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Geochemistry Study of Cross-castic Magma Alkalinity Evolution

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Abstract - The discrimination of magmatic alkalinity is a classic study that has never stopped for the past ninety years. Various methodologies have been developed since Shand's classification using the method of alumina saturation to approach silica saturation and the methodology without involving alumina and silica such as K_2O vs. Na_2O and others, while the aim is to find out the evolution of alkalinity during the magmatic differentiation. The classical magmatic alkalinity evolution has been known as a castic magma alkalinity evolution, where the initial magma in the form of magma-X(a) will evolve along the stages of differentiation and remain a derivative of the initial magma {magma-X(a)}. The same philosophy is also explained in the ternary AFM diagram. Is the magmatic differentiation, followed by fractional crystallization, always an evolution of alkalinity based on caste? This question often raises current debates. This study takes the example of cogenetic volcanic and albitites. The application of the cogenetic volcanic using the selected diagram, which is 'Three in one an overlaid diagram'. The output of the diagram presents the differentiation of magma which based on the evolution of Mg-series and Fe-series in a discontinuous branch of Bowen 1922 that can take place the castic and cross-castic, *e.g.* (a) from Mg-series to Mg-series {castic}, (b) from Mg-series to Fe-series {cross-castic}, (c) from high-Mg tholeiitic basalt to calc-alkaline series {cross-castic}, (d) from Fe-series to Fe-series {castic}. While the evolution of magmatic alkalinity based on the continuous branch and refer to Trapezoid model generally occurring a cross-castic, *e.g.* (A) from sodic calc-alkaline to sodic alkaline-calcic, (B) from sodic calc-alkaline to shoshonitic alkaline-calcic, (C) from sodic calc-alkaline to potassic calc-alkaline, (D) from potassic calc-alkaline to shoshonitic alkaline-calcic, (E) sodic alkaline-calcic to sodic alkaline/peralkaline, (F) shoshonitic alkaline-calcic to potassic/ultrapotassic alkaline-calcic (cross-castic in subalkaline), (G) shoshonitic/potassic alkaline-calcic to shoshonitic/potassic alkaline/peralkaline. In this study, Fossa delle Felci volcanics (Italy) shows the evolution of magma from Mg-series to Mg-series, but the evolution of alkalinity of magma reveals the cross-caste (from sodic calc-alkaline to shoshonitic alkaline-calcic). Salak volcanics (Western Jawa) shows the evolution of magma from the Mg-series to Fe-series (cross-castic), and also the cross-castic in the evolution of alkalinity from sodic calc-alkaline to alkaline-calcic. Gothara albitites (India) clearly reveal the sodic-rich alkaline, which the magma generates from the evolution of sodic alkaline-calcic to sodic alkaline without the presence of potassic.

Keyword: cross-castic, Trapezoid model, sodic calc-alkaline, shoshonitic alkaline-calcic, sodic alkaline, albitites, Mg-series, Fe-series

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Introduction

The discrimination of magmatic alkalinity has been the subject of ongoing debate over the past nine decades. Various models have been developed since Shand's classification for peralkaline against calc-alkaline magma (Shand, 1927), including the recent Trapezoid model which was developed by Godang *et al.* (2016) for the classification of (sodic/potassic) calc-alkaline, (sodic/shoshonitic/potassic) alkaline-calcic, alkaline, and peralkaline igneous rocks.

Determination of magmatic alkalinity can be done using the alumina saturation method (Shand, 1927 and 1943; Whalen *et al*., 1987), silica saturation (Peacock, 1931; Rittmann, 1957, 1962; MacDonald and Katsura, 1964; Miyashiro, 1978; Peccerillo and Taylor, 1976; Keith, 1983; Frost *et al*., 2001; Calanchi *et al*., 2002), K_2O *vs*. Na_2O without involving the alumina and silica saturation (Middlemost, 1975; Turner *et al*., 1996), and a combination of alumina and/or silica saturation with K_2O and Na_2O {Wright, 1969 and Fadlin *et al*., 2018 (add CaO); Ishihara and Murakami, 2004; Godang *et al*., 2016}(Figure 1). The classic magmatic alkalinity evolution is where the initial magma in the form of magma-X(a) will evolve along the stages of differentiation and remain derivatives of the initial magma {magma-X(a)} (see in Figure 2). The same philosophy is also explained in the ternary AFM diagram as proposed by Irvine and Baragar, 1971 (in Wilson, 1989). The classic magmatic alkalinity evolution in this study is referred to as "castic magma alkalinity evolution". Is the magmatic differentiation, which is followed by fractional crystallization, always an evolution of alkalinity based on caste? This question often raises the current debates. The term of caste is adopted from Hinduism, and the castic pertains to the caste. The ternary Jensen cationic model (Jensen, 1976) is one model diagram that presents a quite different definition, that there are two types of tholeiitic namely high-Mg tholeiitic basalt (primary magma) and high-Fe tholeiitic basalt (differentiated magma). High-Mg tholeiitic basalt will evolve into calc-alkaline series ('cross-castic'), whereas high-Fe tholeiitic basalt will evolve into tholeiitic series. Aso volcanic rock (Kyushu arc, SW Japan) is one of the cases where Hunter (1998) clearly mentioned that the dominantly tholeiitic magma evolved into dominantly calc-alkaline (see also the compilation geochemistry data from Shibata *et al*., 2013). A similarity also occurs at the Okinawa Trough volcanic rock (active back-arc basin, East China Sea; Ishizuka *et al*., 1990). Another review, in which the single chain of evolution of the plagioclase during the magmatic differentiation explains the similar philosophy that the cross-castic alkalinity evolution of (calc-alkali)-plagioclases to (alkali-calcic)-plagioclases (origin of Bowen, 1922, p.190; see also in Figure 3).

