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Petrology and Geochemistry of The Volcanic Arc Tarusan Pluton in Comparison to Lolo Pluton, West Sumatra

Petrologi dan Geokimia Batuan Busur Gunungapi Pluton Tarusan yang Dibandingkan dengan Pluton Lolo, Sumatera Barat

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Abstract- The Volcanic Arc Suite is the group of batholiths in the range of the Barisan Mountains and mostly denotes I-type affinity. Previous investigations of the intrusions in West Sumatra emphasized the crystallization age without completing geochemistry characteristics. No former study discussed a pluton which mapped in the Kota XI Tarusan District. This study explains the geochemistry and petrology of the Tarusan Pluton using polarized microscope, XRF, and ICP-MS at the Center for Geology Survey of Indonesia. The microscopic analysis confirms the granite character of the samples. Although both plutons are identified as I-type calc-alkaline series, the Tarusan Pluton is peraluminous granite whilst the Lolo Pluton denotes wider range from metaluminous to peraluminous of granodiorite to granite. Both the plutons are clearly classified as volcanic arc granitoid in the correlation to Volcanic Arc Suite of Sumatra. Negative Ba, Nb, and P anomalies together with positive K, Nd, and Y anomalies are pronounced on the two felsic intrusions. Negative Eu anomaly on the Tarusan Pluton but the positive one at the Lolo Pluton might explain different magma evolution process.

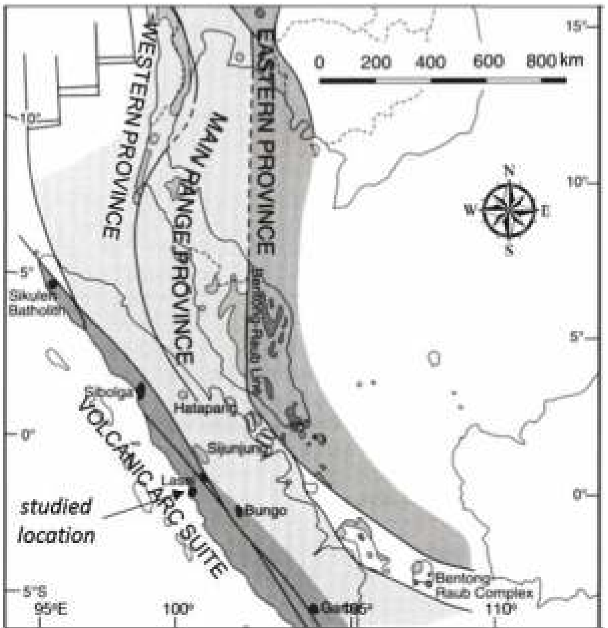
Keywords: volcanic arc granite, geochemistry, Tarusan Pluton, Lolo Pluton.

Abstrak- *Mandala Busur Vulkanik adalah kelompok intrusi di sekitar Pegunungan Barisan dan sebagian besar merupakan tipe-I. Investigasi sebelumnya mengenai pluton di Sumatera Barat terfokus pada umur pembentukan tanpa karakterisasi geokimia yang lengkap. Meskipun terpetakan adanya suatu intrusi di Kabupaten Kota XI Tarusan, belum ada studi yang pernah membahasnya. Penelitian ini menjelaskan karakter geokimia dan petrologi Pluton Tarusan menggunakan mikroskop polarisasi, XRF, dan ICP-MS di Pusat Survei Geologi Indonesia. Karakter granit dapat dikonfirmasi melalui analisis mikroskopis. Meskipun kedua pluton diidentifikasi sebagai batuan kalk-alkalin bertipe-I, Tarusan Pluton adalah granit peralumina sedangkan Lolo Pluton menunjukkan kisaran lebih luas dari granodiorit-granit yang berafiliasi metalumina hingga peralumina. Kedua pluton itu jelas diklasifikasikan sebagai granitoid busur vulkanik dalam korelasinya dengan Volcanic Arc Suite di Sumatra. Anomali negatif Ba, Nb, dan P bersama dengan anomaly positif K, Nd, dan Y ditunjukkan oleh kedua intrusi. Anomali negatif Eu pada Tarusan Pluton tetapi positif pada Lolo Pluton mungkin menjelaskan proses evolusi magma yang berbeda.*

Katakunci: *Granit busur vulkanik, geokimia, Pluton Tarusan, Pluton Lolo.*

INTRODUCTION

Granitoids in Southeast Asia are classified into four segments (Figure 1), namely Eastern Province, Main Range Province, Western Province, and Volcanic Arc Suite (McCourt *et al.*, 1996; Cobbing, 2005). In Sumatra, the granitoids were developed in two different geological periods: i) the older group which is situated in Main Range Granite Province of Southeast Asia and associated with tin mineralization and ii) the younger group of Volcanic Arc Suite which is geographically restricted alongside the Barisan Mountains and shows large range of composition (Cobbing, 2005; Setiawan *et al.*, 2017). The tin associated granites are hypothesized of Triassic Age and part of Main Range Granite Province of Southeast Asia. Sungai Isahan Granite, Tiga Puluh Batholiths, Rokan Granite, Siabu Granite, and Bukit Batu Granite are denoted as S-type of Main Range Province (Cobbing, 2005; Kurniawan, 2014; Setiawan *et al.*, 2017). Although Hatapang Granite shows tin mineralization, its geochemical and isotopic range does not represent the Triassic Main Range Province, but more likely to be the part of Western Province which emplaced in Cretaceous to Neogene Age. Previous work suggested that the Western Province elongated southward to Central Sumatra with younger granite into an area dominated by older stanniferous granite (Clarke & Beddoe-Stephens, 1987; McCourt *et al.*, 1996). Sikuleh Batholith, Sibolga Granite, and Garba Plutons are classified in I-type Volcanic Arc Suit as their locations alongside the Barisan Mountains (Barber, 2000; Kurniawan, 2014; Setiawan *et al.*, 2017).



Sources: modified after Cobbing (2005)

Figure 1. The four granite provinces in Southeast Asia. Studied granite is located in the range of the Barisan Mountains.

