

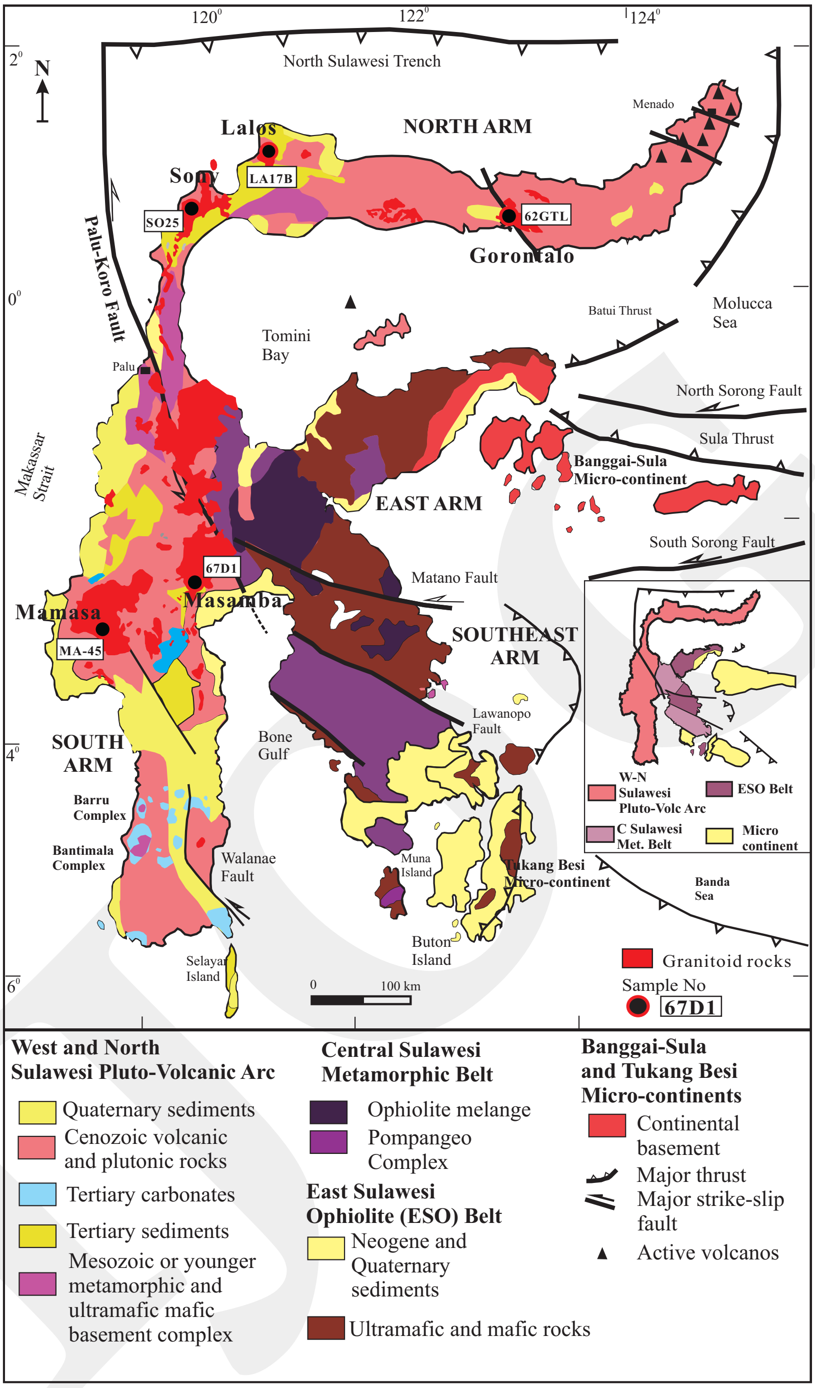

Figure 1. Geological setting of Sulawesi Island and lithotectonic division map (Maulana, 2009; Maulana *et al.*, 2016). Distribution of granitoid rocks and sample location are also included in the map.

central and northwestern parts of the province, and assumed to have resulted from the collision between fragments of Gondwana and the active Asian margin in the Late Oligocene or Early Miocene (van Leeuwen *et al.*, 2007). They consist of the Palu, Karossa, and Malino Metamorphic Complex, composed of continental fragments that were derived from the Australian-New Guinea margin (van Leeuwen *et al.*, 2007). The Palu Metamorphic Complex extends from the central portion of the province (Palu Zone) to the neck of the island. It comprises biotite schist and gneiss, amphibolite, amphibolite schist, and locally higher-grade metamorphic rocks, including granulite, eclogite, and garnet peridotite (Helmers *et al*., 1990). The protolith of the metamorphic rocks are determined as Permo-Triassic metasediments and metagranitoids of Australian-New Guinea derivation, but also metabasite of MORB affinity and possibly Sundaland derived rocks (van Leuween *et al*., 2007). The Devonian to Early Carboniferous Malino Metamorphic Complex located in the western part of the northern arm and composed of mica schists and gneisses are interpreted to be derived from proximal turbidite and granitoid protolith with intercalation of greenschist, amphibolite, marble, and quartzite. The isotopic signature and zircon age dating results suggest that the complex was derived from the New-Guinea Australian margin of Gondwana (van Leeuwen *et al*., 2007). The Karossa Metamorphic Complex crops out in the southwestern part of the Lariang region, comprising dominantly metapelite and metabasite units which have MORB affinity (van Leeuwen *et al*., 2007). The central region of this province is cut by a prominent N−S trending structural feature which is seismically active with a rapid displacement rate (Walpersdof *et al*., 1998; Bellier *et al*., 2001).

Tertiary sediments are found in the western part of 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 (Sukamto, 1982). They are composed of arkosic sandstones, siltstones, claystone, marls, and conglomerates, intercalated with layers or lenses of coal and limestone. The Mallawa Formation unconformably overlies the Balangbaru Formation and locally the Langi Volcanics, whereas the Toraja Formation overlies the Latimojong Formation. In the northern part, a thick sequence of Paleogene flysch-like and other marine sediments and interbedded volcanics (Tinombo Formation in the west and Papayato in the east) were deposited in a fore-arc basin on a metamorphic basement. Tertiary carbonates are found in some areas including the southern tip of the Western Sulawesi Province (Selayar Formation), surrounding the Bantimala Complex (Tonasa Formation) and in the middle part of the province (Makale Formation) (Wilson and Bosence, 1996).

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 Cenozoic volcanic and plutonic rocks. The granitic rocks intruded the Mesozoic or younger metamorphic basement rocks and Tertiary sediments, ranging from 14 - 2 Ma (Elburg *et al*., 2003; Maulana *et al*., 2016). In some regions, the granitic rocks occur in a relatively high altitude (up to 3,000 m). Quaternary sediments in this province are found in the Walanae Graben and Palu areas, occuring as Sulawesi Mollasse.

Eastern Sulawesi Province

The Eastern Sulawesi Province extends from the Central Sulawesi Trough to the east and southeast arms, including Buton and Muna Islands. It is made up of tectonically dismembered and highly faulted ophiolite associated with Mesozoic metamorphic rocks, ophiolitic mélange, and sedimentary rocks (Hamilton, 1979; van Leeuwen and Pieter, 2011). These form the basement of this region, which is overlain by Neogene to Quaternary sediments (Kadarusman *et al*., 2004).

Large masses of ultramafic and mafic rocks forming ophiolite complex are distributed over most of the eastern arm and the northwestern part of the southeast arm, and also in Buton and Kabaena Islands. The belt is interpreted as a Neogene accretionary complex formed by westward dipping subduction and by partial underthrusting of the Sula and Tukang Besi platforms.

The ophiolitic mélanges composed of a highly complex mosaic of tectonized and metamorphosed ophiolite fragments, schist fragments, and variably disrupted Mesozoic sedimentary rocks, were formed during the Middle to Late Oligocene as shown by 32 - 28 Ma K/Ar age. The Mesozoic metamorphics and sediments include the Pompangeo Metamorphic Complex in central eastern Sulawesi and the Mekongga Metamorphic Complex and Mesozoic clastic and carbonate sequences (Meluhu Formation) (Surono and Bachri, 2002). Those metamorphic rocks consist of blueschist and greenschist-amphibolite facies (Parkinson, 1998). The metamorphic rocks in the northwest central Sulawesi are cut by the Palu-Koro Fault, consisting of a prograde medium P metamorphic belt ranging from the chlorite zone up to staurolite-kyanite zone. Neogene and Quaternary sediments, known as Celebes Mollasse, are found in the southern part of the province consisting of coarse- to fine-grained clastic sequences with shallow marine carbonate sequences (Surono and Bachri, 2002).