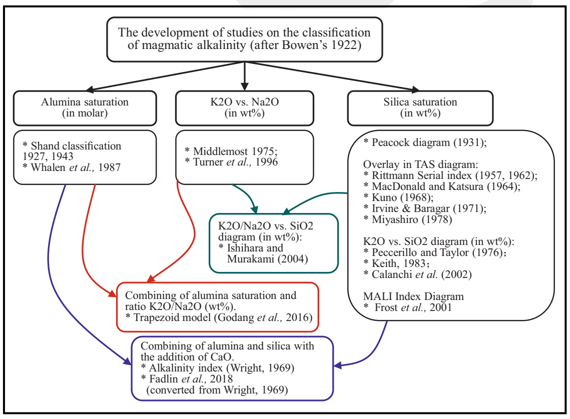


Figure 1. The development of studies on the classification of magmatic alkalinity.

The aim of this geochemistry study is to provide a clearer picture of the magmatic alkalinity evolution in the continuous branch of Bowen (1922) and the magma evolution of Mg-series and Fe-series in a discontinuous branch. The methodologies use multi-discrimination of alkalinity diagrams, Mg-series *vs*. Fe-series diagram, tholeiitic *vs*. calc-alkaline diagrams, Trapezoid model, and a new simple ternary magmatic alkalinity evolution model (CaO-K_2O-Na_2O).

Materials and References of Geochemical Data

This study is a geochemical compilation from representative calc-alkaline volcanic rocks (Le Maitre, 1976; in Winter, 2014), Gothara albitites (Rajasthan, India; Kaur and Mehta, 2005), and selective geochemical data from cogenetic magmatic sources taken from Salak Volcano (Western

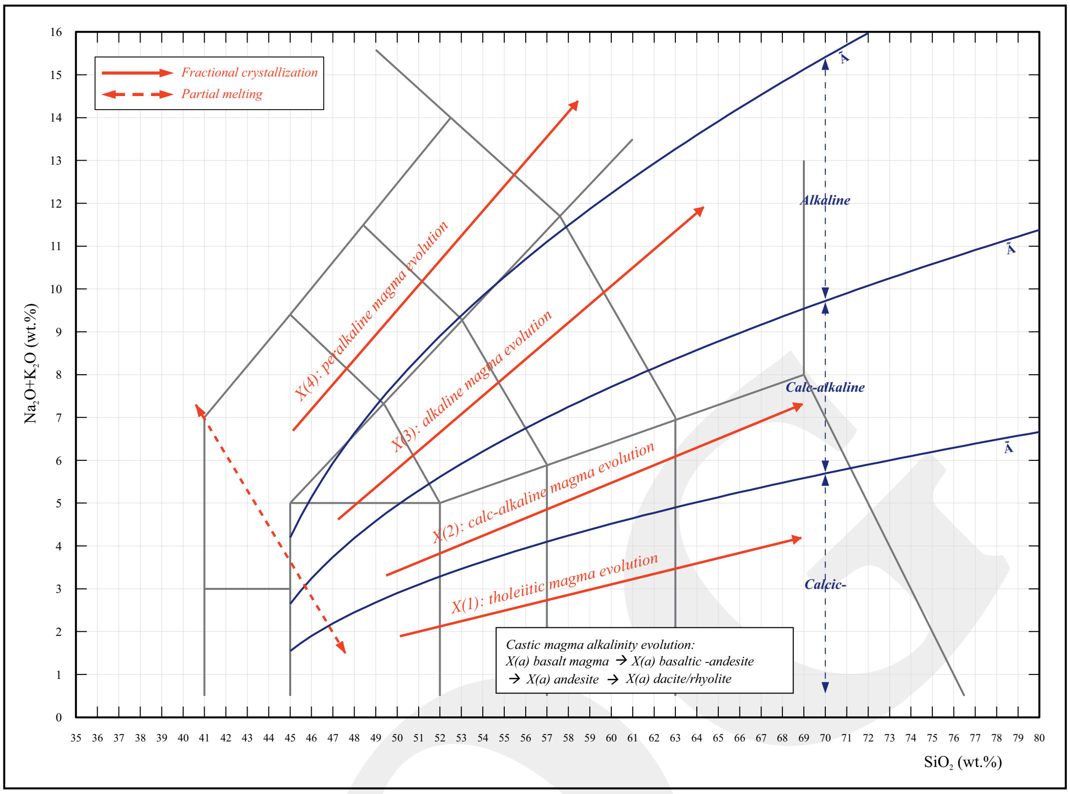


Figure 2. Castic magma alkalinity evolution by fractional crystallization (Gill, 2010). The overlay diagram between TAS (after Le Bas *et al*., 1986) with the Rittmann Serial index (1957, 1962). σ= [(Na_2O+K_2O)^2]/(SiO_2–43) (in wt.%).