The felsic intrusions are spread in the West Sumatra Province as small batholiths which mostly denotes volcanic arc affinity such as Lassi Pluton in Solok Regency, Sulit Air Granite at Kanagarian Sulit Air, Padang Granite on Padang Panjang Regency, Tanjung Gadang Granite near Tanjung Gadang district, Singkarak Granite which is located close to Singkarak Lake and Lolo Pluton in Kanagarian Lolo. The age of these Volcanic Arc Suit plutons ranges in Paleocene to Miocene and are classified as I-type (McCourt *et al.*, 1996; Barber, 2000; Cobbing, 2005; Imtihanah, 2005; Kurniawan, 2014). Besides, Sijunjung Granite in Sijunjung Regency is likely to be the part of Volcanic Arc Suite which was emplaced in Triassic age with A-type affinity (Irzon *et al.*, 2018). The A-type character on several parts of Sibolga Granite (Setiawan et al., 2017) emphasizes that some other granite might also form in different tectonic evolution with the plutons alongside Barisan Range.

Previous studies about the granitoids in West Sumatra emphasized more about the age of crystallization with incomplete geochemistry characteristic. As many other felsic intrusions in the Volcanic Arc Suite, a small area of granitoid is mapped in the Kota XI Tarusan District in Pesisir Selatan Regency at the west coast of Sumatra (Rosidi *et al.*, 2011). No previous study has ever been conducted about the pluton which is situated about 33 km from the northwest of Gunung Talang as the part of the Barisan Mountains. The main goal of this study is to examine the geochemistry and petrology of Tarusan Pluton which is located in the range of Barisan Mountains. Moreover, a new rock from Lolo Pluton location was taken and was analyzed in this study to be combined with the data of previous study (Imtihanah, 2005) in order to give broader geochemistry perspective and become a comparison to Tarusan Pluton.

Geology of Studied Area

Tarusan Pluton is situated at the western part of the Geological Map (Figure 2) of The Painan and Northeastern Part of Muara Siberut Quadrangle (Rosidi *et al.,* 2011). Pesisir Selatan Regency comprises of several rock units from the oldest to the youngest: the Oligo-Miocene Volcanic Rock (Tomp), the Upper Member of Ombilin Formation (Tmo), the Tertiary Granite (Tgr), the Undifferentiated Acid Volcanic Rock (Qou), and the Alluvium (Qal). The oldest Tertiary volcanic rock unit consists of lava, breccias, tuff breccias, crystal tuff, and lithic tuff. The sedimentary Upper Member of Ombilin Formation is built of sandy claystone, tuffaceous sandstone, quartz sandstone, glauconitic sandstone, marly sandstone, and conglomerate. Three series of plutonism are identified in the map: in Jurassic which developed the Granite (Jgr) and the Diorite (Jd), in Cretaceous with the Granitic Rocks (Kgr) and the Diorite (Kd) intrusions, and the Granite (Tgr) and the Granodiorite (Tgdr) which were emplaced during Tertiary age. Tarusan Pluton as the focus in this study is classified in the Tertiary Granite (Tgr) whilst Lolo Pluton is situated in Cretaceous Granitic Rocks domain (Kgr; Rosidi *et al.*, 2011). However, Imtihanah (2005) proposed that Lolo Pluton was formed in Miocene - Pliocene based on Rb/Sr geochronology. Because of the wide use and clear description of the method, the later age data from Imtihanah (2005) is applied in this study. The Undifferentiated Acid Volcanic Rock was formed in Quaternary consisting of lava, crystal and vitric tuff, tuff, ignimbrite, and acidic to intermediate obsidian.

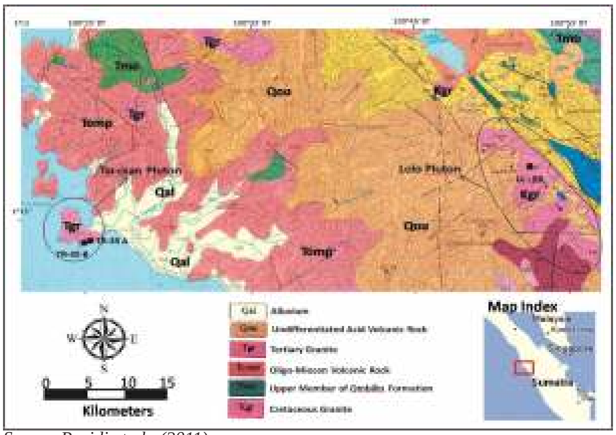
METHODOLOGY

Samples Description and Selection

Two samples were attained from the domain of Tarusan Pluton at the west coast of Sumatra. TR-35 A is a pinkish, phaneritic, coarse grain, and massive rock from a granitoid outcrop in Batu Kalang Beach - XI Kota Tarusan. Blocks of granitoid are located about 100 m near the outcrop from which TR-35 B was taken. TR-35 B is relatively more brownish than TR-35 A to indicate a higher degree of weathering. Megascopically, both rocks consist of quartz, K-feldspar, and plagioclase. The new sample of Lolo Pluton (LL-59) location was attained from Pantai Cermin, Solok Regency. The rock is a light grey, phaneritic, medium grain, and fresh granite. Quartz, K-feldspar, and biotite are the main minerals of the samples with minor hornblende are detected megascopically. The last sample is then combined with the data of four samples from the previous study about geochemistry on Lolo Pluton (Imtihanah, 2005). Some field conditions are given in Figure 3.

Analytical Techniques

The rock samples were brought to Laboratory of Center for Geology Survey - Indonesia to be prepared and analyzed (petrographic and whole rock analysis). Thin sections were prepared on all samples for microscopic observation. Petrographic observations were conducted using a Nikon polarization optical microscope to acquire modal compositions and observe textures. The hand specimens were cut off for approximately 1 cm thick before they were marked to identify the front or the back surface. Ultrasonic cleaning was adapted to remove the dirt material from the sawing pores and fractures of the sample. The surface specimens were then mounted on a grease-oil- and dust-free satin finished object-slide. On the next step, a diamond saw blade was used to cut off the specimen depending on the material to a thickness of 0.5 to 1 mm before covering the cut surface with a thermoplastic resin and a microscopic coverslip glass. Final labeling of the thin section preparation was performed after removing the excess resin and cleaning with alcohol under the fume hood.



