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Geochemical Signatures of Potassic to Sodic Adang Volcanics, Western Sulawesi: Implications for Their Tectonic Setting and Origin

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Abstract - The Adang Volcanics represent a series of (ultra) potassic to sodic lavas and tuffaceous rocks of predominantly trachytic composition, which forms the part of a sequence of Late Cenozoic high-K volcanic and associated intrusive rocks occurring extensively throughout Western Sulawesi. The tectonic setting and origin of these high-K rocks have been the subject of considerable debates. The Adang Volcanics have mafic to mafitic-intermediate characteristics (SiO_2: 46 - 56 wt%) and a wide range of high alkaline contents (K_2O: 0.80 - 9.08 %; Na_2O: 0.90 - 7.21 %) with the Total Alkali of 6.67 - 12.60 %. Al_2O_3 values are relatively low (10.63 - 13.21 %) and TiO_2 values relatively high (1.27 - 1.91 %). Zr and REE concentrations are also relatively high (Zr: 1154 - 2340 ppm; Total REE (TREY = TRE): 899.20 - 1256.50 ppm; TRExOy: 1079.76 - 1507.97 ppm), with an average Zr/TRE ratio of ~ 1.39. The major rock forming minerals are leucite/pseudoleucite, diopside/aegirine, and high temperature phlogopite. Geochemical plots (major oxides and trace elements) using various diagrams suggest the Adang Volcanics formed in a postsubduction, within-plate continental extension/initial rift tectonic setting. It is further suggested magma was generated by minor (< 0.1 %) partial melting of depleted MORB mantle material (garnet-lherzolite) with the silicate melt having undergone strong metasomatism. Melt enrichment is reflected in the alkaline nature of the rocks and geochemical signatures such as Nb/Zr > 0.0627 and (Hf/Sm)PM > 1.23. A comparison with the Vulsini ultrapotassic volcanics from the Roman Province in Italy shows both similarities (spidergram pattern indicating affinity with Group III ultrapotassics volcanics) and differences (nature of mantle metasomatism).

Keywords: Adang Volcanics, sodic and potassic/ultrapotassic, within-plate continental extension/initial rift, metasomatized silicate melts, leucite/pseudoleucite

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Introduction

Large parts of the Western Sulawesi Province are covered by thick (up to 5000 m) piles of Upper Cenozoic shoshonitic to ultra-potassic and subordinate sodic volcanic rocks together with associated intrusives and volcaniclastics. he volcanic rocks occurring in the central part of the province have been subdivided into four units, these are Sekala Formation, Sesean, Adang, and Talaya Volcanics (Ratman and Atmawinata, 1993). The Adang Volcanics are the subject of

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this paper. Their locations are shown in Figure 1. The unit consists of a sequence about 400 m thick of poorly bedded leucite-bearing lapilli tuff, volcanic breccias consisting of leucite basalt fragments embedded in leucite-bearing tuffaceous matrix, and leucite basalt flows (Ratman and Atmawinata, 1993). Major element analyses carried out previously on a number of samples suggest the Adang Volcanics are mafic to intermediate in composition, ranging from trachyte to tephrite and phonolite (Sukadana *et al*., 2015). Waele and Muharam (2014) describe the rocks as phlogopitic and leucitic volcanic rocks. The Adang Volcanics interfinger with the marine sedimentary Mamuju Formation, which has a latest Miocene to Early Pliocene age (Ratman and Atmawinata, 1993), and have yielded K/Ar ages of 5.4 and 2.4 Ma (Bergman *et al*., 1996). The morphology of the volcanics is youthful, showing a volcanic centre and several domal structures (Sukadana *et al*., 2015).

Opinions differ regarding the origin of these and other high-K rocks in the province:

1. Magmatism took place in a postsubduction, continental-margin rift setting with the source mantle having been metasomatized by previous subduction processes (e.g. Yuwono *et al*., 1985; Leterrier *et al*., 1990);
2. The volcanic rocks were formed in an Active Continental Margin (ACM) setting in which magma was generated from mantle melting in the final stage of the subduction process (Puspita *et al*., 2005), which involved subduction of microcontinental crust (Sukadana *et al*., 2015);
3. The volcanics developed as the result of collision between the Banggai-Sula fragment and western Sulawesi (Bergman *et al*., 1996).

The goal of the research is to deduce from the magmatic typology of the Adang Volcanics, their tectonic setting, and the nature of submantle enrichment, using the geochemical approach. The studied area is defined by the following coordinates 118°45’11.10”E - 119°5’13.41”E and 2°33’28.27”S - 2°59’34.52”S, covering the Subregencies of Kalukku, Mamuju, Tabulahan, Simboro, Tapalang, and Malunda.

Materials and Methods

For this purpose, six outcrop samples (locations shown on Figures 1a, b, and 2) were sub-

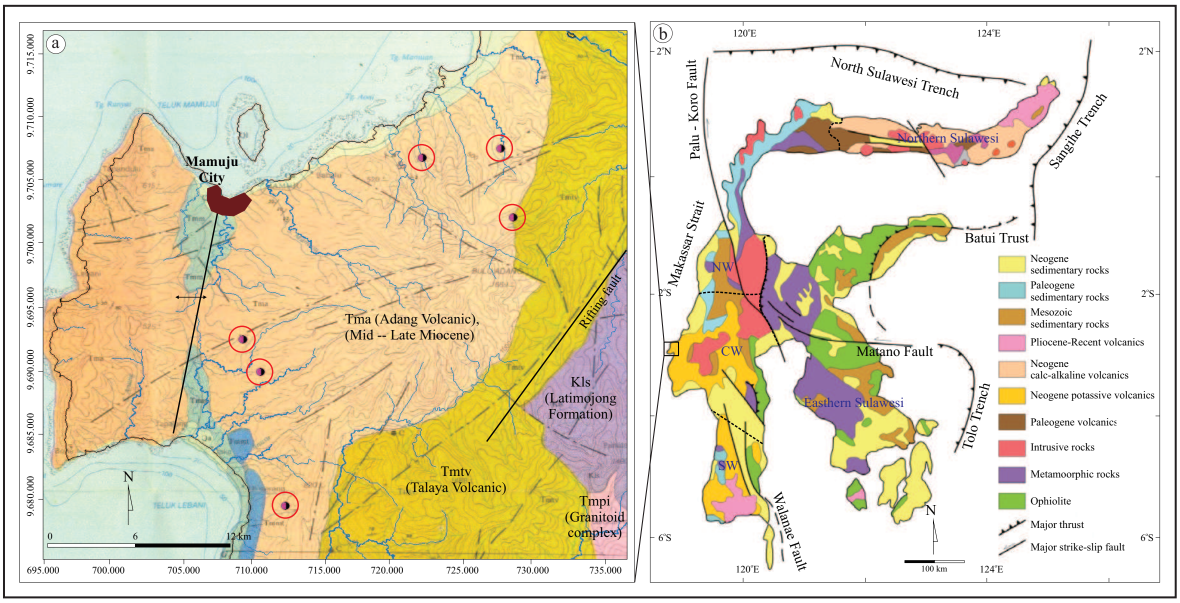

Figure 1. (a). Geological map of central Western Sulawesi (Ratman and Atmawinata, 1993) showing the location of the researched area and the six samples described in the text. Coordinate system UTM Zone 50S; (b). Simplified geological map of Sulawesi (modified after Sukamto, 1975b; Hamilton, 1979; Silver *et al*., 1983; Parkinson, 1991, *in* Van Leeuwen and Pieters, 2011). Western Sulawesi (dashed line) subdivided into NW (northwest; north part of Western Sulawesi), CW (central-west), and SW (southwest) Sulawesi.

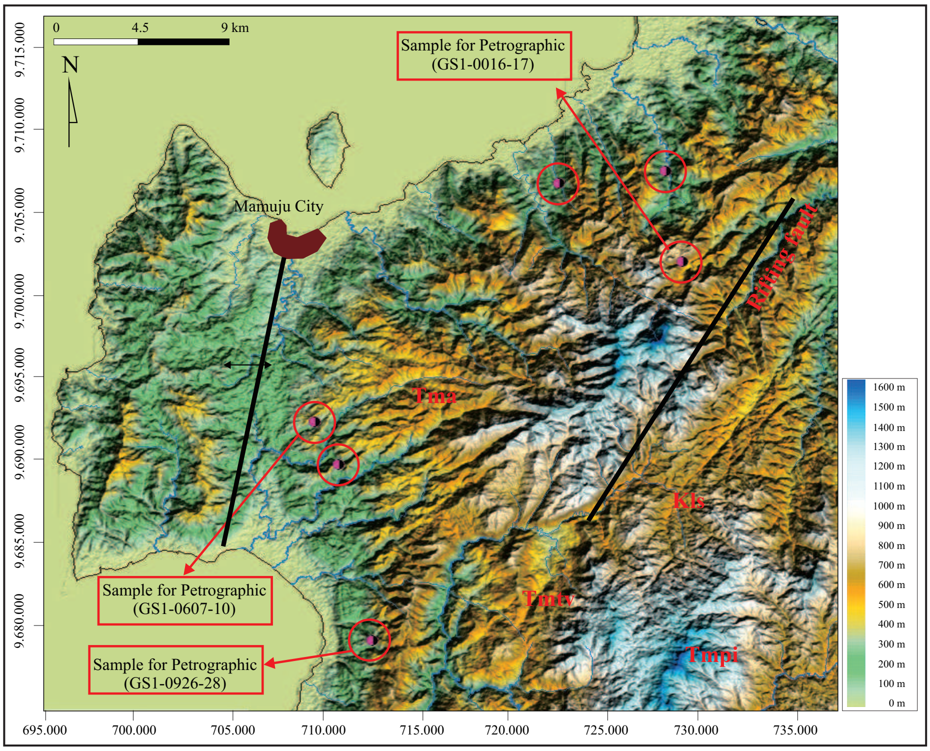

Figure 2. Image of DEM-SRTM (ASTER 30m) and the position of sampling points.

jected to major oxide, trace element, and rare earth element (REE) analyses (Tables 1 and 2). The rocks were petrographically also studied in order to support the interpretation of the geochemical data. Geochemical analyses involved XRF and four acids digest (ICP-OES/MS, ICP-REE) assay methods, which were carried out at Intertek Laboratories in Jakarta and Perth. In addition, trace element data have been plotted on various diagrams previously obtained from 31 company drill core samples, and major oxide data for 36 previously analyzed outcrop samples for which LOI contents were not determined. These samples were also analyzed in the Intertek Laboratories.

Field Relationships

The field and petrologic observations indicate that the Adang Volcanics, covering an area of ~820 km^2 (Ratman and Atmawinata, 1993), are composed predominantly of leucite/pseudoleucite-bearing trachytic tuff, lapilli-tuff, agglomerate, volcanic breccia, volcanic-sedimentary products (volcaniclatics consisting of trachytic weathering residue, trachytic fragments), volcaniclastics and lava intercalations of mafic/mafitic-intermediate composition (consisting of leucite/pseudoleucite, diopside/aegirine and high temperature phlogopite). Other rocks observed locally include peralkaline dyke, a mafic trachyte body, multiple dykes of mafic and leucitic intrusions, subvolcanic sanidine trachyte intrusion, intercalations of crystalline limestone, and other carbonate rocks. The limestone intercalations and the presence of pillow lavas indicate the Adang Volcanics were deposited in a marine environment. Figures 3 and 4 show how the volcanics occur in the field.