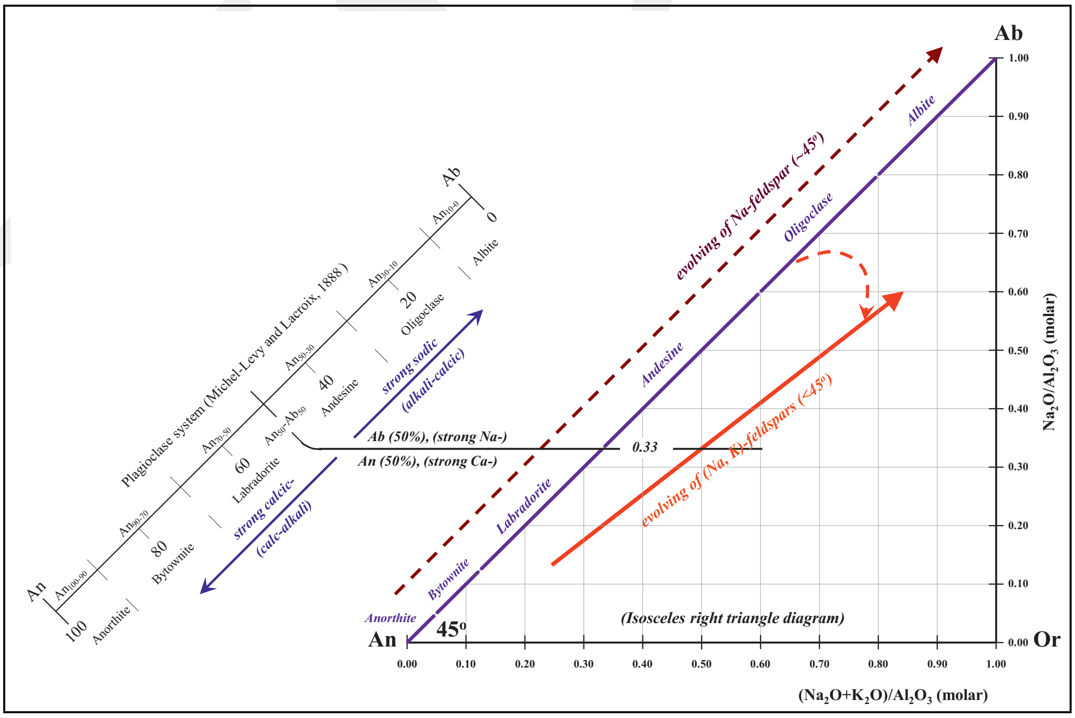


Figure 3. Single chain of evolution of the plagioclase (left diagram; Michel-Levy and Lacroix, 1888) clearly shows the cross-castic alkalinity evolution of (strong Ca, Na)-plagioclases {calc-alkali; *i.e.* bytownite, labradorite} to (strong Na, Ca)-plagioclases {alkali-calcic; *i.e.* andesine, oligoclase} (origin Bowen, 1922). The value of 0.33 on ratio Na_2O/Al_2O_3 (molar) is converted from Ab_{50}-An_{50} (Davies and Whitehead, 2009). The red solid-line arrow reveals the evolution of (Na, K)-feldspars (right diagram; see also in Figure 5 'Trapezoid model').

Jawa; Handley *et al*., 2008) and Fossa delle Felci Volcano (Aeolian arc, Salina Italy; Gertisser and Keller, 2000).

New Model Magmatic Alkalinity Evolution

The new magmatic alkalinity evolution trend diagram presented here has been designed for non-alkaline/peralkaline magma in the form of a ternary model using components of the feldspar group (plagioclase and K-feldspar) namely in the form of variables of CaO, K_2O, and Na_2O, minus Al_2O_3 (in wt.%). This ternary diagram is based on a conversion (modification) of the Trapezoid model (Godang *et al*., 2016), referring to the modified of continuous branch from Bowen's 1922 (Figure 4), and adopting the affirmation of the diagram 'K_2O *vs*. SiO_2' (Harker, 1909) where there is an increase in K_2O along the stages of magma differentiation (from basalt/gabbro to rhyolite/granite). The evolutionary trend of magmatic alkalinity from the Trapezoid Model is shown in Figure 5.

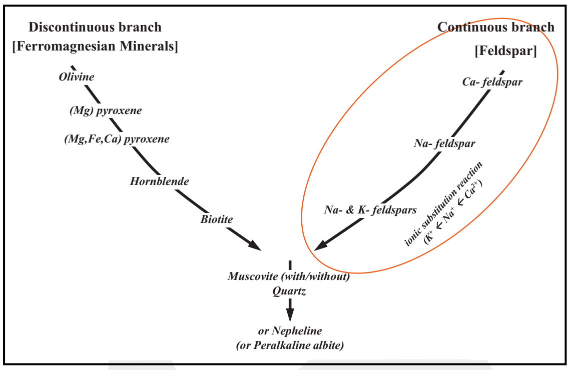


Figure 4. Bowen's reaction series showing the minerals that will crystallize during the differentiation of a basaltic magma (modified from Frost and Frost, 2014).