Source:Rosidi et al., (2011)

Figure 2. The rock units around Pesisir Selatan Regency, West Sumatra.

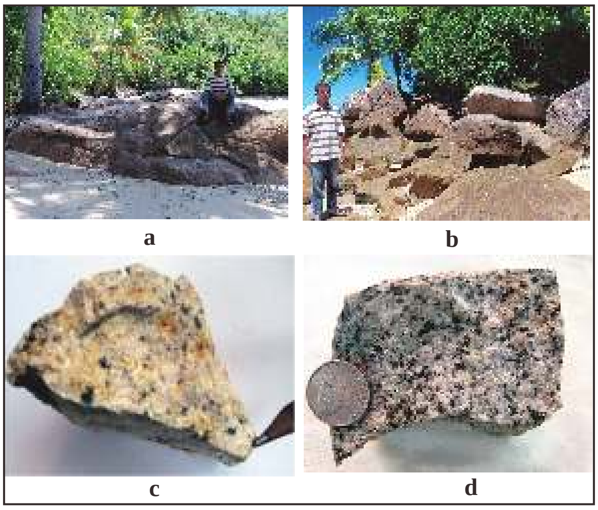


Figure 3. a) TR-35A was attained from an outcrop in Kota XI Tarusan at the west coast of Sumatra; b) TR-35B was taken from blocks of granitoid in Batu Kalang Beach; c) the brownish spots on TR-35B indicate that the sample is slightly weathered; and d) LL-59 is a fresh light grey granitoid with more mafic minerals from Pantai Cermin, at the domain of Lolo Pluton.

The geochemical character of the rocks was analyzed using Advant XP X-Ray Fluorescence (XRF) for major oxide compositions and X Series Inductively Coupled Plasma-Mass Spectrometry (ICP-MS) for trace and rare earth elements contents. After dried under sunlight, the rocks were crushed to 200 mesh. No chemical solution is required in both pressed pellet and fusion bead preparation method for XRF measurement. This study adapted pressed pellet method in order to save time and to avoid the risk of platinum crucible contamination on the other technique and (Devi *et al.*, 2015; Chubarov *et al.*, 2016). The homogenous sample powder was pressed at 300 kN for 30 s on a press machine. LOI is the sum of volatile material in a sample and is typically determined through heating of the sample to high temperature (Yaroshchyk *et al.*, 2010; Lezzerini and Tamponi, 2015; Irzon, 2017). The parameter assigned by burning an empty, dry, and clean porcelain crucible in a furnace. One gram of sample was then put in the crucible and heated at 1000°C for about an hour. Sample together with crucible was then cooled in desiccators and weighted. The LOI calculated from this formula:

$$LOI = \frac{A-B}{A-C}\ x\ 100\%$$

(i.e. Irzon and Abdullah, 2016; Irzon and Abdullah, 2018)
A = mass of crucible+sample
B = mass of crucible+residue
C = mass of empty crucible

Acid digestion procedure was adopted on the sample preparation before ICP-MS analysis. 100 mg of the crushed rocks were digested using nitric acid (ultrapure grade), formic acid (ultrapure grade), and perchloric acid (pro analysis grade). The samples together with 10 ml of fluoric acid and 3 ml of nitric acid were placed in Teflon-glass prior to microwave digestion at 170°C. After two hours, the solutions were heated on a hotplate at 170°C to let the acids to evaporate. The preparation was considered complete if no residue is detected. Besides, 5 ml of fluoric acid and 3 ml of perchloric acid should be added to the sample and reheated on the hotplate at 170°C. The sample solutions were then diluted by deionized water, transferred into acid-cleaned High-Density Polyethylene (HDPE) bottles, and stored as the "mother" solution (~50 ml). Several hours prior to ICP-MS measurement, 1 ml of the mother solution are dissolved by HNO_3 2% to 10 ml.

RESULT AND DISCUSSION

Petrography

The three studied samples (TR-35A, TR-35B, and LL-59) are clearly described as granite based on petrographic analysis. The microscopic study confirms that all of the samples are phaneritic and holocrystalline. However, the thin sections of the Tarusan Pluton are relatively more brownish than Lolo Pluton sample. The rock from the outcrop on Batu Kalang Beach (TR-35 A, Tarusan Pluton) is mainly built of quartz (33%), K-feldspar (24%), and plagioclase (15%) with minor apatite (12%), opaque mineral (8%) and iron oxide (3%). Quartz occurs as subhedral to anhedral crystals whilst The K-feldspars are subhedral and some of them are sericited at about 5% total volume to confirm the weakly altered condition of the rock. Plagioclases are subhedral but characterized by albite and carlsbad-albite twinning. Apatites are subhedral and occur as inclusion in quartz. Both of the dark opaque minerals and the reddish iron oxides are anhedral. The minerals description of TR-35B is almost the same as TR-35A but with different volume-based composition. TR-35B consists of quartz, K-feldspar, plagioclase, opaque mineral, apatite, and sericite with the volumetric composition of 37%, 26%, 10%, 5%, 18%, and 2%, respectively. However, chlorites (2%) as the alteration mineral of plagioclase are only detected in the sample from the granite blocks (TR-35B).

The new Lolo Pluton sample (LL-59) comprises a higher quantity of quartz (45%) but much lower K-feldspar (5%) than the Tarusan Pluton samples. Biotite (7%) and amphibole (5%) are the mafic minerals in the rock. Some of opaque minerals and amphiboles happen as inclusions. Both plagioclases (20% of total volume) and K-feldspars are subhedral. Albite, carlsbad-albite twinning, and opaque minerals inclusion are identified on the plagioclases. The biotites and amphiboles occur as anhedral and subhedral mineral respectively. The pale green chlorites are the alteration minerals of amphiboles and biotites with whilst the yellowish and anhedral sericites might be the alteration result of plagioclases and K-feldspars. Petrographic microphotographs of the studied samples are shown in Figure 4. In the QAP (Streckeisen, 1974) diagram TR-35A, TR-35B, and LL-59 falls in monzogranite, syenogranite, and quartz-rich granitoid field, respectively (Figure 5).