Northern Sulawesi Province

The Northern Sulawesi Province consists of a Late Miocene to Recent subduction-related volcanic arc (Elburg and Foden, 1998) built on an oceanic substrate. The oldest formation comprises the Cretaceous and/or Early Tertiary thick sequence of basaltic rocks (pillow lava, spillite, *etc.)* with interlayered deep-sea sediments, locally intruded by swarms of basic dyke. A chain of intermediate and acid calc-alkaline volcanoes, known as Bilungala Volcanics, was built on this oceanic basement during the Miocene, with reef limestone fringing the volcanic island. Contemporaneous volcaniclastic, pyroclastic, and lava flows (Dolokapa Formation, Randangan Beds) were deposited in shallow basins flanking the volcanic chain. Numerous bodies of plutonic rocks (known as Bone Diorite and Boliohutu Diorite) ranging from granite to diorite in composition (van Leeuwen *et al*., 2007) intrudes the volcanic pile. The results of limited radiometric dating for the plutonic rocks suggest that batholith-sized bodies were emplaced during the Early–Middle Miocene (16 - 12 Ma), whereas irregular stocks and dykes of diorite to monzodiorite composition during the Middle to Late Miocene, and small stock and plugs of quartz diorite composition during the latest Miocene (van Leeuwen and Pieters, 2011).

Volcanism which occurred just after the 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 Formations (Taylor and van Leeuwen, 1980). In the northern tip of the province, some young Lower Miocene arc-related-rock and Pliocene to active Quaternary volcanicity known as the Sangihe Arc are still active. They are closely related with post-collisional rifting and uplift of the arc and inception of subduction along the Sulawesi Trench during Late Miocene to Quaternary.

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 (Garrard *et al*., 1988), whereas the Tukang Besi microcontinent comprises Buton, Muna, and surrounding smaller islands. Banggai-Sula has a metamorphic basement which is intruded by Late Paleozoic granitoids and overlain by Triassic felsic to intermediate volcanic rocks (Pigram and Panggabean, 1984). The region is interpreted to have been originated from New Guinea in the Late Cenozoic and transported by the extension of Sorong Fault during the Neogene (Audley-Charles *et al*., 1972). The Buton Island were rifted from the Australian-New Guinea Gondwana margin during the Mesozoic which then collided with Sulawesi in the Neogene (Hamilton, 1979). It consists of metamorphic rocks associated with ophiolite, Mesozoic-Paleogene deep water limestone with minor terrigenous clastic rocks, ultramafic and mafic rocks, and Neogene and Quaternary sediments. Most of the Tukang Besi Platform is submerged, while the exposed part of the platform is occupied by Upper Neogene and Quaternary reef limestone. Like other microcontinents in the region, Buton and the rest of the Tukang Besi Platform are interpreted as an Australian continental fragment (Hinschberger *et al*., 2005).

Analytical Method

Five samples were selected for hornblende thermobarometry, comprising two samples from the Mamasa and Masamba Plutons, two samples from Lalos-Toli and Sony Plutons, and one sample from Gorontalo Pluton (Figure 1). The sample from Mamasa Pluton was taken from the core of the pluton body, whereas the Mamasa sample was derived from the rim of the pluton body. Due to a high alteration process in the core of the pluton body, samples from Sony, Lalos-Toli, and Gorontalo were taken from the outer rim of the pluton.

Optical petrography was undertaken manually by using a Nikon petrographic microscope with 10× eyepieces and 5×, 10×, 20×, and 40× objective lenses, equipped with a Nikon E4500 camera attached to the trinocular port for micrography.

The selected samples were analyzed for concentration of major elements. Approximately 1 kg of each sample was crushed and milled to 200 mesh, and then thoroughly mixed using a swing mill. Major element compositions were determined on fused disc and pressed powder using an X-ray fluorescence spectrometer Rigaku RINT-300 at the Department of Earth Resources Engineering, Kyushu University. LoI values were calculated after heating the sample powder to 100º C for 2 hours. Following this, it was weighed and reheated to 500º C for 1 hour and finally to 900º C for 1.5 hours.

Electron microprobe analysis was carried out with JEOL JXA-8800R at the Peking University. The quantitative analyses for the rock-forming minerals were performed with a 20 kV accelerating voltage, a 20 nA beam current and a 2 - 5 µm beam size. The counting time at each peak was 20 - 30s.

Mineral assemblages of all selected samples have a typical assemblage of quartz, plagioclase, hornblende, K-feldspar, biotite, magnetite, and titanite, which is an important prerequisite for aluminium-in-hornblende barometry as suggested by many workers (*e.g.* Schmidt, 1992; Anderson and Smith, 1995; Hollister *et al*., 1997; Stein and Dietl, 2001).

Results

Petrography

The granitoid rocks from the central part of Mamasa and Masamba Pluton are characterized by coarse-grained texture (1 - 6 mm), composed mainly of quartz (15 - 30% modal), plagioclase (35 - 50%), K-feldspar (5 - 15%), biotite (3 - 10%) and hornblende (4 - 10%) (Figure 2a and b). This wide range of modal composition causes the variation in petrographic and chemical composition in the granitoid rocks. For example, sample MA-45 from Mamasa Pluton has a higher content of plagioclase (up to 50%) but lower content of

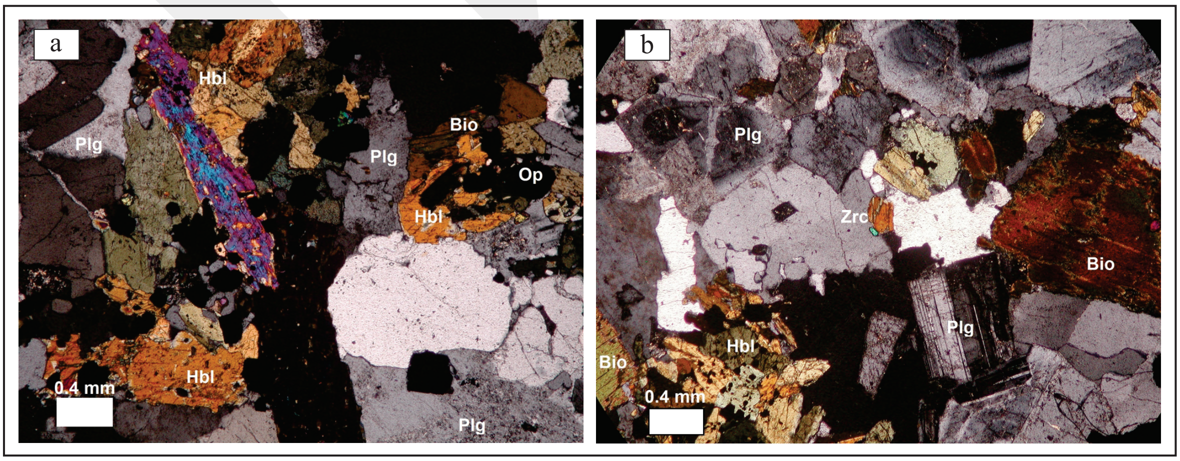

Figure 2. Photomicrographs of granitoid samples: (a) Sample MA-45 showing hornblende (Hbi), biotite (Bio), plagioclase (Plg), and quartz (Qtz) as major minerals; (b) Plagioclase in sample 67D1 showing zoning texture occurs with hornblende (Hbi), biotite (Bio), quartz (Qtz), and zircon (Zrc).

K-feldspar (5%) and quartz (15%), compared to sample 67D1 from Masamba Pluton which contains lower plagioclase (35%) but higher quartz (30%), and relatively higher K-feldspar (15%). The first is classified as quartz monzodiorite, whereas the latter as granodiorite based on the normative modal abundance plotted in QAP diagram of Streckeisen (1976) (Figure 3). Amphibole is the major mafic mineral in sample MA-45 (up to 15%) compared to biotite (8%) as shown in Figure 2a. The portion of amphibole and biotite is almost equal in sample 67D1 (less than 10%), but the total amount of these two minerals in this sample is relatively lower than sample MA-45. Plagioclase occurs as prismatic, euhedral to subhedral phenocryst, 1 - 3 mm long and sometimes up to 5 mm long. In more felsic granitoid rocks (sample 67D1), large plagioclase crystal shows oscillatory zoning (Figure 2b). K-feldspar occurs in sample 67D1 as subhedral to euhedral crystals in the groundmass, showing perthitic texture. Abundance of K-feldspar and quartz increases in more evolved rock (67D1). Biotite occurs as euhedral to subhedral crystals and generally less than 3 mm long. Amphiboles show a typical cleavage, subhedral to euhedral crystals which contains inclusion of oxide minerals. Titanite occurs as an accessory mineral along with apatite, small zircon, and oxide mineral (magnetite and ilmenite).