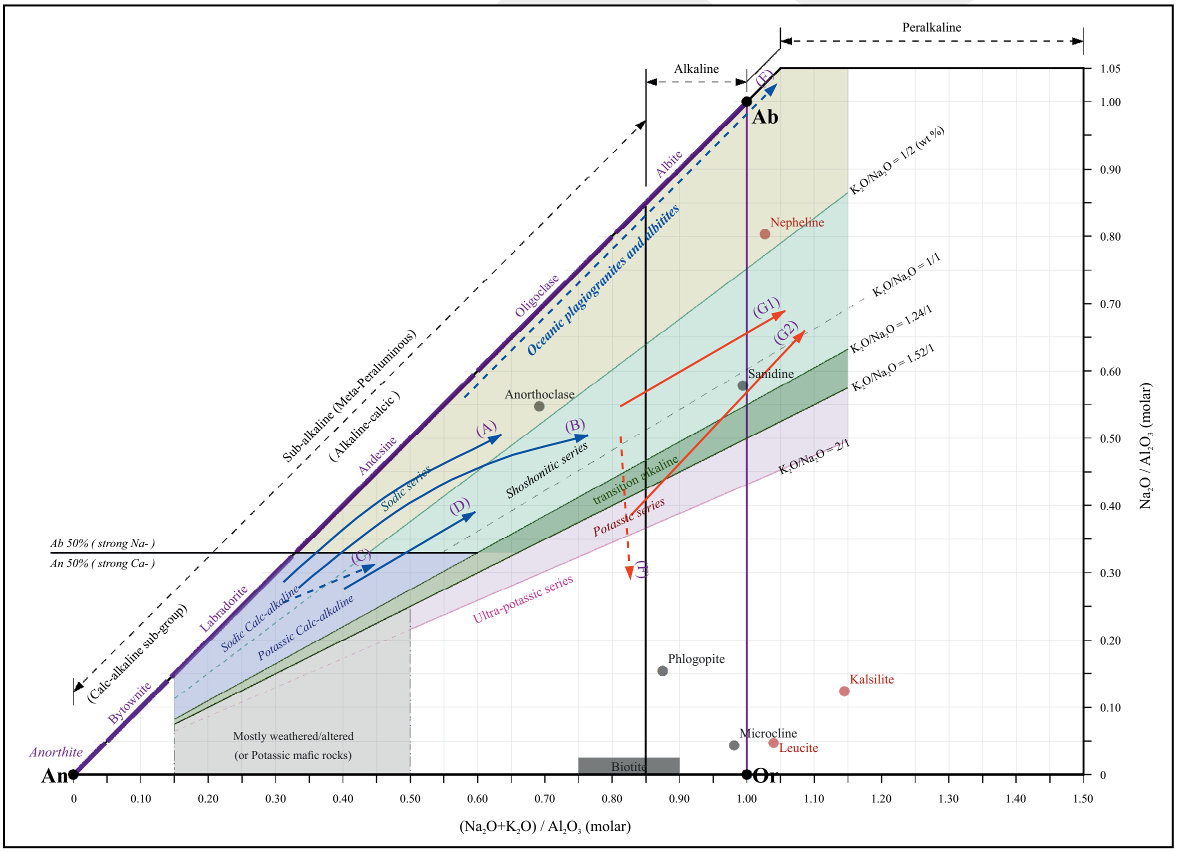


Figure 5. The cross-castic magma alkalinity evolution trend in Trapezoid model (Godang *et al*., 2016). (A) Evolutionary trend of sodic calc-alkaline to sodic alkaline-calcic, (B) Sodic calc-alkaline to shoshonitic alkaline-calcic, (C) Blue dash-line shows the sodic calc-alkaline to potassic calc-alkaline, (D) Potassic calc-alkaline to shoshonitic alkaline-calcic, (E) Blue dash-line shows the evolution of oceanic plagiogranites/albitites from sodic alkaline-calcic to sodic alkaline/peralkaline. (F) Red dash-line shows the evolution of S-type granites from shoshonitic alkaline-calcic to potassic/ultrapotassic alkaline-calcic (cross-castic in sub-alkaline), (G1, G2) Evolution of A-type granites from shoshonitic/potassic alkaline-calcic to shoshonitic/potassic alkaline/peralkaline.

Analysis and the Confirmation of Cogenesis Magmatic Source

To anticipate the possibility of magma contamination from the other magma during the process of magmatic differentiation, such as mantle magma containing rutile-melts, or magma that has interacted with the mantle plume; then the multi-plotting is done as an initial step by using various diagram models. Plot of the major oxides in the Shand classification diagram shows the Salak volcanics, Fossa delle Felci volcanics, representative of calc-alkaline volcanic rocks (RCVR), and Gothara albitites that have the value of ASI < 1.1 and ascertained the origin of the magma is formed from the igneous protoliths (Figure 6).