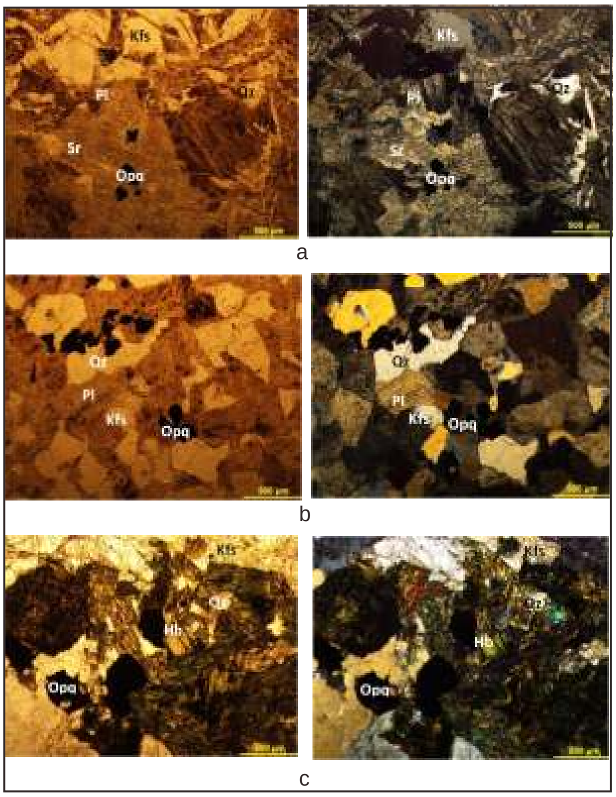
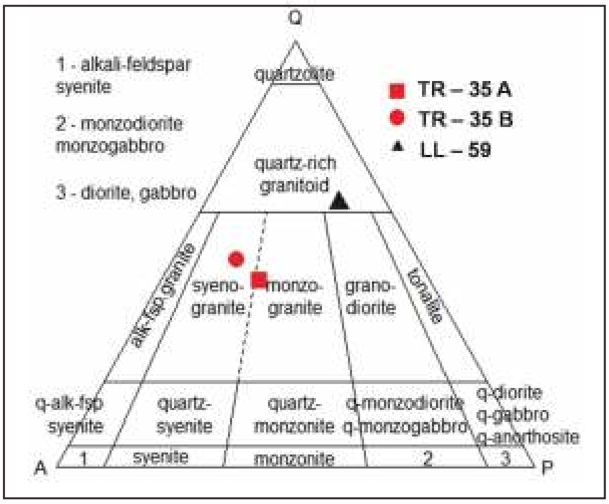


Figure 4. Microphotographs of the studies samples: a) TR-35A; b) TR-35B; and c) LL-59. The petrography analysis confirms that the samples are granites. Parallel nicols are on the left side whilst cross-nicols are on the right ones. Qz = quartz, Kfs = K-feldspar, Pl = plagioclase, Opq = opaque mineral, and Hb = hornblende.



Source:Streckeisen (1974)

Figure 5. Classification of studied samples based on the modal composition of quartz, alkali feldspar and plagioclase.

The studied samples are generally dominated by quartz, plagioclase, and K-feldspar. However, hornblendes and biotites are only identified on the Lolo Pluton sample but not in the Tarusan Pluton to picture dissimilar magma source and/or unequal differentiation process. The two mafic minerals indicate that the Lolo Pluton was the result of more hydrous basic magma with more abundance of Fe and Mg. Otherwise, Tarusan Pluton might have run through a higher degree of differentiation process than the Lolo Pluton according to the petrographic study.

Whole-rock chemical compositions

The acid character of the samples is defined on the two highest oxide compositions in the rock samples are SiO_2 and Al_2O_3 in the range of 67.44% to 71.77% and 16.46% to 17.61% respectively. Na_2O, K_2O, and Fe_2O_3T are the next abundant oxide in the average of 4.51%, 3.87%, and 1.66% successively. The other major oxides are relatively low at averagely <1%. The more Fe and Mg compositions on Lolo Pluton explain the previous petrographic result about the more mafic magma source than Tarusan Pluton. Ignoring Fe_3+ bearing phase, FeO was calculated by multiplying total Fe_2O_3 obtained from XRF analysis with a conversion factor of 0.8998 (Shellnutt and Hsieh, 2016). The LOI proposed as a good indicator of the degree of weathering and organic matter concentration in geology study (i.e. Ishiga *et al.*, 2013; Irzon, 2018). The low loss on ignition (LOI) values (0.51%-1.19%) of the samples (Table 1) imply that granites have only gone through a weak degree of weathering and/or alterations. Moreover, the higher LOI of Tarusan Pluton compared to that of Lolo Pluton indicates the more degree of weathering and might explain the more brownish color on the thin sections.

Table 1. Major oxides, trace and rare earth elements compositions of the studied samples. I-98-9, I-98-10, I-98-11, and I-98-13 are the secondary data from the previous study on Lolo Pluton (Imtihanah, 2005)