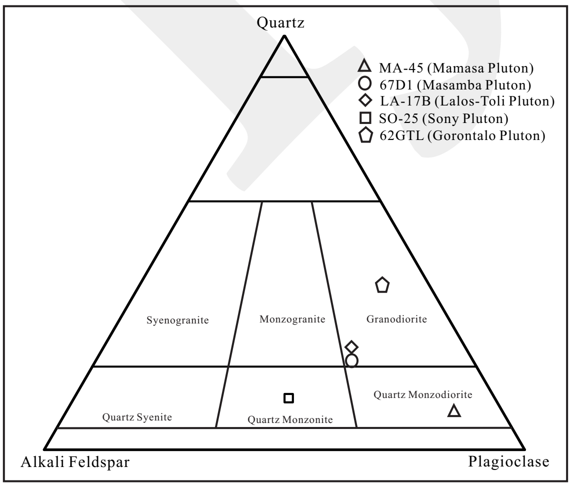

Figure 3. QAP diagram (after Streckeisen, 1976) of the granitoid rocks in the study areas.

The samples from the northeastern part of the Western Sulawesi Province consist of granodiorite (LA-17B) and quartz monzonite (SO-25). K-feldspars are rare in granodiorite (LA-17B), but increase their modal percentage in quartz monzonite (SO-25). Plagioclase is the main mineral and occurs as euhedral to subhedral crystals with oscillatory zoning, particularly in sample LA-17B (Figure 4a). Plagioclase found as phenocrysts, range from 2 up to 6 mm in size and are rarely zoned. Hornblende is rhombic and shows a typical cleavage with twinning in sample SO-25 with numerous inclusions and varies in size (Figure 4b). Biotite occurs as euhedral and subhedral crystals, never exceed 2 mm long and sometimes shows kink band structure in sample SO-25. Minor minerals are titanite, ilmenite, magnetite, apatite, and zircon.

The granitoid rock from the Northern Sulawesi Unit (62-GTL) is characterized by a coarse-grained rock consisting mainly of plagioclase (45% modal), quartz (40%), hornblende (10 - 12%), and rarely biotite. Based on this modal composition, the sample is classified as granodiorite. This sample is characterized by the aggregation of plagioclase and quartz grain with some hornblende. Plagioclase occurs as euhedral to subhedral crystals which have been sericitized (Figure 4c). Hornblende is brown to reddish, 0.2 to 0.8 mm in size, and sometimes altered into chlorite. Minor minerals include titanite, apatite, and small zircon with magnetite (Figure 4d).

Whole Rock Composition

The whole rock composition of the studied samples and their CIPW (Cross-Iddings-Pirsson-Washington) normative mineral assemblage are shown in Table 1, respectively. The SiO_2 contents of the samples range from 62 to 65 wt% except sample from the Gorontalo sample which shows high SiO_2 content (up to 72 wt%). The Al_2O_3 and CaO contents are relatively similar for all samples, ranging from 13 to 15.4 wt% and 3.31 to 4.41 wt%, respectively. The MgO and FeO total contents show a large variation in which sample MA-45 shows the highest value and decrease in

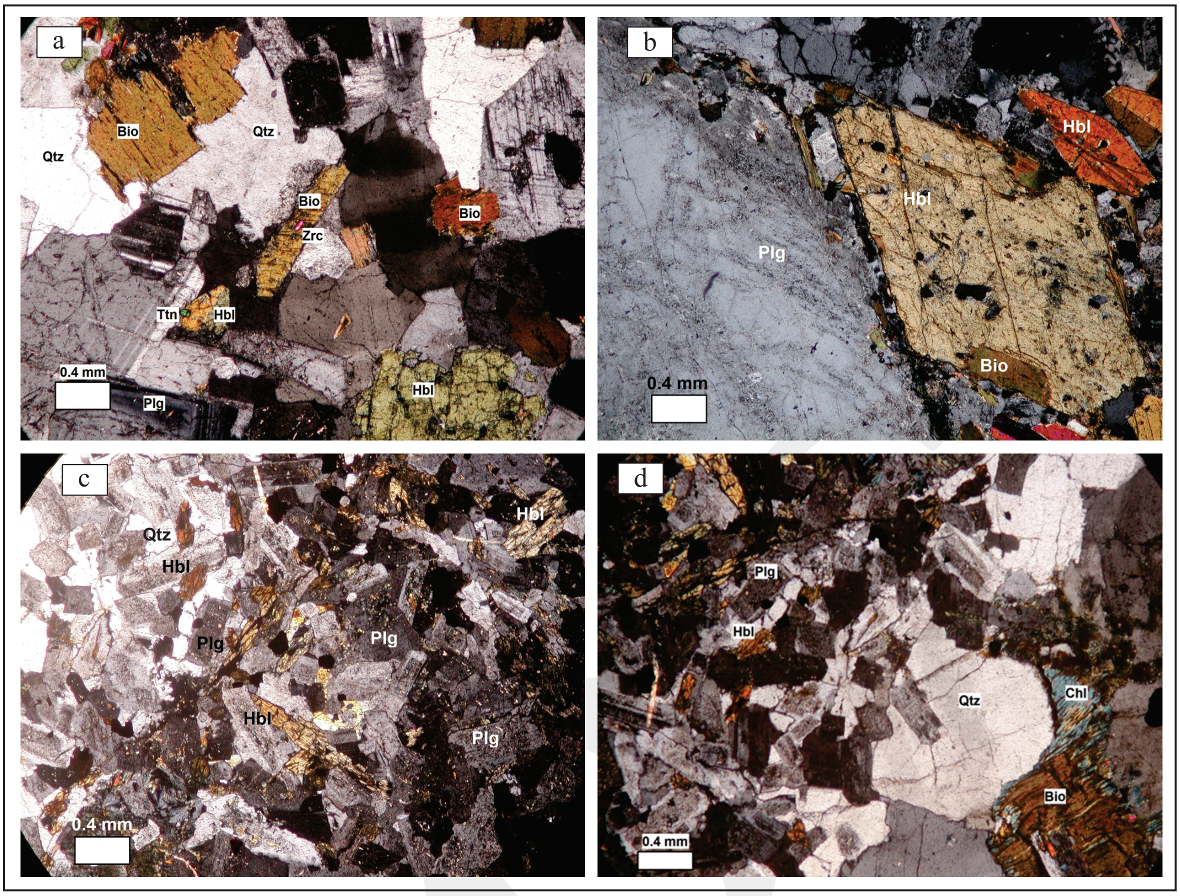

Figure 4. Photomicrographs of granitoid samples: (a) Zoned plagioclase (Plg), quartz (Qtz), biotite (Bio), and hornblende (Hbi) along with tiny zircon (Zrc) in sample LA-17B; (b) Plagioclase (Plg) occurs as phenocryst along with rhombic hornblende (Hbi) showing twinning in SO-25; (c) Aggregation of plagioclase (Plg) and quartz grain (Qtz) in sample 62GTL, showing tonalitic texture. (d). Granodiorite from Gorontalo (62 GTL), consisting of quartz (Qtz), and plagioclase groundmass (Plg) with hornblende (Hbi) and chloritized biotite (Chi).

sample 62GTL. The Na_2O and K_2O of the samples also show a wide variation. Samples MA 45 and 62GTL contain high Na_2O but very low K_2O, whereas other samples show the opposite. The A/CNK (molecular Al_2O_3 / $CaO + Na_2O + K_2O$) ranges from 0.68 to 0.94, whereas the A/NK (molecular $Al_2O_3 Na_2O + K_2O$) ranges from 1 to 1.77.

The CIPW norm calculations were done using Fe_2O_3 as 0.15 of total iron. The normative assemblage shows that the rocks are quartz normative and contain normative K-feldspar, albite, anorthite, diopside, and hypersthene among others. The AFM diagram of Irvine and Baragar (1971) shows that the rocks have calc-alkaline affinity (Figure 5a). The plot of A/CNK *vs* A/NK classifies the rocks as metaluminous and plots in the I-type field of Chappell and White granite classification (Figure 5b).