The crosscheck of the possibility of magma contamination with other magmas containing the rutile-melts, then the plotting is expanded by involving the ratio of Nb/Ta *vs*. SiO_2 (after Foley *et al*., 2002 and after Asaah *et al*., 2014). The plotting results show the cogenetic magmatic differentiation, free of contamination from rutile-melts (Figure 7). The ratio of Nb/Zr *vs*. Th/Zr for the Salak volcanic and Fossa delle Felci volcanics respectively in the range 0.0416 - 0.0444 *vs* 0.0186 - 0.0263, and 0.049 - 0.0598 *vs* 0.0418 - 0.0610 indicate that both magmatisms were generated from ACM (Continental Arc) which was not contaminated with mantle plume (after Sun *et al.,* 2006, modified from Godang *et al.,* 2016).

The diagram using the ratio of Nb/Zr *vs*. SiO_2 shows the Fossa delle Felci and Salak volcanics respectively in the form of a single magma source that undergoes an ideal differentiation, and has the ratio values Nb/Zr <0.0627 strongly indicating the magma was generated from DMM (Depleted MORB Mantle). Furthermore, it is clear that there is no increase in the Nb/Zr ratio from the basaltic to dacitic composition during the magma differentiation and fractional crystallization (Figure 8). To anticipate more possibilities for sediment recycling input, which generally carries the potassic and can influence the increase of potassic (K_2O) in the magma source during the differentiation process, then the additional plotting was also done using the ratio Th/Ce *vs*. SiO_2 (after Hawkesworth *et al*., 1997; after He *et al*., 2008;

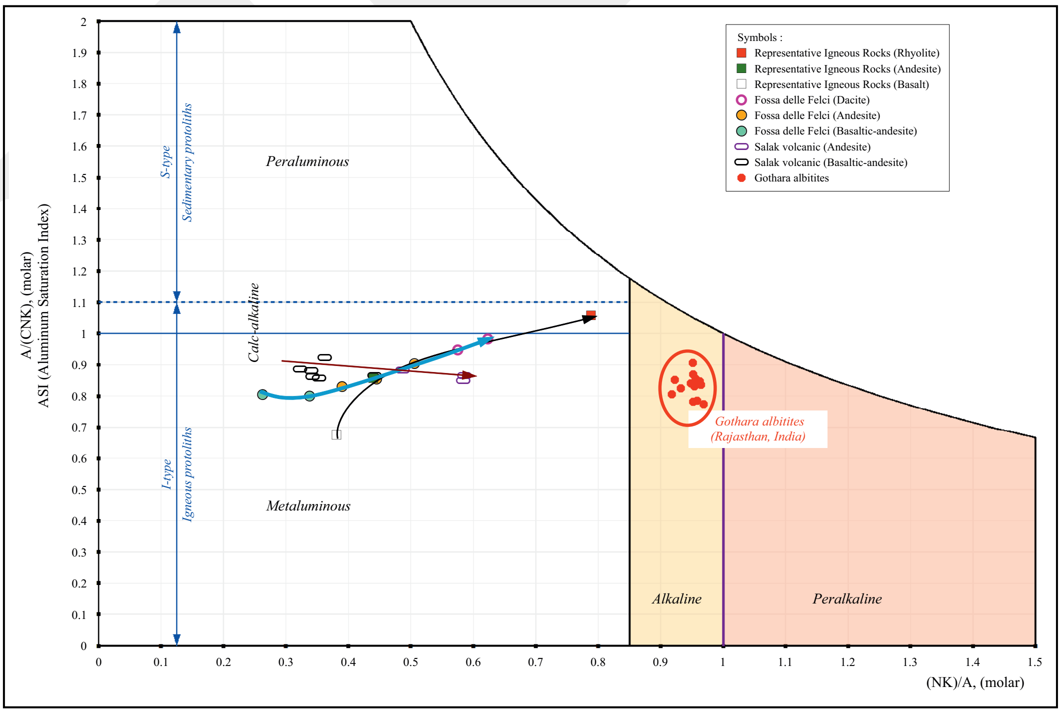


Figure 6. Aluminum Saturation Index (ASI) Diagram (rectified after origin Shand, 1927). The discrimination of Alkaline ((NK)/Al > 0.85) is adapted from Whalen *et al*., 1987. A/(CNK) = (Al_2O_3)/($CaO+Na_2O+K_2O$). (NK/Al) = (Na_2O+K_2O)/Al_2O_3, in molar.