Analytical Results

The mineralogy of three samples in thin secton is shown in Figures 5 - 7. Moreover, major and trace element results for the six samples presented in Tables 1 and 2 respectively have a Mafic Index of Alteration (MIA(o)) ranging from 31.6 to 45.9 (Figure 8). This suggests that all six samples were

Table 1. Major Oxides (wt%) of Six Samples (Adang Volcanics)

No Sample_code	28 GS1-0016-17	75 GS1-0481-85	82 GS1-0533-36	99 GS1-0607-10	121 GS1-0280-86	1002 GS1-0926-28
Rock_types	**Fine Trachyte**	**Mafic Trachyte**	**Leucitic Trachyte**	**Mafic Trachyte**	**Mafic Trachyte**	**Fine Trachyte**
Area	**Salu Dango**	**Takandeang**	**Ampalas**	**Botteng**	**Bebanga**	**Tapalang**
SiO_2 (%)	55.48	49.28	54.86	50.79	49.15	53.74
TiO_2 (%)	1.91	1.77	1.27	1.45	1.70	1.70
Al_2O_3 (%)	10.91	10.92	13.21	10.63	11.89	12.10
Fe_2O_3 (%)	11.78	10.80	7.50	9.82	12.80	11.42
FeO (%)	2.15	2.04	2.83	2.04	3.68	1.49
MnO (%)	0.25	0.19	0.12	0.14	0.18	0.14
MgO (%)	2.54	5.87	3.00	6.19	3.53	2.11
CaO (%)	2.03	6.98	3.83	7.25	4.57	3.32
Na_2O (%)	3.52	0.90	5.52	1.40	1.89	7.21
K_2O (%)	9.08	9.03	1.15	7.86	8.16	0.80
LOI (%)	0.90	1.32	5.70	1.21	1.20	4.32
P_2O_5 (%)	0.22	0.86	0.55	0.56	0.46	0.22
Total (%)	**100.76**	**99.96**	**99.54**	**99.34**	**99.21**	**98.56**
TA=Na_2O+K_2O	**12.60**	**9.93**	**6.67**	**9.26**	**10.05**	**8.01**
K_2O/Na_2O	2.58	10.03	0.21	5.61	4.32	0.11
Cr_2O_3 (%)	0.006	0.01	<0.005	0.04	0.04	<0.005
Radiometric	**345 cps**	**255 cps**	**419 cps**	**200 cps**	**250 cps**	**210 cps**

fresh (after Nesbitt and Wilson, 1992), including two samples (No.82 and No.1002) with relatively high LOI contents (4.3 - 5.7 wt%). This is supported by petrographic observations (Figures 7a, b). The Adang Volcanics samples are mafic/ mafitic - intermediate in composition with relatively low SiO_2 contents (46 - 56 wt%). Na_2O and K_2O contents show a wide range of values, 0.90 - 7.21 wt% and 0.80 - 9.08 wt%, respectively. Four of the samples have high K_2O contents (7.86 and 9.08 wt%) and Na_2O contents varying between 0.90 and 3.52 wt%, which classifies these rocks as ultrapotassic (Foley *et al*., 1987). The other two samples have high Na_2O contents (5.52 and 7.21 wt%) and low K_2O values, indicating they have a sodic composition. It is these two samples that also have high LOI contents, possibly indicating the presence of primary volatiles. Al_2O_3 contents are relatively low (10.63 - 13.21 wt%) and TiO_2 contents relatively high (1.27 - 1.91 wt%) (typical of nonsubduction volcanics {TiO_2 > (-1.161 + 0.1935 x Al_2O_3), (in wt%)} (Figure 9) (Muller and Groves, 1993 and 2000).

Zircon concentrations are high (1,154.00 - 2,3440.00), the Total REE (TREY = TRE) ranges between 899.20 and 1256.50 ppm, and TRExOy between 1079.76 and 1507.97 ppm (Table 2). The percentage of LREE is 88.23 % (La–Sm) and that of HREE 11.77% (Eu–Y). The Th/U ratio is ~ 4.32/1, indicating a "Non-Uranium anomaly", based on a Th/U ratio of ~ 3/1 {normal abundance of the earth crust : Th (6 ppm), U (1.8 ppm)} (https://en.wikipedia.org). Relatively high radiometric signatures (200 - 419 cps) may be related to relatively high contents of Zr, K, Th, U, and Ba (Figure 3g).

Interpretation of Results

The analytical results on various diagrams have been plotted in a diagram to classify the Adang Volcanics, and to elucidate their tectonic setting and the processes in the source mantle that led to their formation.

On the TAS diagram of Le Bas *et al*. (1986) most samples (including the 36 other samples)

Table 2. Trace Element Concentrations (ppm) in Six Samples (Adang Volcanics)

No Sample_code	**28 GS1-0016-17**	**75 GS1-0481-85**	**82 GS1-0533-36**	**99 GS1-0607-10**	**121 GS1-0280-86**	**1002 GS1-0926-28**			
Rock_types	**Fine Trachyte**	**Mafic Trachyte**	**Leucitic Trachyte**	**Mafic Trachyte**	**Mafic Trachyte**	**Fine Trachyte**			
Cr	5.00	56.00	30.00	197.00	5.00	5.00			
Cu	128.00	144.00	122.00	104.00	199.00	96.00			
Mn	1,600.00	1,320.00	831.00	965.00	1,150.00	838.00			
Ni	14.00	46.00	35.00	116.00	17.00	11.00			
P	900.00	3,740.00	2,410.00	2,510.00	2,020.00	870.00			
S	90.00	<50	1,330.00	160.00	1,150.00	60.00			
Sc	7.00	21.00	9.00	23.00	11.00	8.00			
Ti	11,300.00	11,000.00	8,030.00	9,180.00	10,100.00	9,650.00			
V	254.00	218.00	177.00	210.00	350.00	319.00			
Zn	162.00	136.00	130.00	133.00	180.00	101.00			
Ag	<0.1	0.30	0.30	0.30	0.50	0.40			
As	17.00	6.00	29.00	5.00	15.00	4.00			
Ba	>5000	2,450.00	4,970.00	4,270.00	>5000	>5000			
Be	34.20	19.80	28.40	25.10	28.30	39.00			
Bi	1.57	1.53	0.72	0.89	2.49	0.95			
Cd	1.36	0.75	0.75	0.83	1.10	1.06			
Co	22.00	33.00	23.00	30.00	28.00	17.00			
Cs	32.30	57.70	50.60	68.20	31.60	214.00			
Ga	21.40	20.20	23.70	20.10	24.30	23.00			
Ge	0.40	0.60	0.40	0.80	0.20	0.60			
Hf	61.50	36.60	35.20	31.90	45.30	47.20			
In	0.07	0.08	0.06	0.08	0.11	0.10			
Li	61.50	33.10	33.30	30.80	52.00	12.60			
Mo	0.30	0.30	1.80	0.40	0.30	0.20			
Nb	192.00	102.00	117.00	94.70	121.00	104.00			
Pb	330.00	143.00	293.00	147.00	313.00	203.00			
Rb	336.00	636.00	614.00	2,126.26	498.00	1,310.00			
Sb	0.60	0.40	1.40	0.70	0.80	0.70			
Re	<0.05	<0.05	<0.05	<0.05	<0.05	<0.05			
Se	<1	<1	<1	<1	<1	<1			
Sn	29.80	18.10	24.00	15.60	25.70	31.00			
Sr	699.00	1,350.00	930.00	1,300.00	1,410.00	769.00			
Ta	10.00	5.83	6.38	4.82	7.30	8.44			
Te	<0.1	<0.1	<0.1	<0.1	0.10	<0.1			
Th	310.00	154.00	266.80	167.80	230.30	324.10			
Tl	4.84	2.66	1.48	3.43	5.52	12.90			
U	62.80	32.60	68.10	45.80	51.30	75.50			
W	3.00	4.50	18.40	3.20	8.60	2.30			
Zr	2,340.00	1,384.00	1,269.00	1,154.00	1,549.00	1,651.00			
							Average	**%**	**REE**
La	277.00	230.60	234.20	194.20	263.60	292.30	248.65	22.28%	LREE= 88.23%
Ce	552.00	445.40	429.70	371.90	513.70	469.00	463.62	41.54%	
Pr	59.60	52.90	47.50	44.30	58.20	63.10	54.27	4.86%	
Nd	194.00	196.60	166.70	159.70	191.20	211.00	186.53	16.71%	
Sm	32.30	32.80	27.40	26.20	33.70	37.70	31.68	2.84%	
Eu	5.80	6.10	4.90	4.70	6.50	7.20	5.87	0.53%	HREE = 11.77%
Gd	21.70	21.80	20.20	18.10	24.40	30.40	22.77	2.04%	
Tb	3.10	3.00	2.70	2.40	3.20	4.00	3.07	0.27%	
Dy	16.30	13.10	12.60	10.90	15.20	19.20	14.55	1.30%	
Ho	2.50	2.10	2.00	1.70	2.60	3.40	2.38	0.21%	
Er	7.10	5.40	5.40	4.90	6.40	8.90	6.35	0.57%	
Tm	0.90	0.80	0.90	0.60	0.90	1.20	0.88	0.08%	
Yb	5.70	4.20	4.60	3.70	5.40	7.40	5.17	0.46%	
Lu	0.70	0.30	0.60	0.60	0.80	1.00	0.67	0.06%	
Y	67.60	61.90	63.20	55.30	69.40	100.70	69.68	6.24%	
TRE	**1,246.30**	**1,077.00**	**1,022.60**	**899.20**	**1,195.20**	**1,256.50**			
TREO	**1,391.46**	**1,202.53**	**1,142.18**	**1,004.26**	**1,334.62**	**1,404.64**			
TRExOy	**1,497.89**	**1,292.80**	**1,228.36**	**1,079.76**	**1,435.94**	**1,507.97**			
TRE_2O_3	**1,464.03**	**1,265.29**	**1,201.96**	**1,056.78**	**1,404.32**	**1,478.70**			
dEu	**0.67**	**0.70**	**0.64**	**0.66**	**0.69**	**0.65**			

*The average values of Th (242.17 ppm) and U (56.02 ppm); average Th/U ratio = 4.32/1, Zr/TRE (avg) = 1.39

Figure 3. Field observation photos of Adang Volcanics. (a) Volcaniclastic rock (consists of trachytic fragments); (b) Boulder of trachyte lava; (c) Crystalline limestone; overlies the Adang rocks, indicating that it formed after volcanic activity had ceased; (d) Intercalation of heavy concentrate-rich sediment in Adang trachytic rock, indicating the volcanics were deposited in a submarine environment (drill sample A07_14-15m); (e) Pyroclastic sodic-rich fine-grained trachyte breccia (East Tapalang region); (f) Peralkaline dyke (silica and alumina undersaturated), sample of fine-grained trachyte No. 28 (GS1-0016-17); (g) Portable Dosimeter (Thermo Scientific tester), showing relatively high radiometric signature (255 cps) of mafic trachyte rock (sample GS1-0481-85, No.75) with low U (32.60 ppm), Th (154.00 ppm), high Zr (1384 ppm), Ba (2450 ppm), high K (K_2O: 9.03 wt% and Na_2O (0.90%); (h) The marine sedimentary rock (clastic carbonate; drill sample M01_14-15m); (i) Magnifier 40x manual close-up of zircon crystal (tetragonal, yellow), drill sample C03_10-11m; (j) Magnifier 40x manual close-up of green diopside (monoclinic) in leucite trachyte; (k) Leucite trachyte (drill sample A29_22-23m) containing zircon crystal; (l) Magnifier 40x manual close-up of zircon crystal (tetragonal, colorless) from (k) leucite trachyte.

plot in the trachybasalt and basaltic-trachyandesite fields (Figure 10). The two sodic samples fall under the basaltic-trachyandesite field, while the remaining "other samples" are in the tephrite and alkali-basalt fields. On the K_2O *vs*. SiO_2 diagram (after Peccerillo and Taylor, 1976) (Figure 11) the Adang Volcanics are represented by three series: potassic alkaline, alkaline, and subalkaline. If the recently developed Godangs Trapezoid Geochemistry Diagram (Godang, 2016) is used which also

Figure 4. Nature of the Adang volcanic rock textures, showing variation in: (a-f) trachytic textures, (g) mafic aphanitic texture (sample GS1-0481-85), (h) 'pelitic like' texture (sample GS1-0926-28), and (i) 'green pelitic like' texture (sample GS1-0016-17).