Mineral Chemistry

Representative analysis of feldspar from the granitoid rocks is listed in Table 2. Structural formulae of plagioclase and K-feldspar were calculated on the basis of eight oxygens and five cations. In the ternary diagram of Ab-Or-An (Figure 6), the plagioclases are mainly plotted in the albite, oligoclase, and andesine field, whereas K-feldspars are plotted in the field of sanidine. The An contents of plagioclase from the granitoid rocks in Mamasa and Masamba Plutons range from 0.4 to 44.6 mol%. The core of the plagioclase has a lower An content (25.6 mol%) compared to the rim (An= 38 mol%). The An values of the plagioclase in the samples from Lalos-Toli and Sony Plutons vary from 6.1 to 40.1 mol%. However, sample SO-25 shows

Table 1. Whole Rock Composition and CIPW Normative Mineral Assemblage of the Granitoid Rocks from the studied Area

Sample	**MA-45**	**LA-67D1**	**LA-17 B**	**SO-25**	**62GTL**
Pluton	**Mamasa**	**Masamba**	**Lalos-Toli**	**Sony**	**Gorontalo**
Whole Rock (wt%)					
SiO_2	62.24	65	65.31	62.63	72.37
TiO_2	0.63	0.6	0.55	0.61	0.4
Al_2O_3	13.17	14.75	15.04	13.55	13
FeOt	5.08	3.71	3.93	4.23	3.33
MnO	0.19	0.07	0.08	0.08	0.09
MgO	5.11	3.37	2.67	3.91	1.33
CaO	3.31	4.41	4.34	3.52	3.31
Na_2O	7.14	3.25	2.91	3.21	3.57
K_2O	1.38	3.47	3.41	5.48	1.82
P_2O_5	0.18	0.19	0.18	0.45	0.09
LOI	1.03	0.97	1.31	0.91	0.6
Total	99.47	99.79	99.73	98.59	99.91
CIPW Norm					
K-Fs	7.09	20.51	20.15	32.4	10.76
Qtz	6.36	17.23	20.06	9.34	33.61
Ab	55.42	27.5	24.62	27.2	30.21
An	4.03	15.41	17.91	6.36	14.07
Ap	0.38	0.45	0.43	1.07	0.21
Ilm	1.22	1.14	1.04	1.17	0.76
Dio	8.87	4.48	2.33	7.15	1.57
Hy	15.42	12.15	11.95	13.12	8.14
A/CNK	0.75	0.90	0.92	0.77	0.94
A/NK	1.11	1.62	1.77	1.21	1.66

an almost pure albite composition (An content= 0.1 mol%). The An content of Gorontalo Pluton (62GTL) ranges from 9.9 to 26.8 mol%. These An ranges indicate that the two end-members (anorthite and albite) are essentially presented in the plagioclase composition of the granitoid rocks. The K-feldspar is found mainly in the sample from Masamba (67D1), occurring as sanidine and has no detectable CaO (An) content, whereas the Ab content is 5.8 mol% ($Or_{94.2}$). Therefore, the feldspar only shows two solid solutions instead of ternary feldspar solid solution. The low Ab content of the feldspar further indicates that they are nearly pure K-feldspar.

Structural formulae for amphibole were calculated on the basis of 23 oxygens and 15 cations following the method outlined in Holland and Blundy (1994). Representative analyses of amphiboles are given in Table 3. Using classification of Leake *et al.* (1997), the hornblende is classified as magnesiohornblende and edenite (Figure 7), and identified as calcic amphibole. The Si content in Mamasa and Masamba Plutons varies from 6.8 to 7.1 a.p.f.u (atom per formula unit), whereas the Mg# (Mg/(Mg+Fe^{2+}) from 0.69 to 0.73. The Si content in the granitoid rocks from Lalos-Toli and Sony Plutons is relatively lower (6.6 to 6.8 a.p.f.u.), whereas the Mg# ranges from 0.58 to

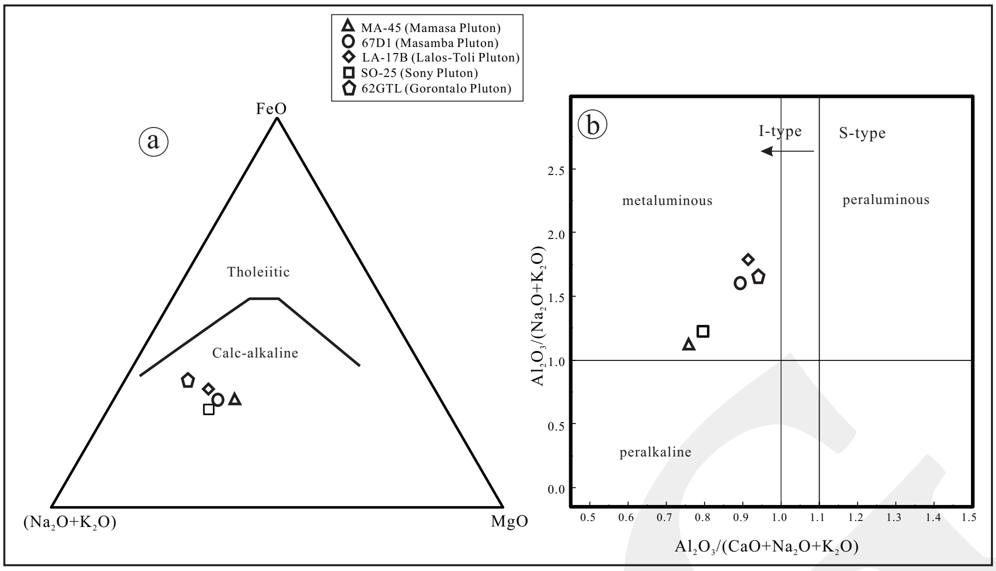

Figure 5. (a) AFM diagram of the studied samples (Irvine and Baragar, 1971). All samples are fall within calc-alkaline field. (b) A/CNK *vs*. A/NK diagram of the granitoid rocks (Shand, 1934). All samples are plotted and classified as I-type and metaluminous granitoid rocks.

0.71. The Si content from the Gorontalo Pluton shows relatively higher values (7 to 7.2 a.p.f.u), but contains lower Mg# (0.55) compared to other units. The amphiboles in all these plutons are of igneous origin, since their Si values do not exceed the 7.50 a.p.f.u. of the limit for igneous amphibole (Leake, 1971, 1997).

Representative analyses of biotites are given in Table 4. Structural formulae were calculated on the basis of 22 oxygens. Biotite contain 8.8 - 9.49 wt% of K_2O, 10.9–13.76 wt% of MgO, 17.24 - 21.49 wt% of FeO Total, and 13.62 - 14.84 wt% of Al_2O_3. The biotites are Fe-rich with Fe# (Fe/(Fe+Mg)) ranging from 0.413 to 0.523 which indicate the composition lying approximately midway between phlogophite and annite (Figure 8). Biotites were plotted in the calc-alkaline field in the discrimination diagram of Abdel-Rahman (1994) (Figure 9). This is concordant with the calc-alkaline affinity showed by the whole rock composition in AFM diagram (Figure 5a).

Geothermobarometry

Hornblende-Plagioclase Thermobarometry

Since hornblende and plagioclase commonly coexist in calc-alkaline igneous rocks, many workers have used these minerals for thermometry (*e.g*. Blundy and Holland, 1990; Anderson and Smith, 1995; Stein and Dietl, 2001). Based on hornblende solid solution models and well constrained natural and experimental systems, two hornblende-plagioclase thermometers (thermometer A and B) were calculated by Holland and Blundy (1994). Thermometer A is based on the edenite-tremolite reaction, whereas thermometer B is based on the edenite-richterite reaction as follows:

Edenite + 4 quartz= tremolite + albite……. (thermometer A)

Edenite + albite= richterite + anorthite….. (thermometer B)

Thermometer A is applicable to quartz-bearing igneous rocks, while thermometer B is for both quartz-bearing and quartz-free igneous rocks (Holland and Blundy, 1994). Anderson (1996) further suggested that on the basis of different assessments of Al-in-hornblende thermometric algorithm from plutonic rocks, the edenite-richterite thermometer (thermometer B) was the most reliable calibration. Therefore, edenite-richterite thermometer was used to calculate the crystallization temperature of the granitoid rocks from Sulawesi. Equilibration temperatures for