Sample	TR-35A	TR-35B	LL-59	I-98-9	I-98-10	I-98-11	I-98-13
Major oxides (%)							
SiO_2	71.77	70.79	68.44	71.55	65.88	64.79	74.91
TiO_2	0.12	0.09	0.31	0.33	0.58	0.55	0.18
Al_2O_3	15.46	16.51	16.07	14.10	16.13	16.07	13.54
Fe_2O_{3T}	1.02	0.953	3	3.23	4.78	5.64	1.63
MnO	0.01	0.01	0.01	0.05	0.10	0.09	0.03
CaO	1.56	1.63	3.21	2.87	4.46	5.36	1.61
MgO	0.21	0.23	1.36	0.87	1.66	2.03	0.35
Na_2O	4.5	5.14	3.88	3.52	3.57	3.55	3.28
K_2O	4.69	3.68	3.23	3.06	2.65	1.97	4.30
P_2O_5	0.01	0.01	0.10	0.07	0.14	0.10	0.03
LOI	0.84	1.19	0.51	0.39	0.59	0.48	0.39
Tot	100.21	100.24	100.19	100.04	100.54	100.63	100.24
Trace and REE (ppm)							
Rb	102	90	113	97.7	108.7	62.7	138.8
Sc	1.94	2.08	2.93	10.60	14.2	21	4.2
Ga	19.40	16.40	7.82	13.90	16.7	16.6	12.6
Sr	61.40	79.50	106.38	165.00	283	257	117
Y	25.00	19.20	11.97	21.30	27	27	19.2
Nb	14.80	17.60	2.72	3.50	6.4	3.2	4.8
Ba	279.00	189.00	n.d.	302.00	375	257	369
La	34.02	8.94	7.85	13.00	18	10	15.2
Ce	56.45	21.40	17.50	24.30	39.6	23	29
Pr	7.75	1.60	1.54	-	-	-	-
Nd	26.97	5.55	6.25	12.8	20.8	13.5	13.7
Sm	3.28	0.30	0.58	-	-	-	-
Eu	0.02	0.01	0.23	-	-	-	-
Gd	2.82	0.21	0.31	-	-	-	-
Tb	0.55	0.24	0.33	-	-	-	-
Dy	1.58	0.42	1.00	-	-	-	-
Ho	0.45	0.29	0.38	-	-	-	-
Er	0.61	0.25	0.43	-	-	-	-
Tm	0.26	0.23	0.23	-	-	-	-
Yb	1.40	1.29	1.13	-	-	-	-
Lu	0.18	0.17	0.13	-	-	-	-
Th	13.30	13.43	4.89	7.10	8.6	3.5	8.1
U	1.86	2.16	1.08	-	-	-	-
Tot REE	136.34	40.90	37.89	-	-	-	-
A/CNK	1.0092	1.0716	1.0220	0.9841	0.9566	0.9063	1.0430
Rb/Sr	1.6612	1.1321	1.0623	0.5921	0.3841	0.2440	1.1863
Rb/Ba	0.3656	0.4762	-	0.3235	0.2899	0.2440	0.3762
La/Lu_N	19.3386	5.4162	6.1497	-	-	-	-
Eu/Eu*	0.0223	0.1218	1.6235	-	-	-	-
Ce/Ce*	0.8367	1.3626	1.2122	-	-	-	-

Ga content of the three new samples and four data from the previous study (Imtihanah, 2005) confirm a narrow range of 7.82 -19.40 ppm. The average content of Sr and Ba are more abundant in the Lolo Pluton (185 ppm and 325 ppm) than that of Tarusan Granit (70.45 ppm and 234 ppm). In contrast, Nb and Th concentrations in the Tarusan Granite are higher than the Lolo Pluton. The three collected samples reveal medium REE (Lantanum through Lutetium) abundance of 37.89 ppm to 136.34 ppm with an average of 71.71 ppm. However, it is insufficient to compare REE of both plutons because prior investigation (Imtihanah, 2005) did not measure a complete REE content. Geochemistry composition of the rock samples is provided in Table 1.

Geochemical Characteristic

The GCDkit 4.1 program was applied to the geochemistry characterizations of studied samples. The two samples from the Tarusan Pluton are classified as granite whilst three and two rocks from Lolo Pluton categorize as granodiorite and granite on total alkali versus silica diagram (Middlemost, 1985) (Figure 6). Both granite groups are the result of subduction-related magma based on its calc-alkaline affinity (Fan *et al.*, 2017) as denote in AFM diagram (Irvine and Baragar, 1971; Figure 7a) and in Si_2O versus FeO/MgO plot (Miyashiro, 1974; Figure 7). The two Tarusan samples indicate peraluminous nature because their aluminum oxide molar portion is higher than total alkali oxides and calcium oxides. On the other hand, aluminum saturation index of the Lolo Pluton draws wide range in which three samples are described metaluminous whilst the other two as peraluminous (Figure 8a). The Tarusan samples plot in alkali-calcic whilst the Lolo ones straddle between calcic and calc-alkali field on the modified alkali-lime index (Frost *et al.*, 2001; Figure 8b). Volcanic arc granites affinity is clearly shown in the both studied plutons (Figure 9) to verify its affiliation to granitoid of Volcanic Arc Suite in Sumatra.

The bimodal Harker diagrams which are broadly applied to describe the rock evolution (Moinevaziri *et al.*, 2014; Lu *et al.*, 2017; Wang *et al.*, 2017) are used in this study. However, the number of rock samples (only two samples) of Tarusan Granite is insufficient to draw the geochemical evolution of its parent magma. Lolo Pluton shows strong negative correlations of SiO_2 to TiO_2, Al_2O_3, Fe_2O_3T, MnO, CaO, and MgO with correlation value (r) <-0.93. On the other hand, the pluton displays a strong positive correlation of SiO_2 to K_2O (r = 0.92). These strong correlation values ensure the equal lithology of the new sample with the data of the previous investigation on the Lolo Pluton (Imtihanah, 2005). The trace elements exhibit considerably more scatter than the major elements. The negative correlations on SiO_2 to TiO_2 and CaO might indicate titanite or apatite fractionation whilst the decrease of MgO and Fe_2O_3T during SiO_2 increases may denote biotite separation (Bagherzadeh *et al.*, 2015). Sr shows a negative linear trend with increasing SiO_2 contents to suggest plagioclase fractionation in these suites and is also consistent with negative correlations of Al_2O_3 and CaO to SiO_2 (Matos *et al.*, 2009; Azer *et al.*, 2016). The Harker diagrams for the Lolo Pluton are shown in Figure 10.