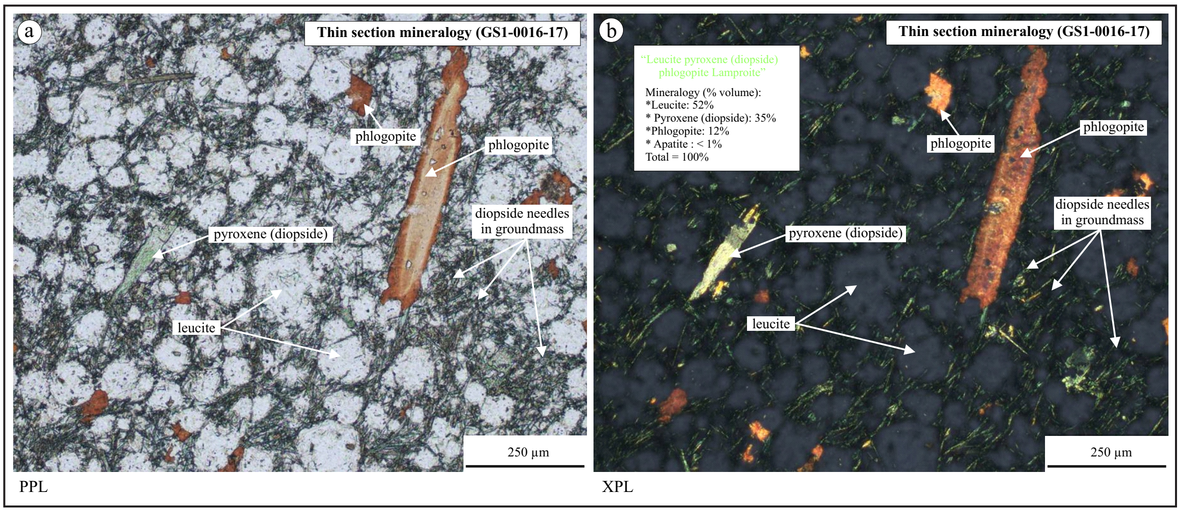

Figure 5. (a) Petrographic (PPL) sample GS1-0016-17 (No. 28; fine-grained trachyte; peralkaline dyke); (b) Petrographic (XPL) sample GS1-0016-17 (No. 28; fine-grained trachyte; peralkaline dyke) showing abundant leucite (52%), interpreted as lamproite.

takes Al_2O_3 and NaO contents into consideration (Figure 12), most of the 43 samples plot in the sodic-series and shoshonitic-series fields, and some in the ultrapotassic-series field. A plot on the Rock Classification Diagram of Pearce (1996), which is based on relatively immobile trace ele-

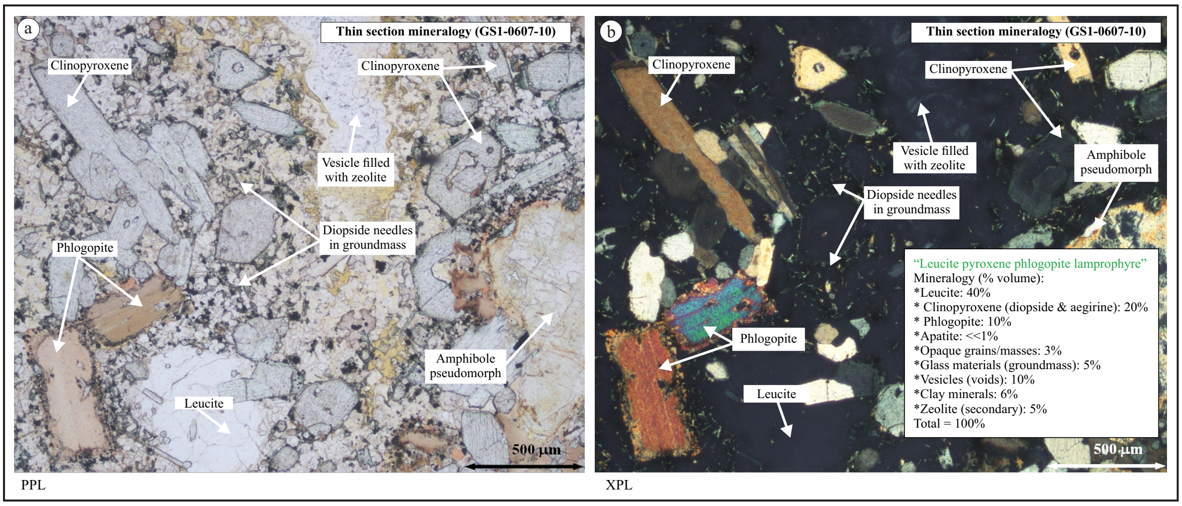

Figure 6. (a) Petrographic (PPL) sample GS1-0607-10 (No. 99; mafic trachyte dyke). (b) Petrographic (XPL) sample GS1-0607-10 (No. 99; mafic trachyte dyke) showing abundant leucite (40%), intrepeted as lamprophyre.

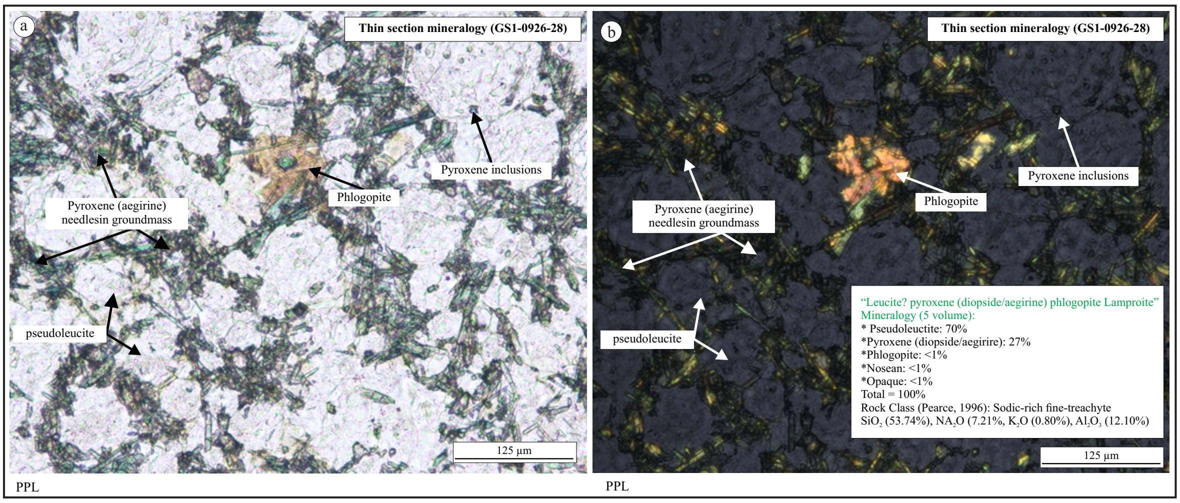

Figure 7. (a) Petrographic (PPL) sample GS1-0926-28 (No. 1002; sodic-rich fine-grained trachyte volcanic breccia) shows clearly unaltered condition. (b) Petrographic (XPL) sample GS1-0926-28 (sodic-rich fine-grained trachyte volcanic breccia) : pseudoleucite (70%): an intergrowth of albite, nepheline, orthoclase; interpreted as lamproite.

ments, indicates that the rocks are of trachyte affinity (Figure 13), consistent with the TAS results.

As a comparison, data for a leucite phonolite have been plotted from the Vulsini Volcano, Roman Province, Italy (Santii *et al*., 2003) on Figure 11, which shows the rock belongs to the ultrapotassic sub-alkaline series (alkaline-calcic character, alumina oversaturated). It should be noted that its alumina content (Al_2O_3: 19.97 - 20.37 %) is significantly higher than that of the Adang Volcanics (Al_2O_3: 10.63 - 13.21 %).

Using the diagram designed by Muller and Groves (1994) to discriminate the tectonic settings of potassic to ultrapotassic rocks, the plotting result shows that the Adang Volcanic samples fall within the anorogenic within-plate field (Figures 9 and 14). In contrast, the Vulsini Volcanics appear to have formed in an arc-related tectonic setting (Alkaline Continental Arc; Supra-subduction Continental Volcanic Arc). Similar settings for the two units are suggested by plots on tectonic discriminant diagrams for mafic rocks using trace elements shown on Figure 15 (after Hollocher *et al*., 2012b) (http://minerva.union.edu), Figure 16 (after Wang *et al*., 2001; modified in this paper), and Figure 17 (after Sun *et al*., 2006; modified in this paper).

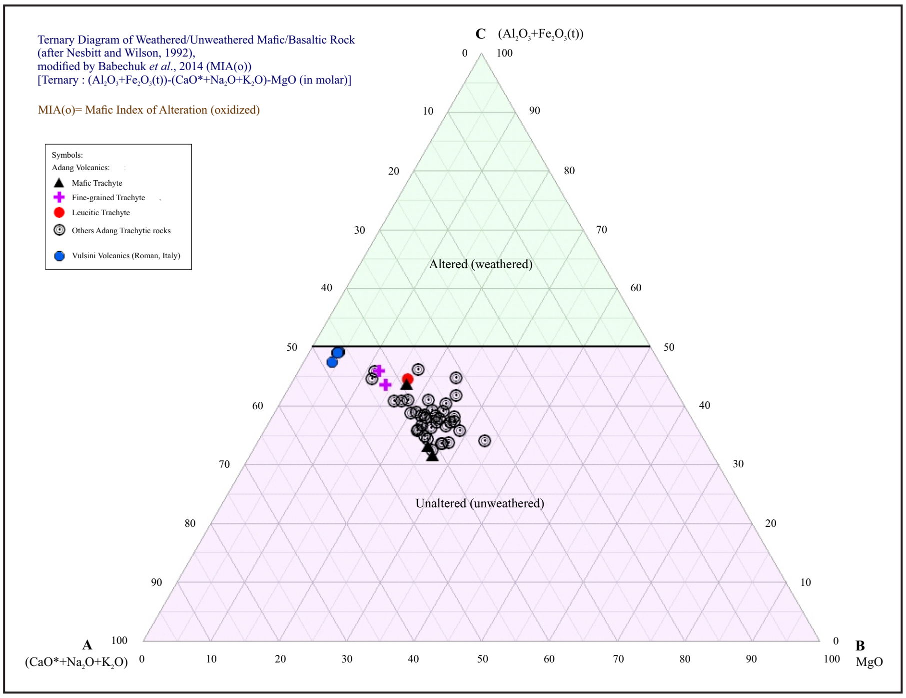

Figure 8. Plots in Ternary Diagram of weathered/unweathered rock (after Nesbitt and Wilson, 1992), showing all Adang Volcanic samples (6), others Adang Trachytic rocks (36 outcrop samples) and Vulsini Volcanic samples (5) are fresh showing unweathered rocks.