Table 2. Representatives Feldspar Composition of the Rranitoid Rocks in Sulawesi

Sample	**MA-45**		**67D1**				**LA-17B**		**SO-25**		**62GTL**	
Spots	**1**	**2**	**rim**	**core**	**3**	**4**	**1**	**2**	**1**	**2**	**1**	**2**
Pluton	**Mamasa**		**Masamba**				**Lalos-Toli**		**Sony**		**Gorontalo**	
SiO_2	56.79	55.94	58.69	62.36	66.20	65.09	59.38	58.95	67.92	68.97	61.47	66.63
TiO_2	0.00	0.00	0.01	0.00	0.04	0.00	0.00	0.00	0.01	0.04	0.01	0.01
Al_2O_3	27.27	26.92	25.73	23.93	18.91	18.55	25.98	26.96	20.43	19.45	24.61	21.50
Cr_2O_3	0.00	0.00	0.01	0.00	0.00	0.02	0.00	0.03	0.00	0.00	0.00	0.00
FeO	0.21	0.17	0.11	0.10	0.04	0.05	0.14	0.19	0.03	0.41	0.12	0.04
MnO	0.02	0.02	0.01	0.00	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.01	0.01	0.02	0.01	0.00	0.00	0.00	0.02	0.00	0.00	0.00	0.00
CaO	9.41	9.37	7.96	5.43	0.08	0.00	7.50	8.62	1.32	0.02	5.85	2.17
Na_2O	6.30	6.45	7.00	8.37	2.90	0.61	7.61	6.95	11.20	11.36	8.54	10.68
K_2O	0.25	0.27	0.27	0.52	11.93	15.10	0.36	0.24	0.12	0.00	0.42	0.39
Totals	100.26	99.13	99.81	100.71	100.10	99.42	100.97	101.95	101.03	100.25	101.01	101.41
Number of ion on the basis of 8 oxygens												
Si	2.547	2.541	2.630	2.750	3.002	3.005	2.632	2.592	2.947	3.002	2.711	2.893
Al tet	1.442	1.441	1.359	1.244	1.011	1.009	1.358	1.398	1.045	0.000	1.280	1.101
Al oct	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.998	0.000	0.000
Ti	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000
Cr	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.000	0.000	0.000	0.000
Fe^{2+}	0.008	0.007	0.004	0.004	0.001	0.002	0.005	0.007	0.001	0.015	0.004	0.001
Mn	0.001	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.001	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.000	0.000
Ca	0.452	0.456	0.382	0.257	0.004	0.000	0.356	0.406	0.061	0.001	0.276	0.101
Na	0.548	0.568	0.608	0.715	0.255	0.055	0.654	0.592	0.942	0.959	0.731	0.899
K	0.014	0.015	0.016	0.029	0.690	0.890	0.020	0.014	0.006	0.000	0.024	0.021
Total	5.013	5.030	5.002	5.000	4.964	4.962	5.026	5.011	5.004	4.977	5.026	5.017
Ab%	54.0	54.7	60.5	71.5	26.9	5.8	63.5	58.5	93.3	99.9	70.9	88.0
An%	44.6	43.9	38.0	25.6	0.4	0.0	34.6	40.1	6.1	0.1	26.8	9.9
Or%	1.4	1.5	1.6	2.9	72.7	94.2	2.0	1.3	0.6	0.0	2.3	2.1
Total	100	100	100	100	100	100	100	100	100	100	100	100

the hornblende-plagioclase assemblage were calculated based on iteration using the pressure derived from Al-in hornblende barometer of Anderson and Smith (1995). Table 5 shows the type of thermometer used for estimation of the temperature. From the analyzed rocks, the calculated temperatures are in the range of 677 to 729°C for the granitoid rocks from Mamasa Pluton and 756 to 774°C for Masamba Pluton. The granitoid rocks from the Lalos-Toli Pluton and Sony Plutons show a temperature range of 731 to 736°C and 601 to 609°C, respectively. Gorontalo

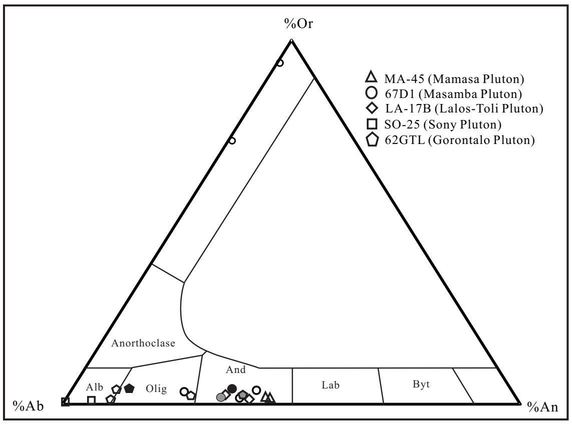

Figure 6. Ternary diagram Ab - Or - An of feldspar for granitoid rocks from Sulawesi.

Pluton, which is represented by sample 62GTL, shows a temperature range from 662 to 668°C.

Al-in Hornblende Geobarometry

Hammarstrom and Zen (1986) and Hollister *et al*. (1987) showed that in the presence of an appropriate buffer assemblage (amphibole+plagioclase+K-feldspar/quartz at medium to high oxygen fugacity condition), the total Al content of calcic amphibole increased linearly with solidus pressure. Field-based and experimental studies (*e.g.* Schmidt, 1992; Anderson and Smith, 1995) have provided a general confirmation of increasing Al content of hornblende with increasing pressure. In addition, many workers have utilized this barometer to estimates pressure of magmatic crystallization and to constrain the emplacement depth (*e.g.* Ague and Brandon, 1992; Stein and Dietl, 2001; Zhang *et al*., 2006; Sepahi *et al.,* 2012).

Several calibrations have been proposed for Al-in-hornblende barometry. Hammarstrom and Zen (1986) proposed an empirical correlation between estimated pressure (P) of solidification of calc-alkaline plutons and the total content of Al in hornblende (23 oxygens basis) expressed as follows:

P(±3 kbar)= -3.92+5.03 Al (total)

Hollister *et al.* (1987) proposed a relatively similar but more precise equation:

P(±1 kbar)= -4.67+5.64 Al (total)

Johnson and Rutherford (1989) provided a calibration, expressed as:

P(±0.5 kbar)= -3.46+4.23 Al (total)

Schmidt (1992) calibrated the amount of Al in hornblende in a natural tonalite and proposed the expression:

P(±0.6 kbar)= -3.01+4.76 Al (total)

Anderson and Smith (1995) provided a calibration with T range from 600 to 800°C:

P(kbar)= 4.76 Al (total) - 3.01 - [(T - 675)/85] x [0.53Al+0.005294 (T - 675)]

In this study, the calibration of Anderson and Smith (1995) was used to calculate the solidification pressure of the granitoid rocks from Sulawesi. This calibration is more reliable for considering the influence of temperature on the pressure calculation than the other methods (Stein and Dietl, 2001; Zhang *et al*., 2006).

Estimations of pressure and depth of emplacement of the granitoid rocks from Sulawesi are given in Table 5. The results indicate that the pressure varies from 0.91 to 1.2 and 2.3 to 2.8 kbar for Mamasa and Masamba Plutons, respectively. Pressures of 3.1 to 3.3 kbar and 3.2 to 3.4 kbar are estimated for the granitoid rocks in the Lalos-Toli and Sony Plutons, respectively. The pressure calculation on the sample from Gorontalo Pluton gave a pressure range of 2.6 to 2.7 kbar.

Discussions

Emplacement Depth Estimations

To estimate the emplacement depth, the pressure from the calibration by Anderson and Smith (1995) was used. The pressure values were converted to emplacement depths on the assumption that the average crustal density was 2.8 g/cm^3. The correction factor of the calibration (Anderson and Smith, 1995) was ± 0.6 kbar, which corresponds to an emplacement depth uncertainty of ± 2.1 km.

The Mamasa and Masamba Plutons are represented by quartz monzonite (MA-45) and granodiorite (67D1), yielding an average emplacement

Table 3. Representative Hornblende Composition of the Granitoid Rocks from Sulawesi