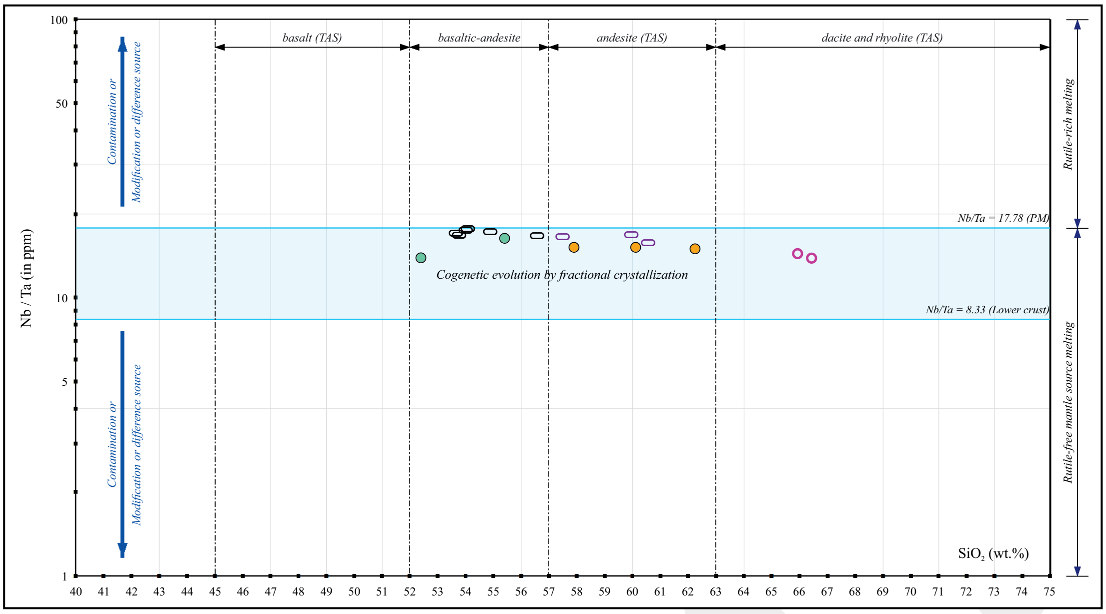


Figure 7. Diagram modified of Harker. The contamination vs. cogenetic evolution by fractional crystallization diagram (after Asaah et al., 2014; after Foley et al., 2002). The Fossa delle Felci volcanic (Italy) and Salak volcanic (western Jawa) show the cogenetic magma evolution by fractional crystallization. Symbol in Figure 6.

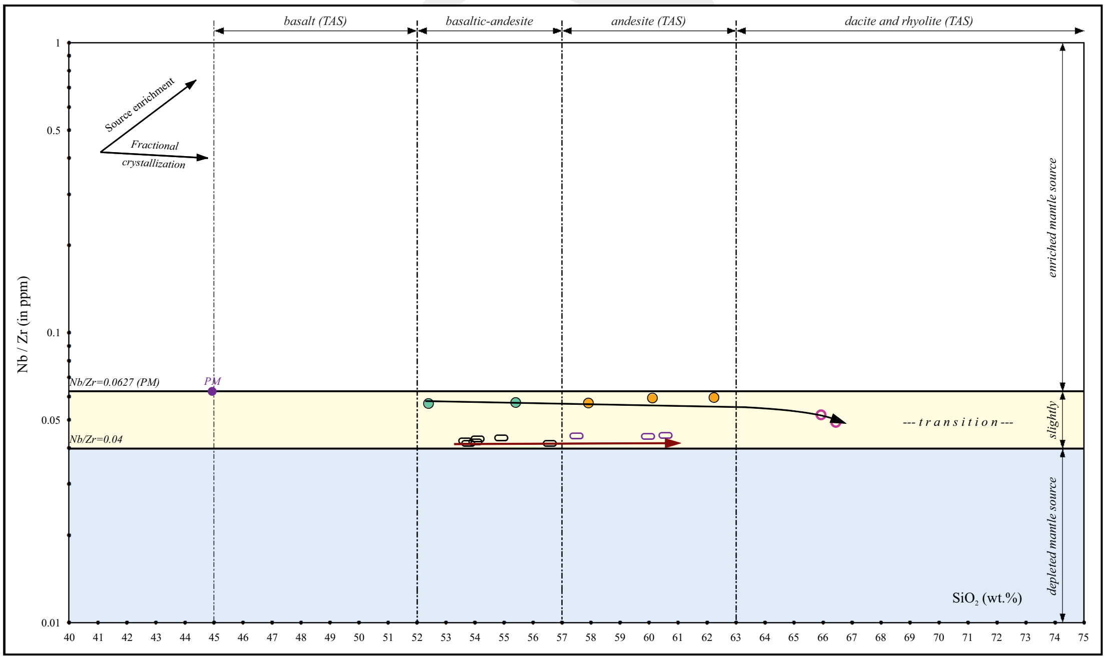


Figure 8. Diagram depleted and an enriched mantle source (after Le Roex et al., 1983).

Figure 9). The plot shows minor sedimentary input in Fossa delle Felci and Salak volcanics. As a comparison, the Merapi volcanic rock (central Jawa; Gertisser and Keller, 2003) was also plotted which had the ratio of Th/Ce between 0.15–0.22 (Th/Ce > 0.1) significantly involved the sediment recycling. The isotopic ratio diagram $^{143}Nd/^{144}Nd$ *vs*. $^{87}Sr/^{88}Sr$ (Figure 10) reveals the Fossa delle Felci and Salak volcanics having similarity in the isotopic value. Furthermore, both volcanics are far away from the sedimentary line (North Indian Ocean silicious sediments; Hartono, 1994) and the boundary of Indian Ocean sediments (Handley *et al*., 2008). This interpretation corresponds