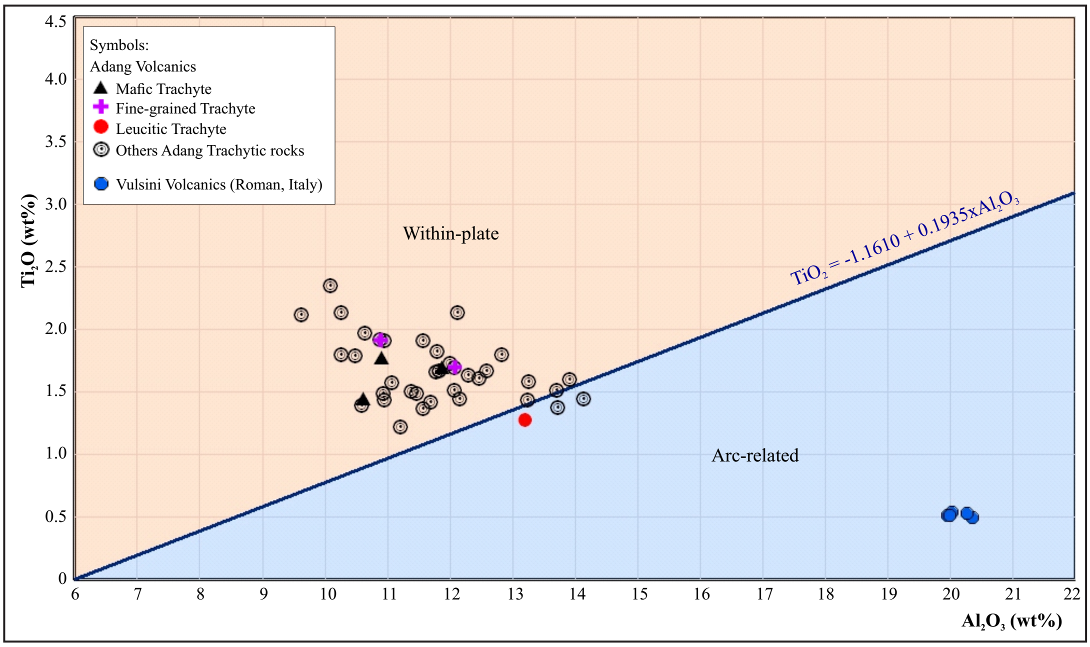

Figure 9. Geotectonic diagram for within-plate *vs.* Arc-related (Muller and Groves, 1993 and 2000) suggesting the Adang Volcanics, others Adang trachytic rocks and Vulsini Volcanic rocks were formed in different tectonic settings.

Figures 18 and 19 are diagrams designed by La Fleche *et al.* (1998) for mafic rocks to identify different metasomatic processes in the mantle. Plots of the six Adang Volcanic outcrop and 31 drill core samples suggest that the rocks were formed by mantle metasomatism during the silicate melting processes, whereas the Vulsini Volcanics were derived from a hydrated mantle

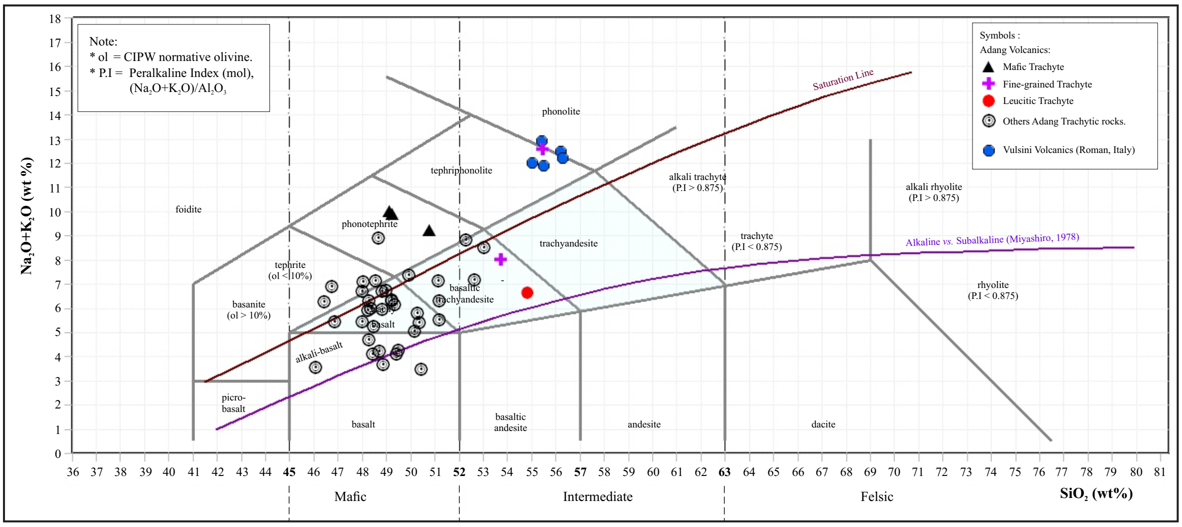

Figure 10. Plot in TAS Diagram (after Le Bas *et al.*, 1986) Vulsini Volcanics show peralkaline magma series (silica undersaturated), whereas Adang Volcanics and other Adang trachytic rocks show subalkaline to peralkaline series.

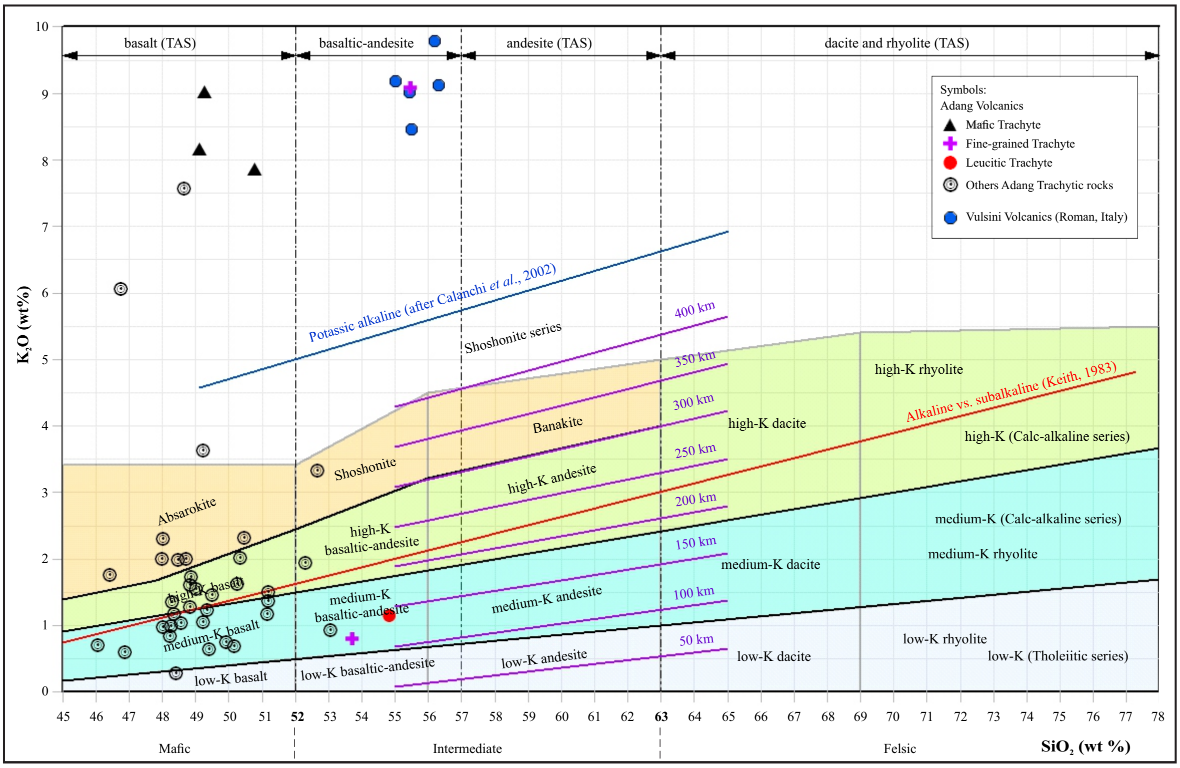

Figure 11. Volcanic rocks classification for orogenic zone (K_2O *vs.* SiO_2, wt%), (Peccerillo and Taylor, 1976). The depth to Benioff Zone 15 (modified by Fadlin and Godang, 2015 (*in* Godang, 2015; after Hatherton and Dickinson, 1969). The plotting result of Vulsini Volcanic (Table 3) shows ultrapotassic rocks whereas the Adang Volcanics and others Adang trachytic rocks showed medium-K calc-alkaline to potassic peralkaline.

source (subduction arc-related). This is reflected in the relatively high Zr and REEs contents (with geochemical signature $(Hf/Sm)_{PM} > 1.23$) of the Adang rocks, and low Zr contents relative to Total REE (with geochemical signature $(Hf/Sm)_{PM} < 1.00$) of the Vulsini volcanic rocks (Table 3).

Figure 20 (diagram after Aldanmaz *et al.*, 2000; modified in this paper) suggests the mantle source from which the Adang Volcanics

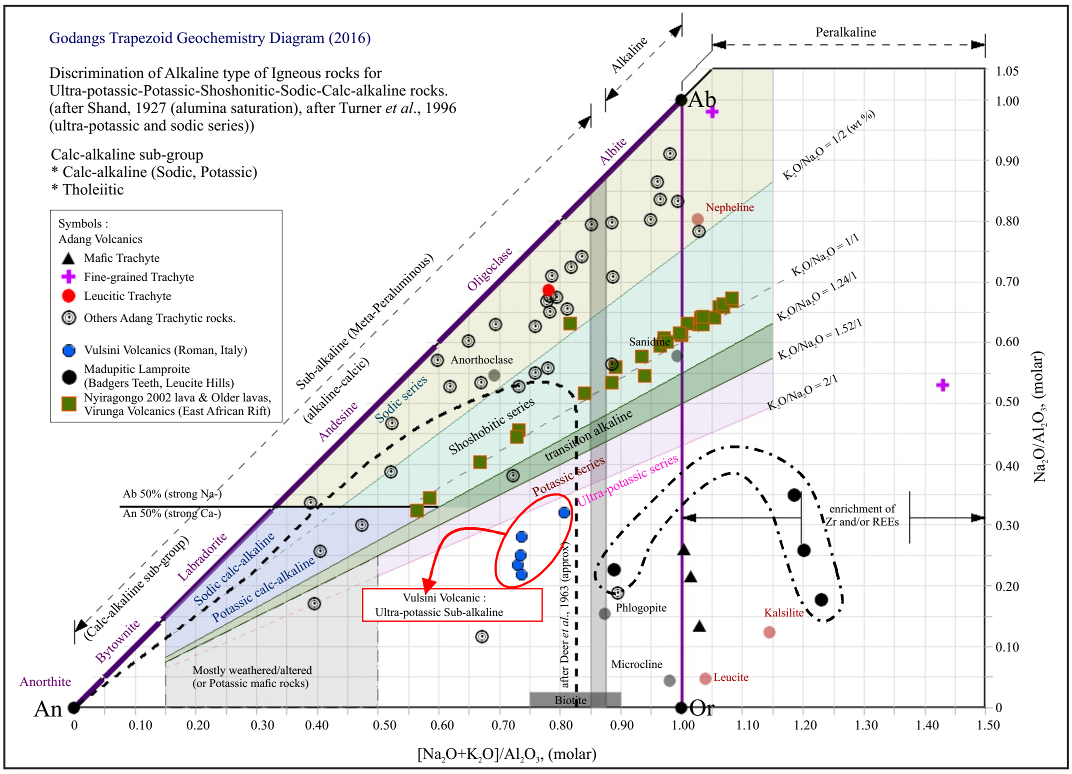

Figure 12. Plots in Godangs Trapezoid Geochemistry Diagram (Godang, 2016). The Vulsini Volcanics show the ultrapotassic subalkaline (alkaline-calcic character, alumina oversaturated; higher Al_2O_3 contents), whereas Adang Volcanics and others Adang rocks show a contrast multimagmatic affinity (sodic series, shoshonitic, potassic, and ultrapotassic with alumina from oversaturated to undersaturated). Madupitic lamproite indicates ultrapotasic alkaline - peralkaline, whilst Virunga Volcanics are shoshonitic subalkaline - alkaline - peralkaline.