Sample	**MA-45**		**67D1**		**LA-17B**		**SO-25**		**62GTL**	
Spots	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**	**1**	**2**
Location	**Mamasa**		**Masamba**		**Lalos-Toli**		**Sony**		**Gorontalo**	
Unit										
wt%										
SiO_2	48.21	49.12	46.59	48.53	45.23	45.79	46.94	46.83	48.38	47.59
TiO_2	0.99	0.86	1.09	1.05	1.26	1.24	1.22	1.40	0.65	0.95
Al_2O_3	5.82	4.78	7.86	6.92	8.68	8.25	7.32	7.58	5.14	6.17
FeO	14.31	12.81	14.46	14.36	18.11	18.08	14.41	14.34	20.67	20.86
MgO	14.59	15.51	13.36	14.31	10.84	11.25	14.03	13.63	10.34	10.20
MnO	0.46	0.53	0.42	0.43	0.50	0.50	0.34	0.35	1.52	1.52
CaO	11.80	11.76	11.96	11.84	11.86	11.70	12.01	11.88	10.32	9.98
Na_2O	1.26	1.09	1.50	1.30	1.25	1.56	1.58	1.61	1.00	1.35
K_2O	0.52	0.43	0.83	0.64	0.92	0.91	0.77	0.83	0.40	0.45
Total	97.96	96.89	98.07	99.37	98.64	99.27	98.63	98.43	98.42	99.07
Formulae *per* Holland and Bundy (1994)										
<u>T-sites</u>										
Si	7.027	7.190	6.806	6.938	6.675	6.719	6.809	6.817	7.191	7.032
Al^{iv}	0.973	0.810	1.194	1.062	1.325	1.281	1.191	1.183	0.809	0.968
Sum T	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000	8.000
<u>M1,2,3 sites</u>										
Al^{vi}	0.027	0.015	0.160	0.105	0.185	0.146	0.062	0.118	0.092	0.105
Ti	0.108	0.095	0.119	0.113	0.139	0.136	0.133	0.153	0.073	0.106
Fe^{3+}	0.377	0.273	0.462	0.559	0.571	0.526	0.504	0.416	0.493	0.571
Mg	3.170	3.384	2.909	3.048	2.383	2.459	3.034	2.956	2.290	2.246
Mn	0.057	0.065	0.052	0.052	0.063	0.062	0.042	0.043	0.191	0.190
Fe^{2+}	1.261	1.167	1.298	1.123	1.659	1.670	1.225	1.314	1.862	1.782
SUM M1-3	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000	5.000
<u>M4 site</u>										
Fe	0.107	0.128	0.007	0.034	0.005	0.022	0.019	0.015	0.215	0.225
Ca	1.844	1.844	1.871	1.813	1.875	1.839	1.867	1.853	1.643	1.580
Na	0.050	0.029	0.122	0.153	0.120	0.139	0.114	0.132	0.142	0.196
SUM M4 sites	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000	2.000
<u>A site</u>										
Ca	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000
Na	0.305	0.281	0.302	0.209	0.238	0.305	0.329	0.321	0.145	0.191
K	0.097	0.079	0.154	0.116	0.173	0.170	0.143	0.153	0.077	0.084
Sum A	0.402	0.361	0.456	0.324	0.410	0.475	0.472	0.475	0.222	0.276
Sum cations	15.402	15.361	15.456	15.324	15.410	15.475	15.472	15.475	15.222	15.276
Al (Total)	1.000	0.826	1.354	1.166	1.510	1.427	1.253	1.301	0.901	1.074
Mg#	0.72	0.74	0.69	0.73	0.59	0.60	0.71	0.69	0.55	0.56

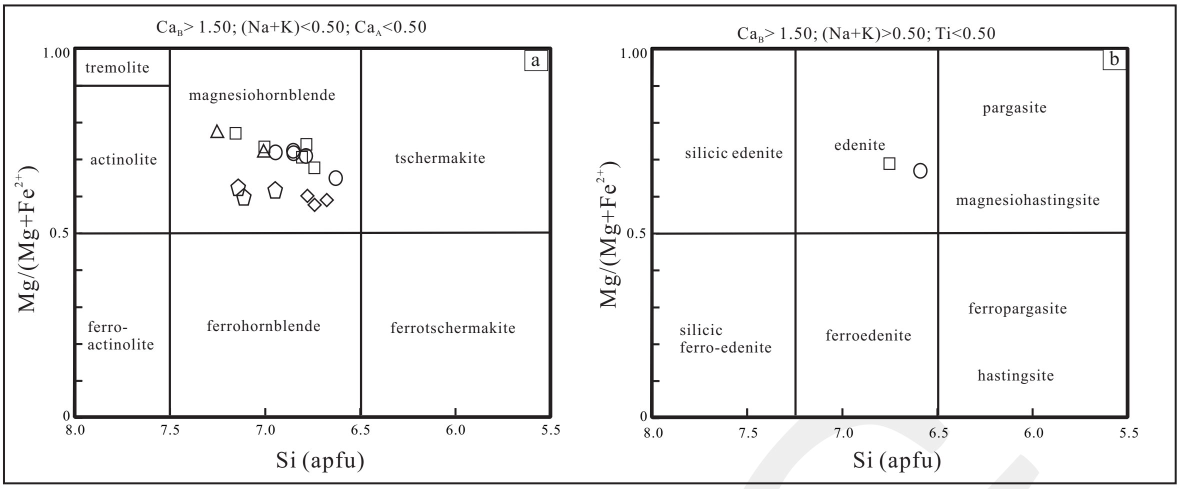

Figure 7. Hornblende composition diagrams according to nomenclature of Leake *et al.,* (1997). Symbol as in Figure 6.

Table 4. Representatives Analyses of Biotite from Granitoid Rocks in Sulawesi

Sample No	**MA-45**			**67D1**				**LA-17B**		**SO-20**	
Pluton	**Mamasa**			**Masamba**				**Lalos-Toli**		**Sony**	
SiO_2	36.85	36.80	37.54	37.21	37.60	38.08	37.87	37.18	37.02	37.57	37.62
TiO_2	4.21	4.41	4.48	3.77	3.80	3.77	3.90	4.00	3.89	3.82	3.96
Al_2O_3	13.90	13.87	13.91	13.88	14.27	14.04	13.91	14.84	14.48	14.09	13.62
Cr_2O_3	0.02	0.02	0.01	0.08	0.09	0.06	0.05	0.01	0.02	0.01	0.13
FeO	17.16	17.80	18.31	18.36	17.55	18.12	17.25	21.33	21.49	17.24	17.56
MnO	0.25	0.27	0.32	0.27	0.17	0.30	0.25	0.33	0.44	0.26	0.24
MgO	13.28	13.42	13.42	13.37	13.38	13.76	13.34	10.90	11.03	13.73	13.64
CaO	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.01	0.00	0.03	0.01
Na_2O	0.16	0.08	0.16	0.05	0.02	0.17	0.14	0.17	0.15	0.10	0.13
K_2O	8.80	9.11	8.96	9.04	9.23	9.08	8.89	8.82	9.12	9.11	9.00
Totals	94.64	95.77	97.14	96.03	96.11	97.38	95.59	97.58	97.63	95.95	95.90
Si	5.600	5.554	5.583	5.604	5.631	5.638	5.684	5.573	5.569	5.629	5.649
Al tet	2.400	2.446	2.417	2.396	2.369	2.362	2.316	2.427	2.431	2.371	2.351
Al oct	0.090	0.021	0.021	0.069	0.149	0.088	0.145	0.194	0.136	0.117	0.059
Ti	0.481	0.500	0.501	0.428	0.427	0.420	0.440	0.451	0.440	0.430	0.447
Cr	0.003	0.002	0.001	0.009	0.011	0.006	0.005	0.001	0.002	0.001	0.016
Fe^{2+}	2.181	2.246	2.278	2.313	2.197	2.244	2.165	2.674	2.704	2.160	2.205
Mn	0.032	0.035	0.040	0.034	0.022	0.038	0.032	0.041	0.055	0.032	0.030
Mg	3.009	3.019	2.975	3.003	2.987	3.036	2.984	2.434	2.473	3.067	3.053
Ca	0.000	0.000	0.005	0.000	0.000	0.000	0.000	0.002	0.000	0.005	0.001
Na	0.047	0.022	0.047	0.013	0.005	0.049	0.041	0.049	0.043	0.028	0.037
K	1.706	1.754	1.700	1.738	1.763	1.715	1.703	1.687	1.750	1.741	1.724
Total	15.549	15.600	15.569	15.607	15.561	15.596	15.515	15.534	15.603	15.581	15.572
Total Al	2.490	2.467	2.438	2.465	2.519	2.450	2.461	2.621	2.567	2.488	2.410
$Fe^{2+}(Fe^{2+}/Mg)$	0.420	0.427	0.434	0.435	0.424	0.425	0.420	0.523	0.522	0.413	0.419

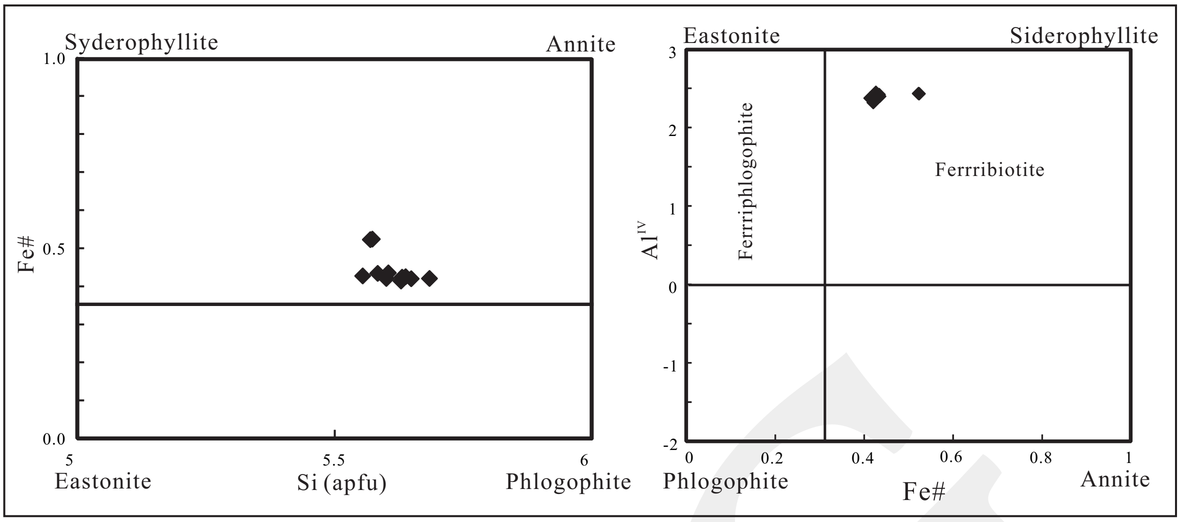

Figure 8. Diagrams showing the classifications of biotite in granitoid rocks from Sulawesi, according to the nomenclature of Speer (1984) (left) and Deer *et al.* (1986) (right).