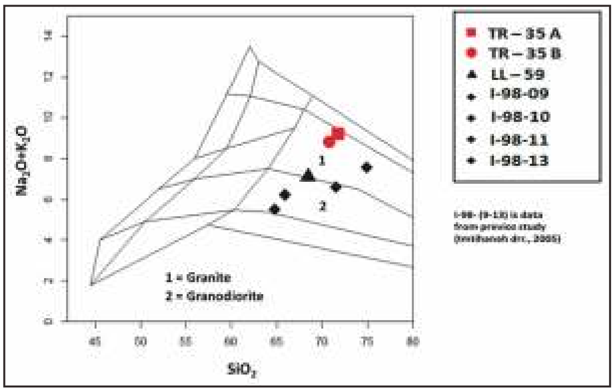


Figure 6. The two samples of the Tarusan Pluton are described as granite whilst two and three samples of the Lolo Pluton are classified as granodiorite and granite, respectively on the total alkali-silica classification of Middlemost (1985).

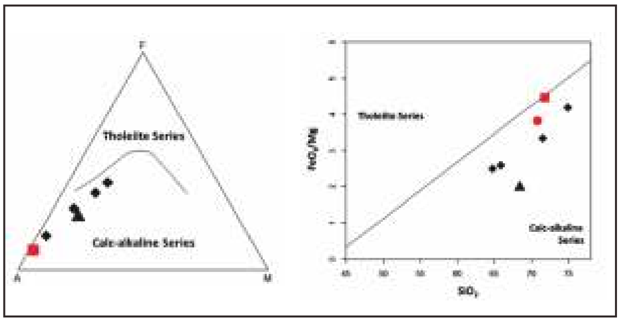


Figure 7. Both Tarusan Pluton and Lolo Pluton fall within calc-alkaline series in a) AFM diagram (Irvine and Baragar, 1971); and b) SiO_2 versus FeO/MgO plot (Miyashiro, 1974). Symbols are the same as Fig.6.

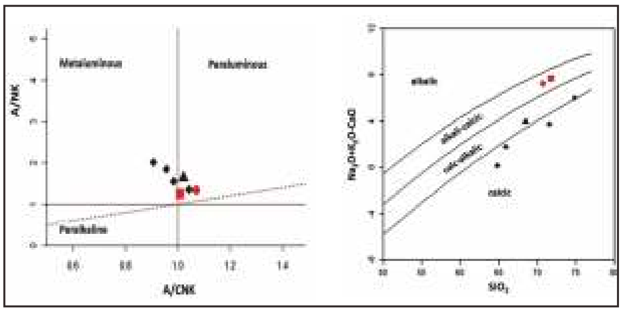


Figure 8. a) Peraluminous character is shown on the two samples of the Tarusan Pluton whilst the Lolo Pluton indicates wide range from metaluminous to peraluminous on A/CNK – A/NK plot (Shand, 1943); b) The more alkali content on Tarusan Pluton than the Lolo Pluton is denoted in Frost *et al.* (2001) discrimination. Symbols are the same as Fig.6.

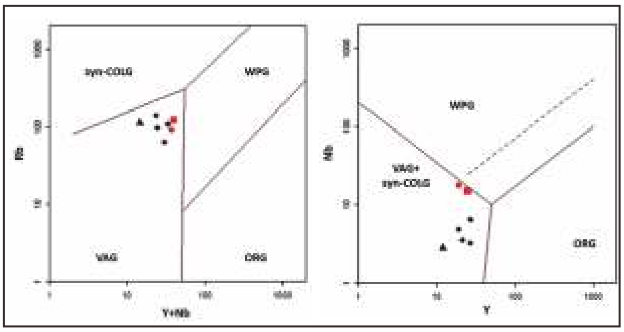


Figure 9. The two studied plutons fall within VAG (Pearce *et al.*, 1984) to confirm their correlation to Bukit Barisan Volcanoes. VAG = volcanic arc granite, WPG = within-plate granite, ORG = ocean ridge granite, COLG = collision granite. Symbols are the same as Fig.6.

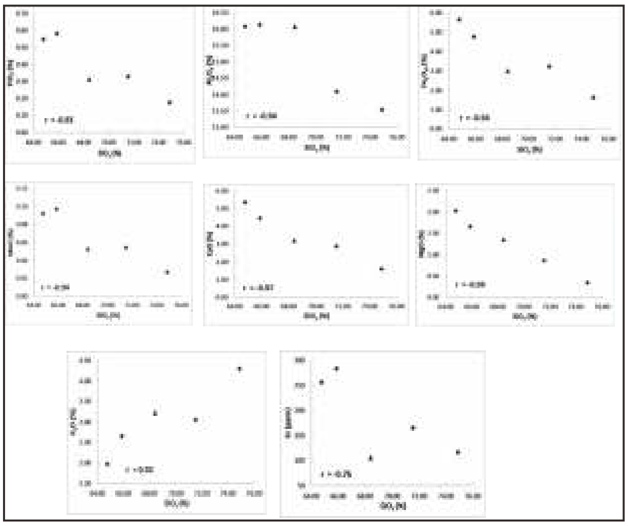


Figure 10. Bimodal diagrams of SiO_2 versus TiO_2, Al_2O_3, Fe_2O_3T, MnO, CaO, MgO, K_2O, and Sr.▲= primary data of this study,◆= data from Imtihanah (2005)

Although Cobbing (2005) describes that most batholiths of Volcanic Arc Suite are classified as I-type, some sub-location of Hatapang Granite (Clarke & Beddoe-Stephens, 1987) and Sibolga Granite (Setiawan et al., 2017) indicate A-type affinity. A-type granites are rift-related or anorogenic alkaline rock containing high composition of High Field Strength Elements (HFSE) such as Zr, Y, Nb instead of low Sr, Ba, Eu, CaO, and Al_2O_3 concentrations.Moreover, the Ga/Al, FeOt/(FeOt+MgO), $(Na_2+K_2O)/CaO$ ratios of this type of granite are preferably high (Collins *et al.*, 1982; White & Chappell, 1983; Setiawan *et al.*, 2017). The five diagrams from a previous study (Whalen *et al.*, 1987) confirm that the studied samples are not classified as A-type, but I- or S-type (Figure 11.). The results emphasize that these plutons are not potential sources of REE which are more abundant in A-type granites (Eby, 1990).