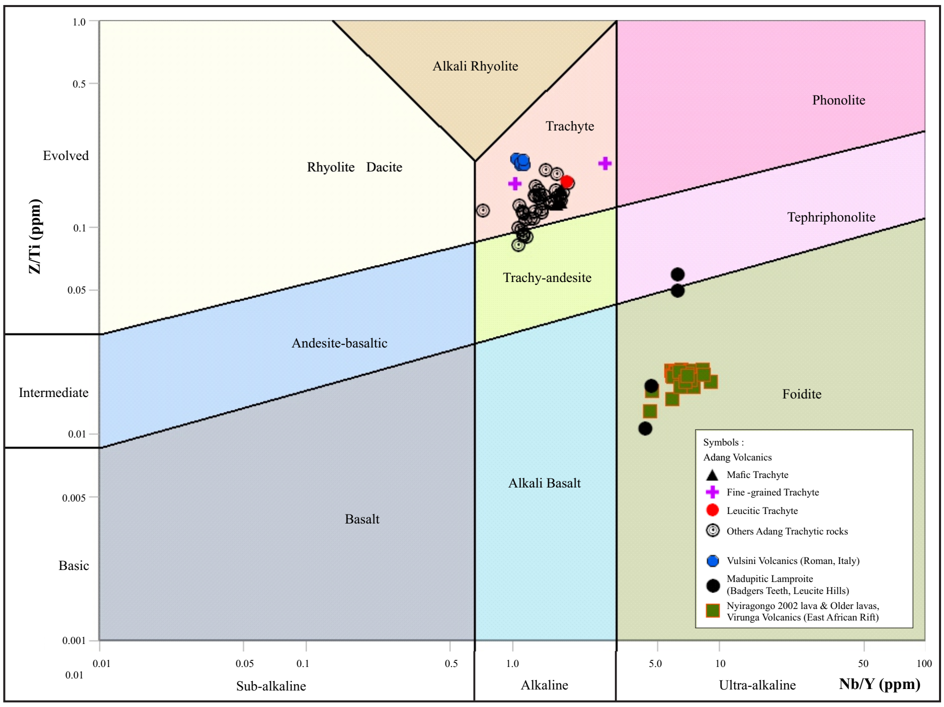

Figure 13. Rock Classification Diagram (Pearce, 1996) showing Adang Volcanics, others Adang trachytic rocks and Vulsini Volcanics to have trachytic composition, whereas Virunga Volcanics (East African Rift) and Madupitic lamproite (Leucite Hills) showing the foiditic composition.

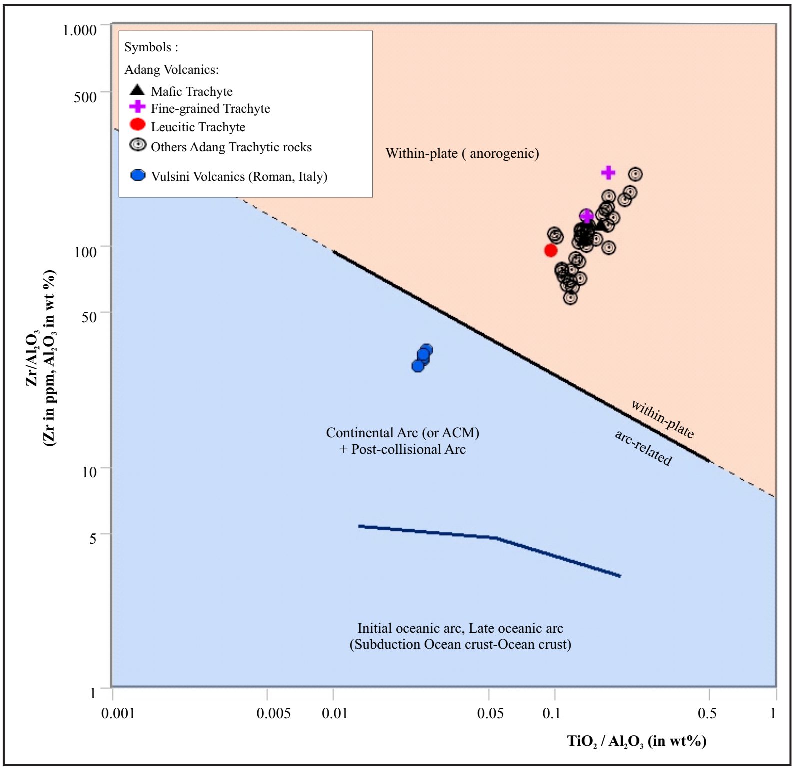

Figure 14. Tectonic discrimination diagram for high-K igneous rocks (Muller and Groves, 1994) suggesting the Adang Volcanics, other Adang trachytic rocks were formed in different tectonic settings.

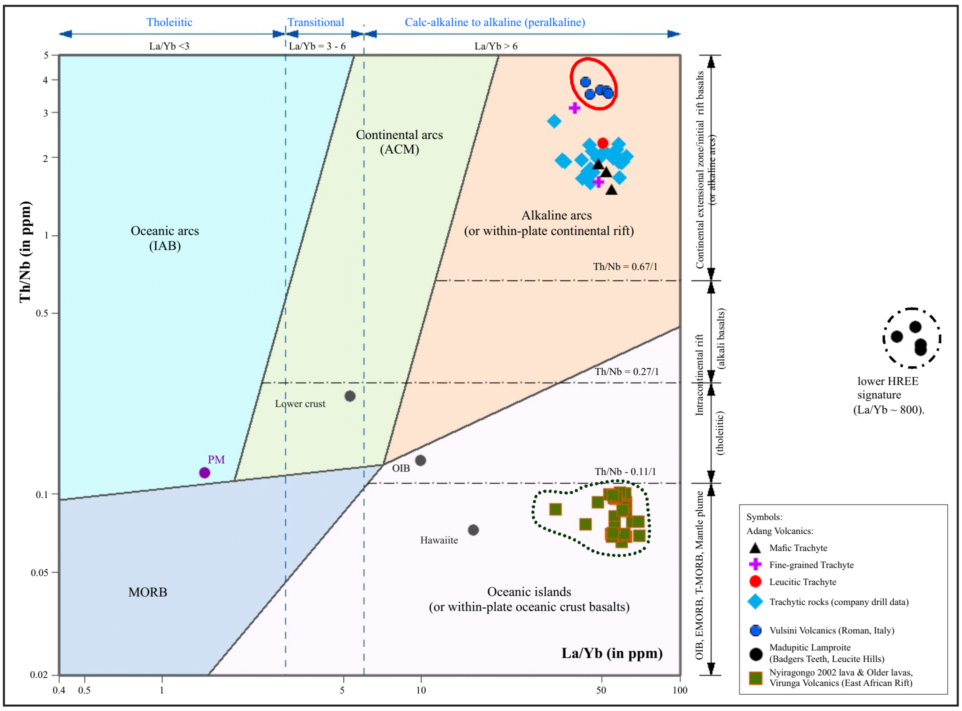

Figure 15. Tectonic discrimination diagram for Basalts (after Hollocher *et al.*, 2012b). Magmatic Affinity: ratio La\Yb for Tholeiitic--Transitional--Calc-alkaline to Alkaline (MacLean and Barrett, 1999), ratio Th/Nb (after Sun *et al.*, 2006). Plot in Figure 15 and overlaying with Figure 14, the result showed Adang Volcanics were formed in within-plate continental extension zone/initial rift and Vulsini Volcanics formed in alkaline arcs, whereas Virunga Volcanics (East African Rift) were formed from within-plate oceanic island and the magma is possible generated from 'mantle plume'? Madupitic lamproite (Leucite Hills) shows a lower HREE signature (La/Yb ~ 800).

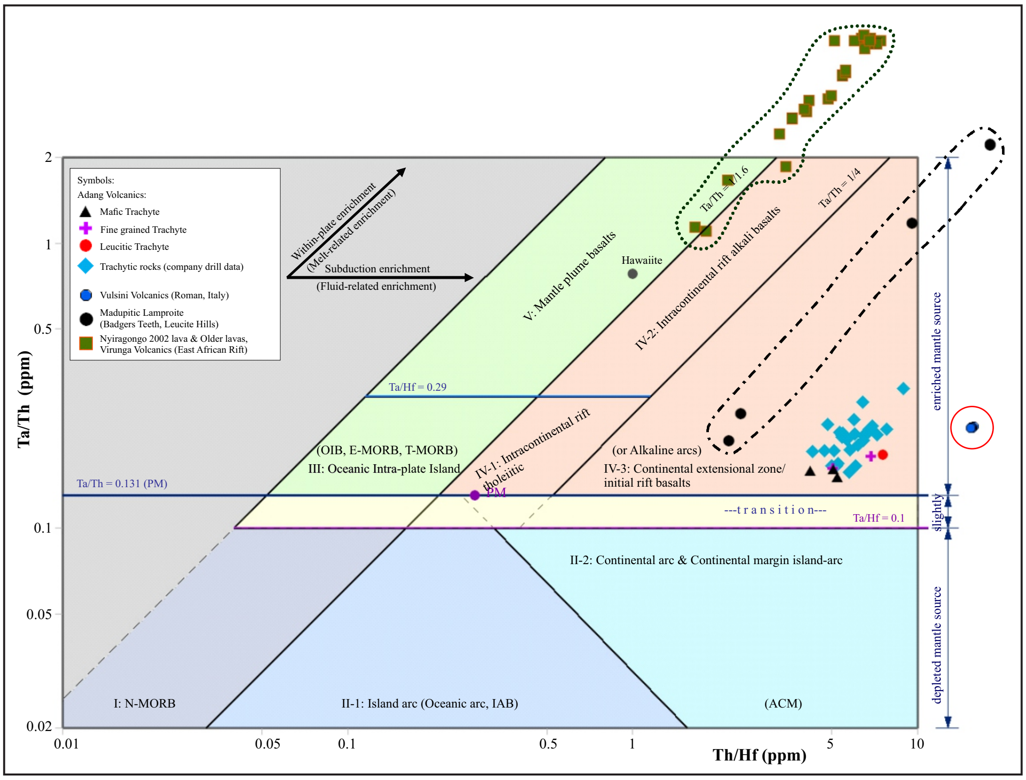

Figure 16. Tectonic discrimination diagram for basalts (after Wang *et al*., 2001; modified in this paper). Overlaying with Figure 14 suggesting the Adang Volcanics were formed in within-plate continental extension zone/initial rift, Vulsini Volcanics were formed in an arc-related (alkaline arcs; supra-subduction continental volcanic arc) and Virunga Volcanics were formed in mantle plume.