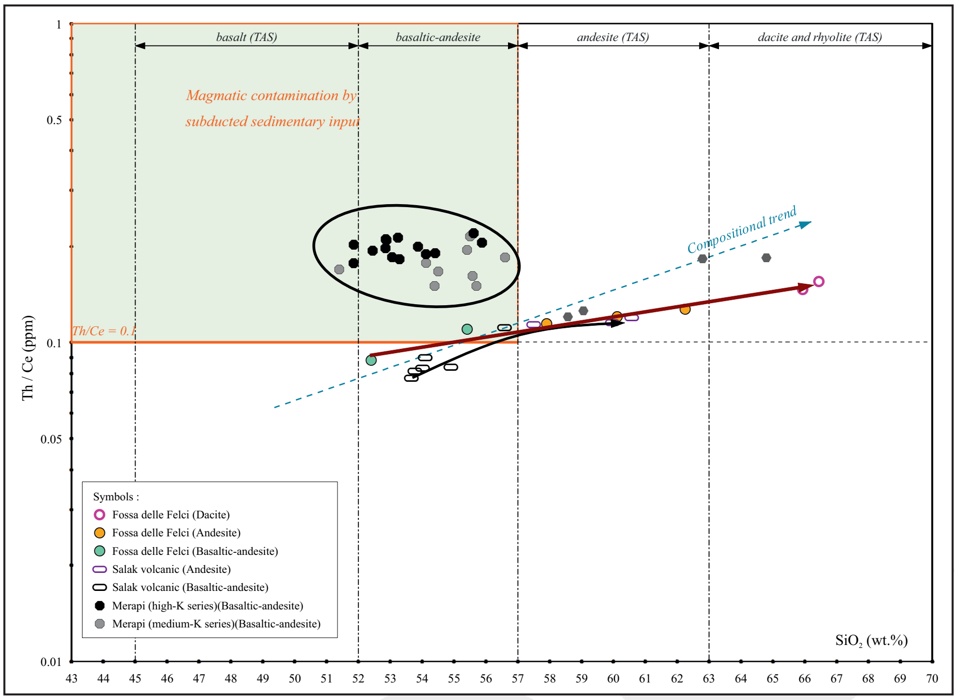
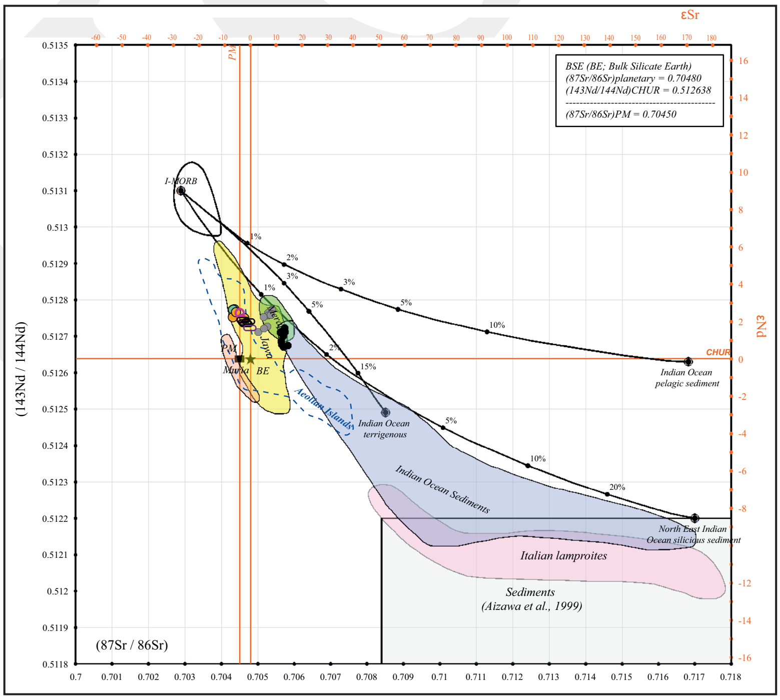


Figure 9. Magmatic Contamination by Subducted Sedimentary Input Diagram (after Hawkesworth *et al*., 1997; after He *et al*., 2008). The dash line shows the compositional trend of the ratio Th/Ce during the magmatic evolution. The Fossa delle Felci volcanics (Italy) and Salak volcanics (western Jawa) show minor sedimentary recycling input during magmatic differentiation. Merapi volcanic rock significantly involves the sediment recycling. GLOSS (Global Subducting Sediment; Plank and Langmuir, 1998), SS (Silicic sediments; Gasparon and Varne, 1998), PAAS (Post-Archean Australian Shale; Taylor and McLennan, 1985), NASC (North American Shale Composite; Gromet *et al*., 1984).



Figures 10. Diagram showing $^{143}Nd/^{144}Nd$ *versus* $^{87}Sr/^{86}Sr$. The mixing lines are shown for I-MORB source composition with average Indian Ocean pelagic sediments, average Indian Ocean and terrigenous/biogenic sediments, average North East Indian Ocean silicious sediments (Hartono, 1994). Jawa and Indian ocean sediments (Handley *et al*., 2008). Sediments (Aizawa et al., 1999). Muria and Merapi volcanics (Sendjaja *et al*., 2009). Italian lamproites (Kempton *et al*., 2018). Aeolian Islands (Francalanci *et al*., 2007). Symbol in Figure 9

to the result of plotting in the diagram Th/Ce *vs*. SiO_2 (Figure 9). In contrast to Merapi volcanics, the results of plotting the isotopic composition are very close to the sediment line and the Indian Ocean sediment boundary.