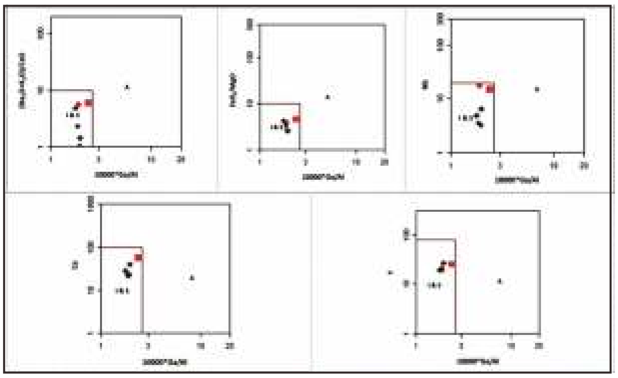


Figure 11. Both Tarusan Pluton and Lolo Pluton are not classified as A-type but are classified as I- or S-type granites based on Whalen (1987) diagrams. Symbols are the same as Fig.6.

I- and S-types were the two first introduced alphabetical granite classification (Chappel & White, 1974). I-type was proposed to be igneous origin whilst S-type was derived from remelting of sedimentary rocks or supracrustal source (Chappell & White, 1974; Chappell & White, 2001). I-type granites are commonly magnetite bearing with high magnetic susceptibility whilst S-type granites are initiated from reduced sources and are ilmenite bearing with low magnetic susceptibility (White *et al.*, 1986). The ratio of the molecular A/CNK of the Lolo Pluton as well as the Tarusan Pluton are in the 0.90-1.07 interval (Figure 12a), hence the rocks are of I-type in the sense of Chappell & White (1974). The average of Aluminium Saturation Index (ASI) of Tarusan Pluton (1.04) is higher than Lolo Pluton (0.98) which may represent more fractionated I-type granites, as these rocks commonly reach and even slightly exceed aluminum saturation or it is due to the contamination by reaction with country rocks (Khalaji *et al.*, 2007). The high Na2O content of the studied rocks is another indicator of I-type granite as shown in the N2O vs K2O plot (Figure 12b; Chappell & White, 1992; Fan *et al.*, 2017). I-type characteristic is also shown on the FeO/MgO ratio of the rocks in the range of 1.98-4.19 and 3.81-4.46 for Lolo Pluton and Tarusan Pluton, respectively (Setiawan *et al.*, 2017).

Trace elements compositions also support the rock classification. The Rb/Sr and Rb/Ba ratios of Lolo Pluton are 0.25-1.19 and 0.24-0.38 respectively which are more similar to I-type granites (Rb/Sr ~ 0.6, Rb/Ba ~ 0.3) than to S-type granites (Rb/Sr ~1.8, Rb/Ba ~ 0.5; Whalen et al. 1987; Schwark et al., 2018). Even though Rb/Ba ratio of Tarusan pluton (0.36-0.47) is in the range I-type of previous studies, its Rb/Sr ratio is in the border of I-and S-type granites (1.13-1.66). Rb/Sr ratio is often used as an index of differentiation as Rb is more incompatible than Sr in nearly all magmatic systems so that Rb/Sr ratio increases with the rise of the degree of fractionation (Halliday *et al.*, 1991; Fogliata *et al.*, 2012). The more fractionation degree of Tarusan Pluton is expressed in its higher Rb/Sr ratio and in agreement with its microscopic characteristics and higher A/CNK ratio than Lolo Pluton as discussed above (Table 1, Figure 12a).

Spider Diagrams

In the Lolo Pluton, Rb and K gain the two most enrichments at about 100 times without any depletions, except Ti on one sample, relative to primitive mantle composition (Sun & McDonough, 1989). On the other hand, Tarusan Pluton rocks are P, Eu, and Ti depleted whilst only one sample is indicated with Ti depletion on Lolo Pluton (Figure 13a). Both plutons are characterized by pronouncing negative Ba, Nb, and P anomalies together with positive K and Nd Y anomalies. These anomalies are denoted in some other I-type rocks: Granitoid Complex of Boroujerd - Iran (Khalaji *et al.*, 2007) and Suyunhe Intrusive Complex – China (Shen *et al.*, 2017) as shown in Figure 13b. Moreover, stronger negative Nb anomaly is denoted on the Lolo Pluton whilst bigger P anomaly is denoted at the Tarusan Pluton.

The samples compositions are normalized to chondrite value of Boynton (1984) on drawing the REE spider diagram. Chondrite-normalized REE patterns display a moderate to steep decrease from La to Sm and a slight decrease from Gd to Lu. Four Lightest-REEs (La, Ce, Pr, and Nd) are enriched 10-100 times than chondrite values whilst only 1-10 times HREE enrichments are shown in the studied samples (Figure 14a). The plots of the previous volcanic arc granitoid studies in the Boroujerd Granitoid Complex (Khalaji *et al.*, 2007) and from the West Junggar (Shen et al., 2017) are given in Figure 14b for comparison. The degree of REE fractionations on the rocks are in the medium range with (La/Lu)N 5.5-19.3. Ce and Eu anomalies (Eu/Eu*) were calculated based on the formula from previous studies: Ce/Ce* = CeN/(LaN x PrN)1/2 and Eu/Eu* = EuN/(SmN x GdN)1/2, respectively (i.e. Kaur *et al.*, 2012; Irzon & Baharuddin, 2016). The sample of Lolo Pluton indicates negative Ce anomaly whilst two types of Ce anomalies are detected on the two Tarusan rocks. Ce anomalies in igneous rocks may be caused by inheritance from source rocks or due to the variation of oxygen fugacity in the melt during magma rise and or by post-magmatic alteration/metamorphism (Gao *et al.*, 2016). Since no strong alteration and/or metamorphism indications are noted on the Tarusan Pluton in both field description and petrography analysis, the last process can be ignored. It is most likely that negative Ce anomaly of the more evolved magma in Tarusan Pluton (TR-35 A, SiO_2 = 71.77%) was caused by the increase of oxygen fugacity (fO_2) when the magma rises and emplaces to the surface than the less evolved magma (TR-35 B, SiO_2 = 70.79%), since the increase of oxygen fugacity would induce Ce_3+ into Ce_4+ and cause the depleted in Ce_3+ relative to other REE3+. The two Tarusan Pluton samples depict negative Eu anomaly (0.12-0.02) to conclude plagioclase fractionation. On the other hand, positive Eu anomaly was observed on the only the Lolo Pluton of 1.62 indicating plagioclase accumulation (i.e. Zeng *et al.*, 2017) and describe the different magma evolution process to Tarusan Pluton.