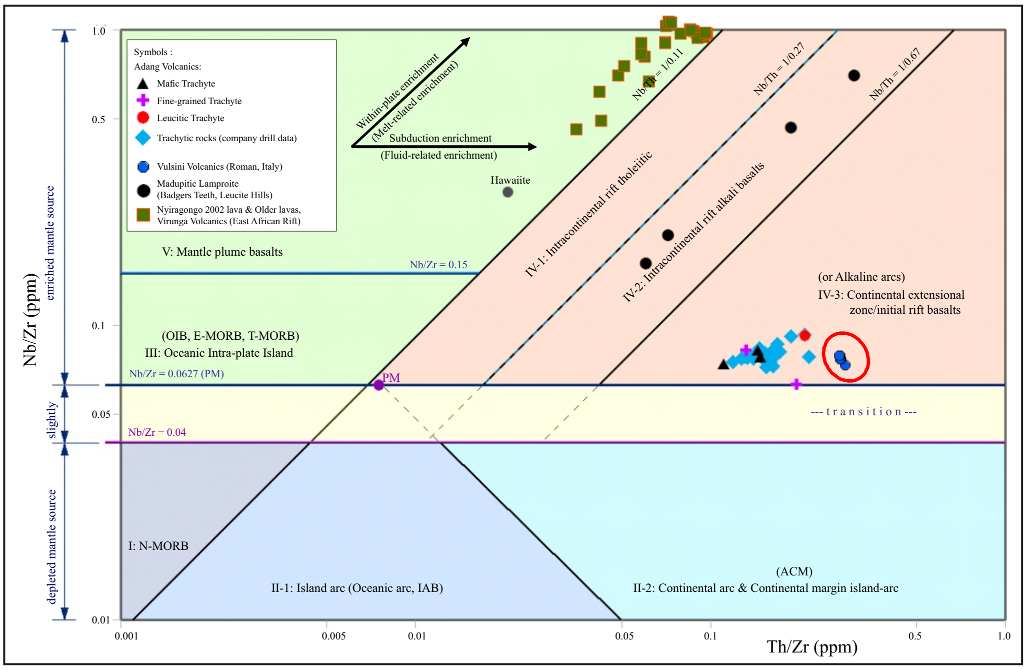

Figure 17. Tectonic discrimination diagram for basalts (after Sun *et al*., 2006; modified in this paper). Overlaying with Figure 14 suggesting the Adang Volcanics were formed in within-plate continental extension zone/initial rift, Vulsini Volcanics was formed in an arc-related (alkaline arcs; supra-subduction continental volcanic arc) and Virunga Volcanics (East African Rift) were formed in mantle plume, but the plot result of Madupitic lamproite (Leucite Hills) showed the difference tectonic setting (after Wang *et al*., 2001 and after Sun *et al*., 2006) is possible indicating to an interaction of two magma sources.

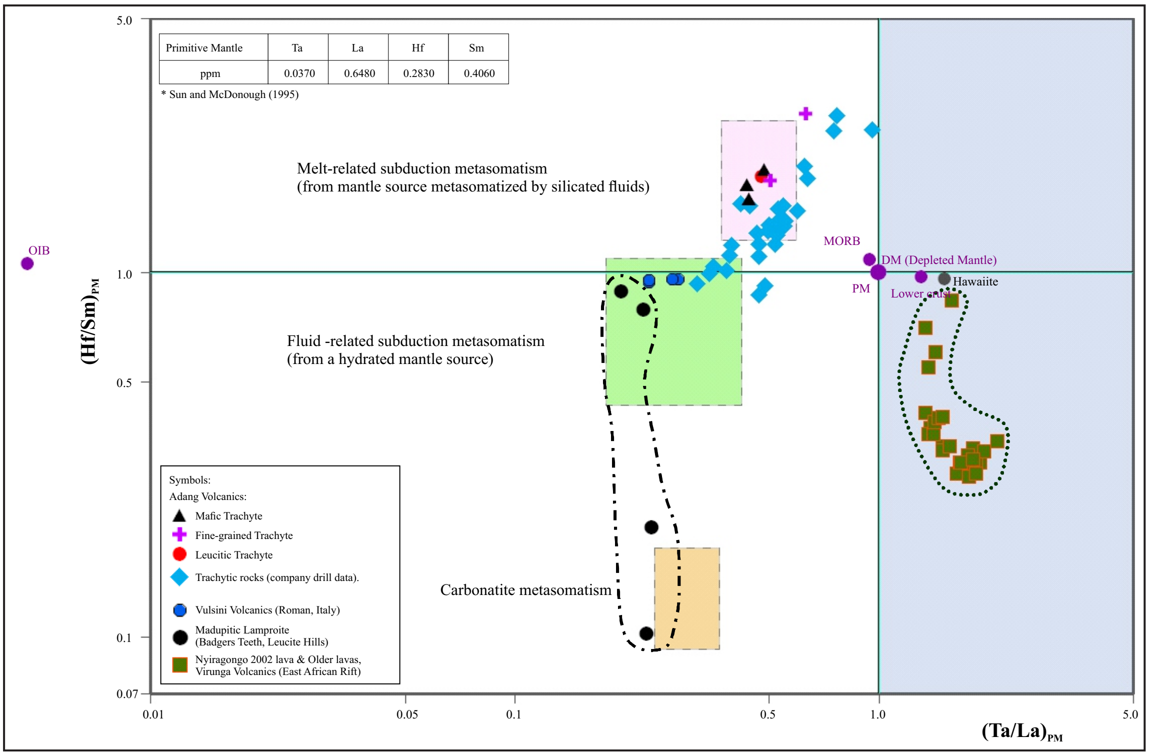

Figure 18. Metasomatism of Mafic Rocks Diagram (La Flèche *et al*., 1998). The plotting result showed Adang volcanics ('Adang Volcanic Complex') were formed by the silicate melt mantle metasomatism + a hydrated mantle source metasomatism process and Vulsini Volcanics was formed by a hydrated mantle source metasomatized, whereas Madupitic lamproite (Leucite Hills) showed forming from a hydrated mantle source + carbonatite metasomatized.

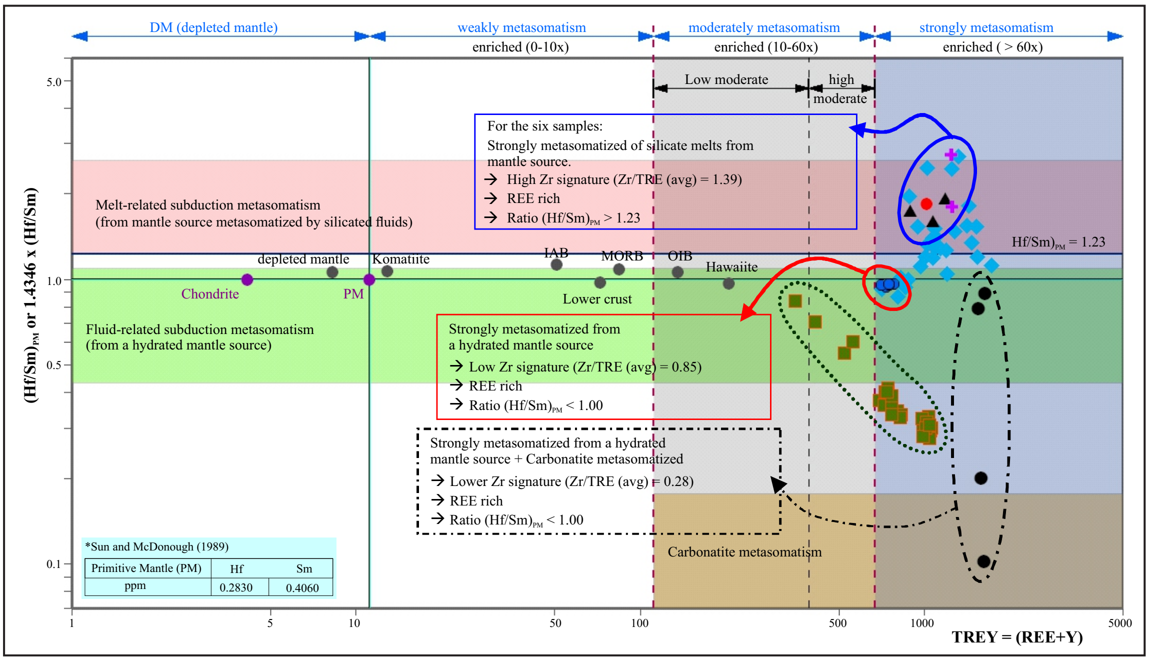

Figure 19. Plot in metasomatism of Mafic Rocks Diagram (after La Flèche *et al*., 1998; modified in this paper) shows Adang Volcanics ('Adang Volcanic Complex') were formed by the silicate melt mantle metasomatism + a hydrated mantle source metasomatism process and Vulsini Volcanics was formed by a hydrated mantle source metasomatized, whereas Madupitic lamproite (Leucite Hills) formed from a hydrated mantle source metasomatism + carbonatite metasomatism (very low HREE signature, Figure 19) and Virunga Volcanics (East African Rift) were formed from moderate to strongly of the hydrated mantle metasomatism process.

Table 3. Major Oxides (%) and Trace Elements (ppm) of Vulsini Volcanics - Roman, Italy (Santi *et al*., 2003)

Code#	#1	#2	#3	#4	#5	Code#	#1	#2	#3	#4	#5
Rock_type	Leucite phonolite	Leucite phonolite	Leucite phonolite	Leucite phonolite	Leucite phonolite	Rock_type	Leucite phonolite	Leucite phonolite	Leucite phonolite	Leucite phonolite	Leucite phonolite
Sample_No#	OSM 1	OSM 2	OSM 3	OSM 4	OSM 7	Sample_No#	OSM 1	OSM 2	OSM 3	OSM 4	OSM 7
SiO_2	55.51	55.03	55.44	56.21	56.31	La	173.00	182.00	189.00	176.00	169.00
TiO_2	0.53	0.51	0.51	0.49	0.52	Ce	345.00	312.00	317.00	304.00	336.00
Al_2O_3	20.04	19.97	20.01	20.37	20.28	Pr	37.30	34.00	34.60	32.20	36.30
Fe_2O_3	4.19	4.08	4.13	3.92	4.18	Nd	124.00	112.00	114.00	106.00	116.00
FeO						Sm	18.40	16.70	16.90	15.70	17.50
MnO	0.14	0.15	0.15	0.15	0.16	Eu	3.67	3.33	3.52	3.26	3.54
MgO	0.77	0.82	0.82	0.82	0.81	Gd	12.30	11.20	11.70	10.80	11.90
CaO	3.81	3.66	3.84	3.66	3.84	Tb	1.56	1.43	1.45	1.37	1.50
Na_2O	3.42	2.83	3.89	2.69	3.07	Dy	8.01	7.28	7.35	6.89	7.62
K_2O	8.46	9.18	9.01	9.78	9.11	Ho	1.47	1.34	1.35	1.26	1.38
LOI	2.34	3.05	1.32	1.93	1.75	Er	4.22	3.74	3.77	3.55	3.93
P_2O_5	0.13	0.13	0.11	0.13	0.13	Tm	0.62	0.55	0.57	0.51	0.57
Total	99.34	99.41	99.23	100.15	100.16	Yb	4.00	3.66	3.60	3.32	3.74
$TA=Na_2O+K_2O$	11.88	12.01	12.90	12.47	12.18	Lu	0.60	0.53	0.54	0.50	0.55
K_2O/Na_2O	2.47	3.24	2.32	3.64	2.97	Y	47.50	42.40	43.80	40.10	45.10
Radiometric	? cps	? cps	? cps	? cps	? cps	TRE	781.65	732.16	749.15	705.46	754.63
V	131.00	130.00	129.00	121.00	129.00	TREO	873.08	817.72	836.73	787.87	842.88
Cr	< 20	< 20	< 20	< 20	< 20	TRExOy	939.94	879.63	899.96	847.68	907.59
Co	6.00	6.00	6.00	6.00	6.00	TRE_2O_3	918.79	860.49	880.52	829.07	886.99
Ni	< 20	< 20	< 20	< 20	< 20	dEu	0.75	0.74	0.77	0.77	0.75
Rb	298.00	395.00	292.00	350.00	294.00	Hf	12.30	10.90	11.20	10.40	11.70
Sr	2,130.00	1,900.00	2,140.00	2,020.00	2,150.00	Ta	2.79	2.44	2.53	2.35	2.62
Zr	677.00	610.00	626.00	584.00	657.00	Pb	183.00	157.00	200.00	217.00	192.00
Nb	49.50	46.60	47.90	45.80	51.40	Th	194.00	170.00	173.00	161.00	180.00
Ba	2,430.00	2,330.00	2,670.00	2,540.00	2,520.00	U	38.40	36.60	34.60	35.30	39.40