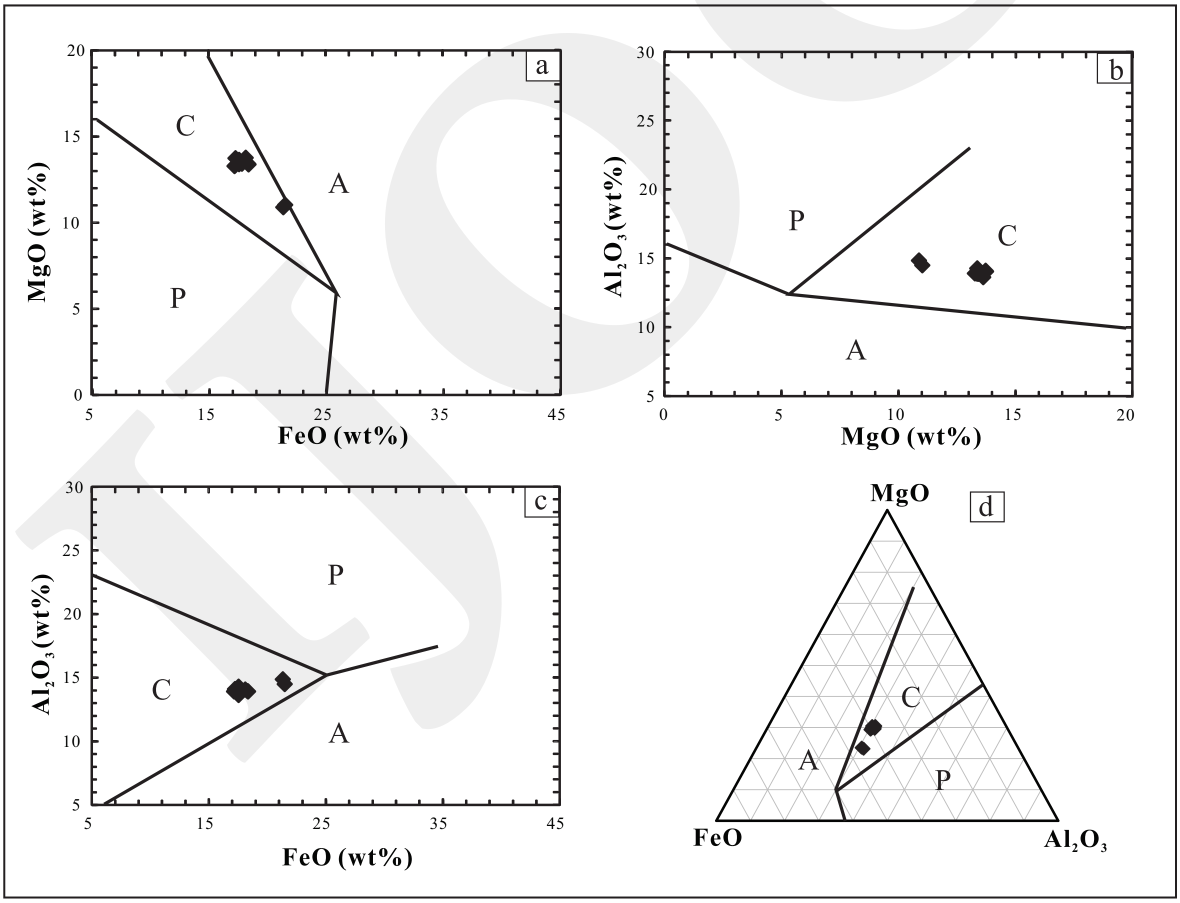

Figure 9. Diagrams showing the classification of magmas based on biotite composition (after Abdel-Rahman, 1994). A= alkaline, P= peralkaline, C= calc-alkaline.

depths of 3.7 km (3.2 - 4.3 km) and 9.1 km (8.2 - 10 km), respectively (Table 5). The average emplacement depths estimated from the granitoid rocks in Lalos-Toli Pluton (LA-17B) and Sony Pluton (SO-25) show a relatively similar depth (11.3 and 11.6 km, respectively). The emplace-

Table 5. Estimations of Pressures, Depth of Emplacement and Oxygen Fugacity Value (*log* fO_2) of the Granitoid Rocks from Sulawesi

Sample/Location	Plag Ab	Amph Al (Total)	T(ed-tr) (C°)	T(ed-ri) (C°)	P-Sch (kbar)	P-A&S (kbar)	Depth (km)	Depth (Av) (km)	log fO2
MA-45/Mamasa	54	0.998	850.3	729	1.75	1.23	4.3	3.75	-15.71
	54.7	0.826	810.4	677	0.92	0.91	3.2		-17.44
67D1/ Masamba	60.5	1.561	833.7	774.2	4.42	2.84	10	9.1	-14.17
	57.5	1.354	796.7	756.8	3.44	2.33	8.2		-14.73
LA-17B/Lalos-Toli	63.5	1.529	772.9	731.1	4.18	3.35	11.7	11.25	-15.35
	58.5	1.448	729.5	736.1	3.88	3.1	10.8		-15.23
SO-25/Sony	93.3	1.253	749.8	609.1	2.95	3.2	11.2	11.6	-19.56
	93.4	1.301	722.3	601.4	3.18	3.44	12		-19.83
62GTL/Gorontalo	88.7	1.191	739.4	666.8	2.66	2.72	9.5	9.35	-17.52
	88	1.165	744.7	662.3	2.53	2.62	9.2		-17.69

ment depth estimation for the monzogranite from Gorontalo Pluton (62GTL) ranges from 9.2 to 9.5 km (average 9.4 km).

These results show that the depth of the emplacement seems to increase from Mamasa and Masamba Plutons which are located in the southern part of the Western Sulawesi Province to the Sony and Lalos-Toli Plutons in the northwestern part of the province, but it decreases towards the Gorontalo Pluton which is located in the Northern Sulawesi Province.

Oxygen Fugacity

The oxygen fugacity of magma is related to its source material, which in turn is dependent on tectonic setting. The I-type granitic magmas were relatively oxidized, whereas the S-type granitic magmas were usually reduced. The original oxygen fugacity of the primary magma of granitoid rocks is difficult to estimate since magnetite usually becomes Ti-free during slow cooling, and ilmenite underwent one or more stages or oxidation and exsolution. However, it is possible to get some inferences of the oxidation state of magma using mineral assemblage and mineral chemistry. Wones (1989) shows that the assemblages of titanite+magnetite+quartz in granitoid rock allow us to estimate the relative oxygen fugacity. The *log* fO_2 estimation from Wones (1989) was expressed by the equilibrium expression Log fO2= -30930/T+14.98+0.142 (P-1) T (where T is temperature in Kelvin and P is pressure in bars). Temperatures and pressures estimated from hornblende-plagioclase thermometry and aluminium in hornblende were used in these calculations. The results of oxygen fugacity (Table 5) range from -14 to -17 for the granitoid rocks from the Mamasa and Masamba Plutons and from -15 to -19 for the granitoid rocks in the Lalos-Toli and Sony Plutons, whereas the oxygen fugacity of the Gorontalo Pluton is -17. These results are close to the hematite/magnetite oxygen buffer, implying a strong association with a highly oxidized I-type series (Lang and Baker, 2001).

Magma Typology

Biotite composition has been used to define the nature of magma from which they crystallized and also gives a clue about the tectonic environment of their host magma (Abdel-Rahman, 1994). In addition, Nockolds (1947) showed that biotite is a good indicator of the conditions of magma crystallization. Albuquerque (1973) has demonstrated the relationship between the occurrence and geochemistry of this mineral from calc-alkaline granitoid rocks in northern Portugal. He showed that compositional variations in biotite correlated with the occurrences of amphibole, primary muscovite and aluminosilicates in the rocks, which in turn, provided information regarding the paragenesis.