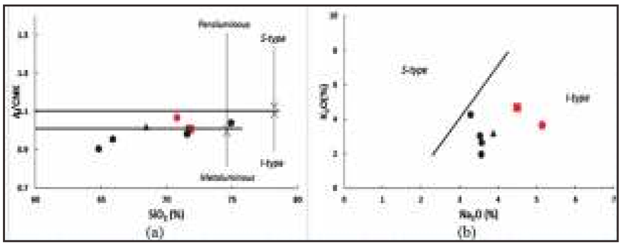


Figure 12. I- and S-type granite discriminations based on a) A/CNK value <1.1; and b) Na_2O versus K_2O ratio. All the studied plutons are clearly classified as S-type. Symbols are the same as Fig.6.

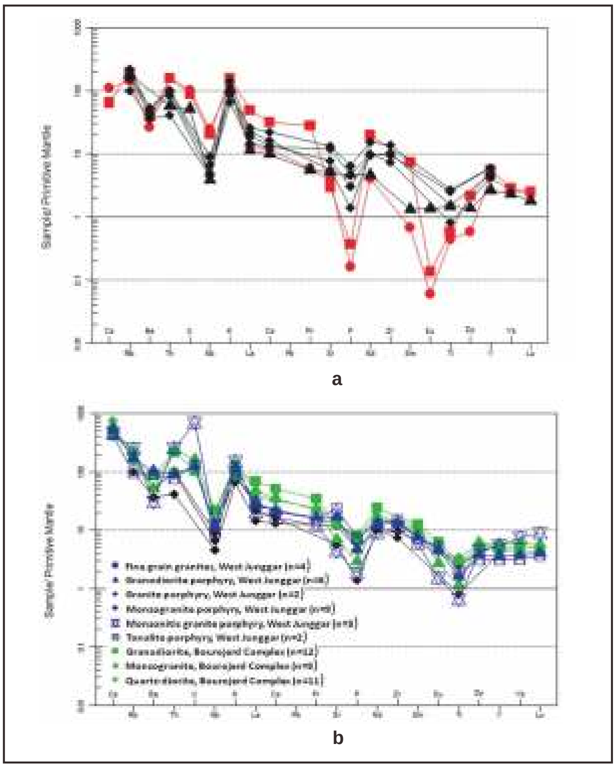


Figure 13. Primitive mantle (Sun and McDonough, 1989) normalized diagrams: a) the studied granite with symbols are the same as Fig.6; b) average composition of granitoid groups in the Boroujerd Granitoid Complex (Khalaji *et al*., 2007) and from the West Junggar (Shen *et al*., 2017).

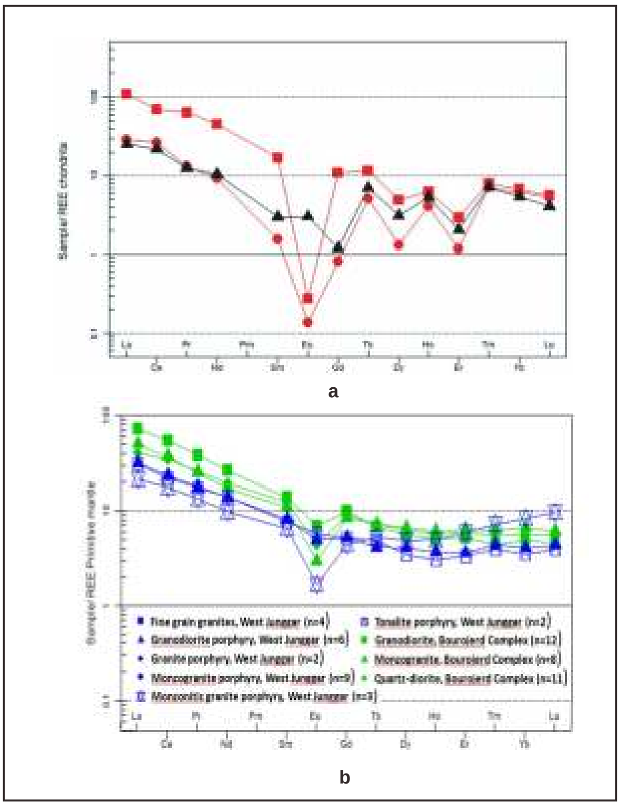


Figure 14. Chondrite (Boynton, 1984) normalized diagrams: a) the studied granite with symbols are the same as Fig.6; b) average composition of granitoid groups in the Boroujerd Granitoid Complex (Khalaji *et al.*, 2007) and from the West Junggar (Shen *et al.*, 2017).

CONCLUSIONS

The microscopic study confirms the granite character of the studied samples. Both the Tarusan Pluton and the Lolo Pluton show I-type calc-alkaline series characters. However, the rocks of the Tarusan Pluton are classified as peraluminous granite whilst Lolo Pluton denotes wider range from metaluminous to peraluminous of granodiorite to granite. Both the plutons are clearly classified as volcanic arc granitoid in the correlation to Volcanic Arc Suite of Sumatra. Another difference is the negative Eu anomaly on the Tarusan Pluton but the positive one at the Lolo Pluton to explain different magma evolution process. The negative Ce anomalies of the more evolved magma than the less one in Tarusan Pluton might be caused by the increase of oxygen fugacity while the magma rises and emplaces to the surface. Petrography and Geochemistry characters of the study imply that the Lolo Pluton might be derived from more mafic magma with a lower differentiation degree than the Tarusan Pluton.

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