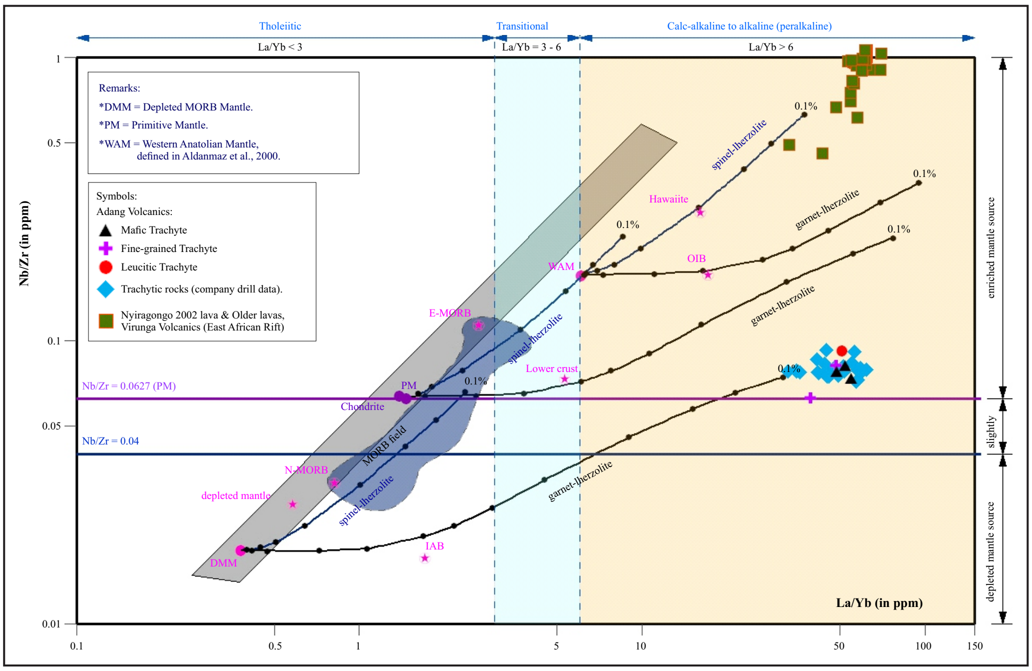

Figure 20. Partial melting curves of mantle source (after Aldanmaz *et al*., 2000; modified in this paper). magmatic affinity: ratio La\Yb (MacLean and Barrett, 1999), Depleted--slightly--enriched Mantle (after Le Roex *et al*., 1983 and after Sun *et al*., 2006), showing the genesis of the Adang Volcanics is related enrichment of DMM (garnet-lherzolite), whereas Virunga Volcanics are related enrichment of WAM (spinel-lherzolite).

are derived was enriched (Nb/Zr > 0.0627) and the magma was generated by small-scale partial melting (< 0.1 %) of Depleted MORB Mantle (DMM) composed of ultramafic (garnet-lherzolite).

Discussion

The results show that the Adang Volcanics are represented by potassic and sodic magma series, and consist predominantly of trachybasalt and basaltic trachyandesite. Furthermore, they indicate that they were formed in a within-plate continental extension/initial rifting tectonic setting after subduction had ceased.

The samples include ultrapotassic rocks. Foley *et al*., 1987 (in Gupta, 2015) have subdivided the within-plate ultrapotassic rocks into four groups, as follows:

1. Group I: Lamproites. These rocks are not readily linked to subduction, although they may occur above a fossil subduction zone. Classic examples are Leucite Hills (Wyoming, USA), West Kimberley, and Gaussberg.
2. Group II: Ultrapotassic rocks of continental rift zones. Included in this group are leucitites, olivine melilities, perovskite, kalsilite, and some micaceous kimberlites. Type localities are in the East African Rift (*e.g.* Virunga Volcanics, Nyiragongo; Cupaello and San Vananzo, Italy).
3. Group III: Ultrapotassic rocks of active orogenic zones. These rocks are a typical feature of many Cenozoic volcanic provinces in the Mediterranean region, including the Roman Province of Central Italy. Group III rocks show a strong association with active or recently active subduction systems.
4. Group IV: which cannot be included in either of the three groups. The type examples of group IV rocks are the potassic rocks of Navajo volcanic field, which lack mantle-derived xenoliths.

The Adang Volcanics clearly belong to Group III based on their spidergram pattern, which is similar to that of the Vulsini volcanic rocks (Figure 21a and b) and other Group III volcanics, which are characterized by distinctly negative spikes in Ba, Nb-Ta, Ti, and P, whereas Rb, Th, and K are strongly enriched (Wilson, 1989). Lamproites of Group I and Group II rocks show a very different pattern (Figure 21b; Wilson, 1989). These differences may be caused by different genesis or metasomatism processes. Lamproites of Group I (*e.g.* Leucite Hills rocks) were formed from mixing between melts from metasomatized hydrated mantle and carbonatite sources (the rocks have a lower Zr/TRE and very low HREE signatures) (Figures 19 and 21b) and Group II rocks {*e.g.* Virunga Volcanics (Nyiragongo, East African Rift)} have a genesis from related enrichment of the Western Anatolian Mantle (WAM) from mantle material spinel-lherzolite (Figure 20). While the patterns shown by the Adang and Vulsini volcanics are very similar, it should be noted that the Adang rocks are more strongly enriched in Zr and Hf (~110–222x) than the Vulsini volcanic rocks (Zr 56x and Hf 38x). This difference can be explained by authors' interpretation that the high Zr-Hf signature displayed by the Adang Volcanics is the result of enrichment of the silicate melt from a source within the mantle itself, whereas the relatively low Zr-Hf signature of the Vulsini volcanic rocks is linked to metasomatism by a hydrated mantle source (see above; Figure 19).

Over the years a number of models have been proposed for the tectonic setting and origin of the Late Cenozoic potassic to ultrapotassic volcanics and associated intrusives in Western Sulawesi. Most favour a post-subduction, within plate extensional setting (cf. Maulana *et al*., 2016), consistent with authors' findings, which some authors based on similarities with the high-K volcanics in the Roman Province (Leterrier *et al*., 1990). It is generally assumed that the magmas were derived from mantle previously metasomatized by one ore more subduction events. As mentioned above, the result suggests, however, the magma that generated (at least part of) the Late Cenozoic volcanics in Western Sulawesi was metasomatized in a different way.

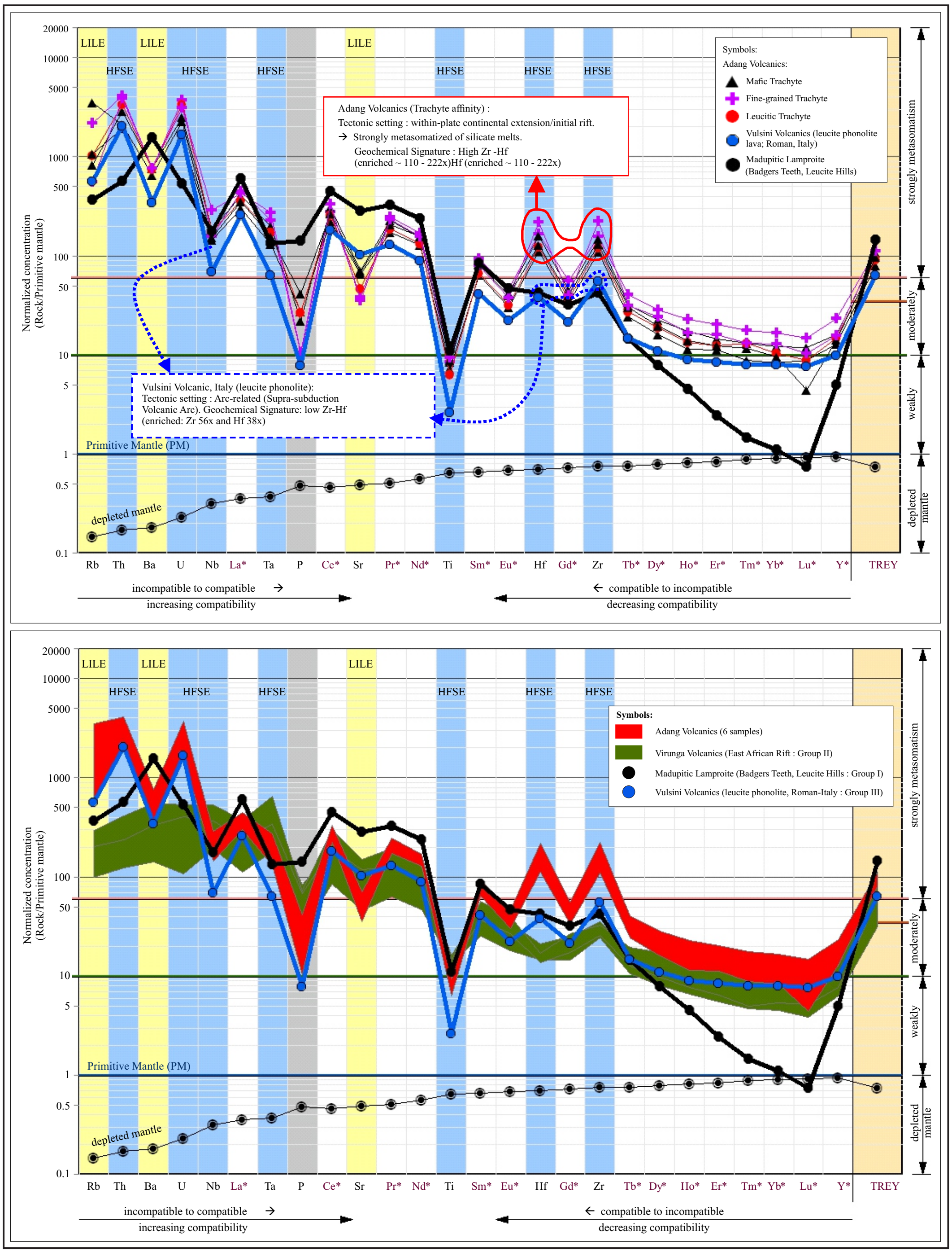

Figure 21. (a) Incompatible to compatible multitrace elements diagram Normalized to Primitive Mantle (the inco patibility sequence: after Zhang, 2014; depleted‒weakly‒moderately‒strongly metasomatism: after La Flèche *et al*., 1998 (Figure 19); modified in this paper) showing plots of the Adang Volcanics, Vulsini Volcanics (leucite phonalite), and Madupitic lamproite (Leucite-Hills); (b) Plots of the Adang Volcanics, Group I (Madupitic lamproite, Leucite-Hills), Group II (Virunga Volcanics: Nyiragongo, East African Rift system) and Group III (Vulsini Volcanics: leucite phonalite, Roman-Italy).

Conclusion and Suggestion

The main conclusion of this study, involving petrographic and geochemical analyses, the results of which have been plotted on a series of diagrams, is that the Adang Volcanics consist of (ultra) potassic to sodic rocks of predominantly trachytic composition, that were formed by minor partial melting (<0.1 % by volume) which has been enriched DMM (Depleted MORB Mantle) of garnet-lherzolite composition. Metasomatic processes accompanying silicate melting caused the strong enrichment in Na, K, Zr, and REEs (with a geochemistry signature of (Hf/Sm)PM > 1.23). The magmatism that gave rise to the Adang volcanic complex took place during a within-plate rifting event. The presence of both potassic and sodic volcanic rocks possibly indicates magma was generated from more than one mantle reservoir.