Using the diagram of Abdel-Rahman (1994), the biotites from the granitoid rocks in Sulawesi belong to the calc-alkaline group. The calc-alkaline affinity is concordant with the bulk rock and trace element composition of the granitoid rocks, which show a strong calc-alkaline trend (Figure 9). Biotites can further be divided into Mg-rich biotite (MgO > 12 wt%) and Fe-Mg rich biotite (FeO >20 wt% and MgO > 9wt%) with relatively low Al_2O_3 content (less than 14wt%). The Mg-rich, Fe-rich, and Al-poor biotites crystallized mostly from I-type and calc-alkaline magma where the role of Al is limited (Chappell and White, 1974). The biotites were also plotted in the field I of the MgO–Al_2O_3–FeO Total diagram of Albuquerque (1973) (Figure 10), indicating that the biotite coexists with hornblende in the calc-alkaline plutonic rocks. This suggests that the granitoid rocks in Sulawesi were associated with subduction environment (Barbarin, 1990:1999; Robert and Clement, 1993; Altherr *et al*., 2000). The subduction-related magma origin is also indicated by a negative Nb and Ta anomaly in the primitive-mantle normalized trace element spider diagram of the granitoid rocks as reported in Maulana *et al.* (2016). The high Mg# of hornblende (range from 0.55 to 0.73) from the granitoid rocks also suggests relatively oxidized magma source.

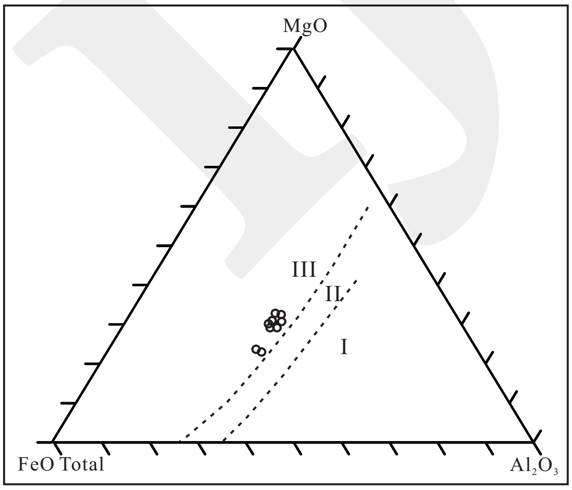

Figure 10. Triangular diagram showing the relationship between the contents of MgO, Al_2O_3, and Total FeO for biotite. Field I= biotite associated with muscovite; II= biotite associated with pyroxene and garnet; III= biotite associated with hornblende.

Exhumation Rate Estimation

Combination of geobarometers with geochronology can be used to define time-pressure histories for granitoid rocks. If reasonable assumptions are made to convert pressure to depth below the surface, then the change in a rock beneath the surface through time can be deduced and history of exhumation can be reconstructed. The rate of exhumation can be defined simply as the rate of erosion or the rate of removal of overburden by tectonic processes (England and Molnar, 1990). Exhumation rate estimation can be calculated from at least three approaches using thermochronological data (Copeland *et al*., 1987). The first method is by obtaining the ratio of the difference in elevation between two identical minerals and the differences in their mineral ages while assuming the closure temperature for both minerals. The second method of approach utilizes two mineral ages from the same sample (either biotite/K-feldspar or K-feldspar/apatite) and dividing the ratio between the differences in closure temperature and mineral ages. The third is by dividing a known amount of exhumation or simply defined as depth by the duration over which the exhumation took place or cooling age. In this case, the third method was used to estimate the exhumation rate of the granitoid rocks from the studied area.

The geobarometer data were combined to get the depth with geochronology using Ar-Ar dating cooling age from Maulana *et al* . (2016) and from the previously reported data to calculate the exhumation rate of each pluton. The calculation suggested that Mamasa Pluton had been exhumed at 0.37 mm/year, whereas Masamba Pluton at 1.6 mm/year. The exhumation rate of the Lalos-Toli Pluton is 1.4 mm/year and Sony Pluton is 2.7 mm/year. Meanwhile, Gorontalo Pluton has been exhumed at 0.42 mm/year. These exhumation rates show strong and systematically regional variations which reflect the greater exhumation in the central part (particularly Sony Pluton) of the Western Sulawesi Province.

Tectonomagmatic Implication

During the Early Miocene, several tectonic processes occurred on the southern margin of

Sundaland. These processes include the collision of the Sula Spur which formed a promontory of the Australian margin with the Northern Sulawesi Volcanic Arc (Hall and Sevastjanova, 2012) and the convergence of the Australian Plate and Eurasia which caused the counter-clockwise rotation of Western Sulawesi and contraction, uplift, and erosion in East and Southeast Sulawesi (Hall, 2011). In addition, subduction roll back in the Banda Arc region which started around Middle to Late Miocene caused the widespread extension in the Sulawesi region, resulting fragmentation of crustal fragments from the Sula Spur and East and Southeast Sulawesi (Hall and Sevastjanova, 2012), formation of Malino Metamorphic Complex (van Leeuwen *et al*., 2007), and block faulting accompanied by HK magmatism in Western Sulawesi. In the Late Miocene to Pliocene, the region also record rapid subsidence and uplift triggered by the collision between Banggai-Sula continental fragments with the Eastern Sulawesi.

The granitoid rocks in the Lalos-Toli and Sony Plutons were emplaced at deeper depths than other units, and at the same time Sony Pluton exhumed in a faster rate (2.7 mm/year). It is interesting to note that the Sony Pluton is located near a regional structure, which is called the Palu-Koro Fault Zone, an active sinistral fault. The association of very high depth emplacement (11.2 km) and rapid exhumation rate in the Sony Pluton (2.7 mm/year) can be associated to the vertical movement of this fault which is still active since Pliocene (Walpersdorf *et al*., 1998) as triggered by the collision between Sundaland fragment and block of microcontinent. The strong uplift and exhumation of the granitoid rocks in the Western Sulawesi Province (especially Sony Pluton) during the Late Miocene to Pliocene is attributed to the above tectonic process, particularly a regional Palu-Koro Fault. It is suggested that despite a lateral strike-slip motion, possible vertical movement of Palu-Koro Fault was also confirmed as suggested by tectonomagmatic data. In addition, this study also shows that faulting between plutons may play an important role on differential exhumation of orogenic belts.

Most researchers proposed a large-scale crustal extension for emplacement model of Miocene granitoid rocks (Stouraiti *et al*., 2010). This model refers to a deduction of an intrusion depth between a brittle-ductile transition zones which can be found in the middle to the lower crust (Ramsay, 1980) in a depth of 15 to 20 km (Brichau *et al*., 2007). The emplacement depth estimation from this study implies that the maximum emplacement depth of the granitoid rocks is less than 15 km. This suggests that the emplacement depth never reached the depth of the transition zone between elastic-fractional (ductile) and quasi-plastic (brittle) where low-angle extension-related mechanism might be triggered. Therefore, the emplacement depth estimates of the granitoid rocks from Sulawesi confined the crustal-scale extension model which required deep-seated melt injection at about 15–20 km into the footwall of a regional detachment fault.

Conclusions

The biotite composition shows that the granitoid rocks has a calc-alkaline character, concordant with the calc-alkaline affinity shown by the whole rock composition. The biotite composition also indicates a strong association with hornblende, suggesting typical I-type granitic rock characteristics.

Mamasa and Masamba Pluton were emplaced at temperatures of 677 - 729°C and 756 - 774°C with pressures of 0.91 to 1.2 kbar, respectively. These equal to the emplacement depth of 3.2 - 4.3 km and exhumation rate at 0.37 mm/year for Mamasa, and 8.2 to 10 km and 1.6 mm/year for Masamba. Lalos-Toli and Sony Plutons were emplaced at temperature of 731 - 736°C and 601 - 609°C and the pressure from 3.1 - 3.3 and 3.2 - 3.4 kbar, respectively, which are equals to 11.3 and 11.6 km depth and exhumation rate of 1.4 and 2.7 mm/year respectively. The Gorontalo Pluton were emplaced at temperature of 662 - 668°C with a pressure range from 2.6 to 2.7 kbar, equivalent to 9.4 km depth and exhumed at a rate of 0.42 mm/year.

The oxygen fugacity values (log fO_2) and XMg of hornblende suggest that the magma was highly oxidized. The biotite composition shows that the granitoid rocks associated with subduction processes.

The significant vertical displacement of the Sony Pluton was actively controlled by the regional tectonic regime (*e.g.* fault), particularly Palu-Koro Fault despite its strike-slip fault mechanism.

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