It would be of great interest to carry out a comparative study on the ultrapotassic leucite/pseudoleucite-bearing volcanics from Gunung Muria and Bawean Island (Central Java) with the aim to establish whether or not those rocks were formed by similar processes as the Adang Volcanics and in a similar tectonic setting. It is further recommend to carry out U/P zircon dating on a suite of representative samples from the Adang Volcanics in order to better constrain the age of this unit, including the temporal relationship between the potassic and sodic series.

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References

Aldanmaz, E., Pearce, J.A., Thirlwall, M.F., and Mitchell, J.G., 2000. Petrogenetic evolution of late Cenozoic, post-collision volcanism in western Anatolia, Turkey. *Journal of Volcanology and Geothermal Research* 102 p.67-95. Elsevier. DOI: 10.1016/S0377-0273(00)00182-7

Aldanmaz, E., Koprubasi, N., Gurer, O.F., Kaymakci, N., and Gourgaud, A., 2006. Geochemical constraints on the Cenozoic, OIB-type alkaline volcanic rocks of NW Turkey : Implications for mantle sources and melting processes. *Lithos* 86 p.50-76, Elsevier. DOI: 10.1016/j.lithos.2005.04.003

Anthony R., Philpotts, and Ague, J.J., 1989. *(2nd edition): Principles of Petrography of Igneous and Metamorphic Rocks*. Cambridge University Press (Fig. 15.10 : Depth to Benioff zone, Hatherton and Dickinson, 1969. DOI: 10.1017/CBO9780511813429

Babechuk, M.G., Widdowsonc, M., and Kamber, B.S., 2014. Quantifying chemical weathering intensity and trace element release from two contrasting basalt profiles, Deccan Traps, India. *Chemical Geology*, 363, p.56-75. (modified of Weathering Ternary Diagram of Mafic/Basaltic from Nesbitt & Wilson (1992), MIA(o)). DOI: 10.1016/j.chemgeo.2013.10.027

Bergman, S.C., Coffield, D.Q., Talbot, J.P., and Garrard, R.A., 1996. *Tertiary Tectonic and Magmatic Evolution of Western Sulawesi and the Makassar Strait, Indonesia - Evidence for a Miocene Continent-Continent Collision*. *In*: (eds Hall, R. and Blundell, D. J.(Eds.), Tectonic evolution of Southeast Asia. Geological Society of London, *Special Publication*, 106, p.391-429. DOI: 10.1144/GSL.SP.1996.106.01.25

Deer W.A. and Andrew R., 2001. *(2nd edition). Rock-Forming Minerals: Framework Silicates (Feldspars)*, Volume 4A. Published by The Geological Society. p.46 (Ternary solid solution An-Ab-Or). DOI: 10.1017/CBO9780511813429

Foley, S.F., Venturelli, G., Green, D.H., and Toscani, L., 1987. The ultrapotassic rocks : Characteristics, classification and constraints for petrogenetic models. *Earth Science Reviews*, 24, p.81-134. DOI: 10.1016/0012-8252(87)90001-8

Godang, S., 2015a. Introduction of Godangs Trapezoid Geochemistry for Determining Magmatic Classification, Review & Discussion with Unsoed's Geo-academician & Geo-colleger.

Godang, S., 2015b. Introduction of Godangs Trapezoid Geochemistry for Determining Magmatic Classification, Guest Lecture STT-NAS and AKPRIND (Jogya).

Godang, S., 2016. Godangs Trapezoid Geochemistry Diagram. In preparation.

Gupta A.K., 2015. *Origin of Potassium-rich Silica-deficient Igneous Rocks*. Springer India. p.11(pseudoleucite), p.72-74. DOI: 10.1007/978-81-322-2083-1_2

Hatherton, T. and Dickinson, W.R., 1969. The relationship between andesitic volcanism and seismicity in Indonesia, the Lesser Antilles, and other island arcs. *Journal Geophysical Research* (74), p.5301-5310. DOI: 10.1029/JB074i022p05301

Hollocher, K., Robinson, P., Walsh, E., and Roberts, D., 2012. Geochemistry of amphibolite-facies volcanics and gabbros of the Støren Nappe in extensions west and southwest of Trondheim, Western Gneiss Region, Norway: a key to correlations and paleotectonic settings. *American Journal of Science*, 312, p.357-416. DOI: 10.2475/04.2012.01

https://en.wikipedia.org/wiki/Abundance_of_elements_in_Earth's_crust (ratio Th/U ~ 3)

https://minerva.union.edu/hollochk/c_petrology/discrim/discrim.htm

La Flèche, R., Camiré, G., and Jenner, G.A., 1998. Geochemistry of post-Acadian, Carboniferous continental intraplate basalts from the Maritimes Basin, Magdalen Islands, Québec, Canada. *Chemical Geology*, 148, p.115-136. DOI: 10.1016/S0009-2541(98)00002-3

Le Bas, M.J, Le Maitre, R.W., Streckeisen A, and Zanettin, B., 1986. A Chemical classification of Volcanic Rocks based on the Total Alkali-silica Diagram. *Journal of Petrology*, 27, p.745-750. DOI: 10.1093/petrology/27.3.745

Le Roex, A.P., Dick, H.J.B., Erlank, A.X, Reid, A.M., Frey, F.A., and Hart, S. R., 1983. Geochemistry, Mineralogy and Petrogenesis of Lavas Erupted along the Southwest Indian Ridge Between the Bouvet Triple Junction and 11 Degrees East. *Journal of Petrology*, 24 (3), p.267-318. DOI: 10.1093/petrology/24.3.267

Leterrier, J., Yuwono, Y.S., Soeria-Atmadja, R., and Muary, R.C., 1990. Potassic Volcanism in Central Jawa and South Sulawesi, Indonesia. *Journal Southeast Asian Earth Sciences*, 4, p.171-187. DOI: 10.1016/S0743-9547(05)80011-X

MacLean, W.H., and Barrett, T.J., 1993. Lithogeochemical technique using immobile elements. *Journal of Geochemical Exploration* 48(2), p.109-133. DOI: 10.1016/0375-6742(93)90002-4

Maulana, A., Imai, A., Van Leeuwen, T., Watanabe, K., Yonezu, K., Nakano, T., Boyce, A., Page, L., and Schertsen, A., 2016. Origin and geodynamic setting of Late Cenozoic Granitoids in Sulawesi. *Journal of Asian Earth Sciences*, 124, p.102-125. DOI: 10.1016/j.jseaes.2016.04.018

Muller D. and Groves D.I., 1997 . Potassic Igneous Rocks and Associated Gold-copper Mineralization. *In*: Bhattacharji, S., Friedman, G.M., Neugebauer, H.J., and Seilacher, A.(Eds.), *Lecture Notes in Earth Sciences*, 56, p.143-166. DOI: 10.1007/978-3-662-00920-8_3

Muller, D. and Groves, D.I., 1993. Direct and indirect associations between potassic igneous rocks, shoshonites and gold–copper deposits. *Ore Geology Reviews*, 8, p.383-406. DOI: 10.1016/0169-1368(93)90035-W

Muller, D., and Groves D.I., 2000. *Potassic igneous rocks and associated gold-copper mineralization*, 3rd edn. Springer, Berlin Heidelberg New York. DOI: 10.1017/S001675680135495X

Nesbitt, H., and Wilson, R., 1992. Recent chemical weathering of basalts, *American Journal of Science*, 292, p.740-777. DOI: 10.2475/ajs.292.10.740

Peccerillo, A. and Taylor, S.R., 1976. Geochemistry of the Eocene calc-alkaline volcanic rocks from the Kastamonu area, northern Turkey. *Contributions to Mineralogy and Petrology*. 58, p.63-81. DOI: 10.1007/BF00384745

Pearce, J.A. 1996. *A user's guide to basalt discrimination diagrams. In Trace element geo-*

chemistry of volcanic rocks, applications for massive sulphide exploration, Short Course Notes. (Bailes, A.H., Christiansen, E.H., Galley, A.G., Jenner, G.A., Keith, Jeffrey D., Kerrich, R., Lentz, D.R., Lesher, C.M., Lucas, S.B., Ludden, J.N., Pearce, J.A., Peloquin, S.A., Stern, R.A., Stone, W.E., Syme, E.C., Swinden, H.S., Wyman, D.A., (ed). Geological Association of Canada 12, p.79-113.

Puspita, S.D., Hall, R., and Elders, C.F., 2005. Structural Styles of the Offshore West Sulawesi Fold Belt, North Makasar Strait, Indonesia. *Proceedings of Indonesia Petroleum Association, 30th Annual Convention*, p.519-542.

Ratman, N. and Atmawinata, S., 1993. G*eological map of the Mamuju Quadrangle, Sulawesi, scale 1:250.000*. Geological Research and Development Centre, Bandung.

Santi, P., Antonelli, F., Renzulli, A., and Pensabene, P., 2003. Leucite phonolite millstones from the Orvieto production centre: new data and insights into the Roman trade. *Periodico di Mineralogia*, 73, p.57-69.

Shand, S.J., 1927. *Eruptive Rocks*. Thomas Murby, London. 360pp. (Gabbroid, Metaluminous, Peraluminous). DOI: 10.1017/S0016756800103504

Sukadana, I.G., Harijoko, A., and Setijadji, L.D., 2015. Tectonic Setting of Adang Volcanic Complex in Mamuju Region, West Sulawesi Province. *Eksplorium*, 36 (1), p.31-44.

Sun, S.Q., Zhang, C.J., and Huang, R.Q., 2006. The Tectonic Settings Discrimination of the Basalts in the Convergent Margin of Plate by Th, Nb and Zr. *Advances in Earth Science*, 21 (6), p.593-598 (in China Mandarin language). (*modified in this paper by Godang et al*., 2016).

Turner, S., Arnaud, N., Liu, J., Rogers, N., Hawkesworth, C., Harris, N., Kelley, S., Van Calsteren, P., and Deng, W., 1996. Postcollision, shoshonitic volcanism on the Tibetan, plateau: implications for convective thinning of the lithosphere and source of ocean island basalts. *Journal of Petrology*, 37, p.45-71. DOI: 10.1093/petrology/37.1.45

Van Leeuwen, T. and Pieters, P.E., 2011. Mineral Deposits of Sulawesi. *Proceedings of the Sulawesi Mineral Resources*. Seminar MGEI-IAGI

Waele, B.D. and Muharam, 2014. Geological Interpretation of the Mamuju Rare Earth Mineral Prospect, West Sulawesi, Indonesia. *PT. SRK Consulting Indonesia* (Unpublished report)

Wang, Y.N., Zhang, C.J., and Xiu, S.Z., 2001. Th/Hf-Ta/Hf identification of tectonic setting of basalts. Acta Petrol Sin (in Chinese), 17 (3), p.413-421. (*modified in this paper by Godang et al*., 2016)

Wilson, M., 1989. *Igneous Petrogenesis - A Global Tectonic Approach*, published by Harper Collins Academic, London, UK, 466pp. (Chap 12: Potassic magmatism within continental plates, p.375-411). DOI: 10.1007/978-1-4020-6788-4_12

Yuwono, Y.S., Bellon, H., Soeria-Atmadja, R., and Maury, R.C., 1985. Neogene and Pleistocene Volcanism in South Sulawesi, *Proceeding PIT XIV Ikatan Ahli Geologi Indonesia*, Jakarta, p.169-179.

Zhang, Y. X., 2014. Quantification of the elemental incompatibility sequence, and composition of the "superchondritic" mantle. *Chemical Geology* 369, p.12-21. DOI: 10.1016/j.chemgeo.2014.01.012