A plot of the Fossa delle Felci and Salak volcanics in a spidergram displays an ideal trend of incompatible to compatible-trace elements (Figures 11a, and b)and incompatible to compatible REE (Figures 12a and b). The enrichment in

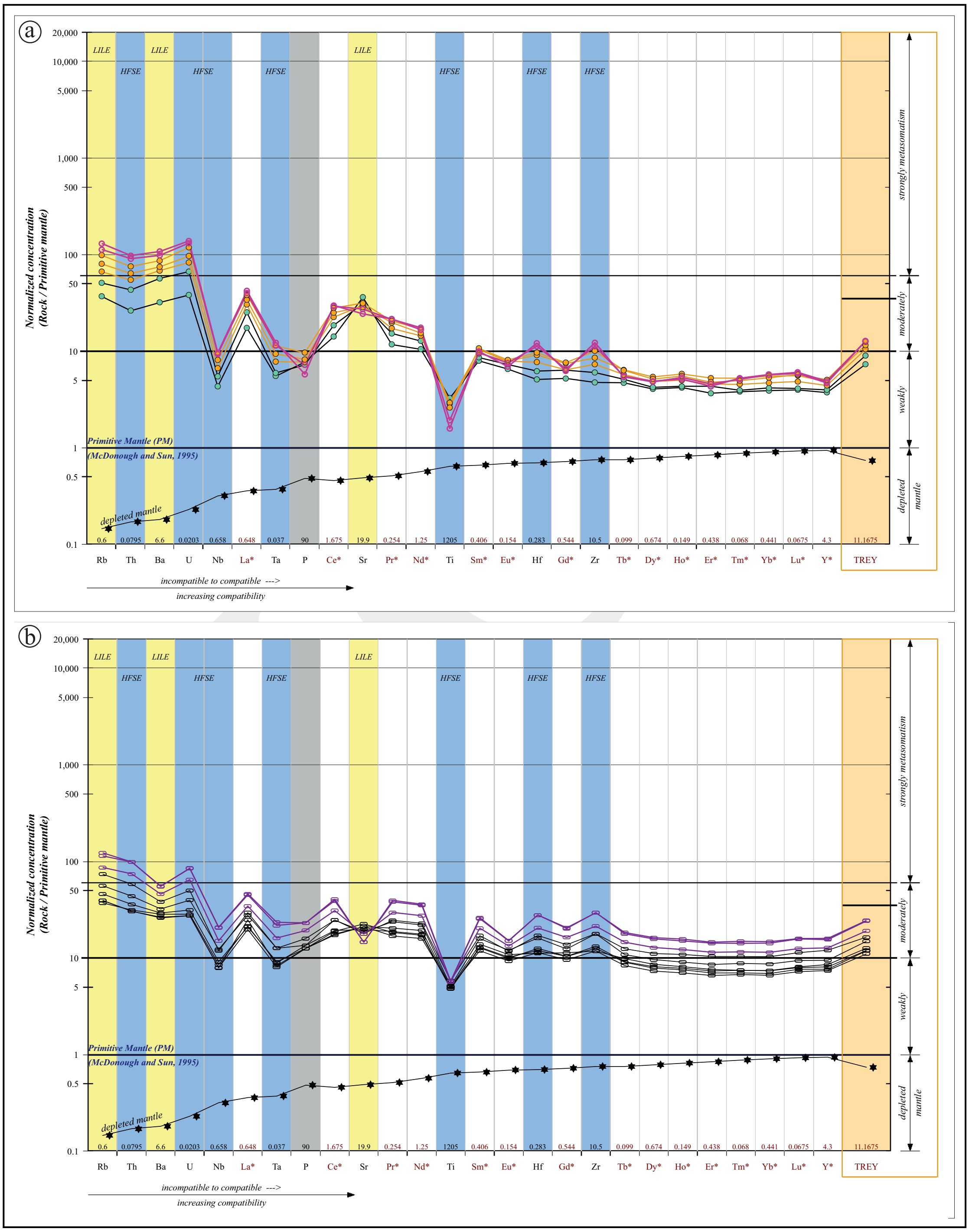


Figure 11. Incompatible to compatible multi-trace elements diagram Normalized to Primitive Mantle. (a) Fossa delle Felci volcanics, (b) Salak volcanics. The description of weakly-moderately-strongly mantle metasomatism is only used for the determination of metasomatism of mafic/basaltic rocks which based on TREY (modified from Godang et al., 2016). Primitive Mantle (PM) values are taken from McDonough and Sun (1995) and Depleted Mantle (DM) from Salters and Stracke (2004).

LILE (Rb, Ba), HFSE (Th, U, Nb, Ta, Hf, Zr) and the decrease in Sr (LILE) occur gradually from basaltic-andesite to andesite/dacite. Ti decreases in the Fossa delle Felci volcanics, but increases slightly in the Salak volcanics. Figures 12a and b display the idealized enrichment for La, Ce, Pr, Nd, Yb, Lu, Y, and TREY.

Based on the result of the multi-plotting diagrams (Figures 6 to 12), it can be concluded that Fossa delle Felci volcanics (Italy) and Salak

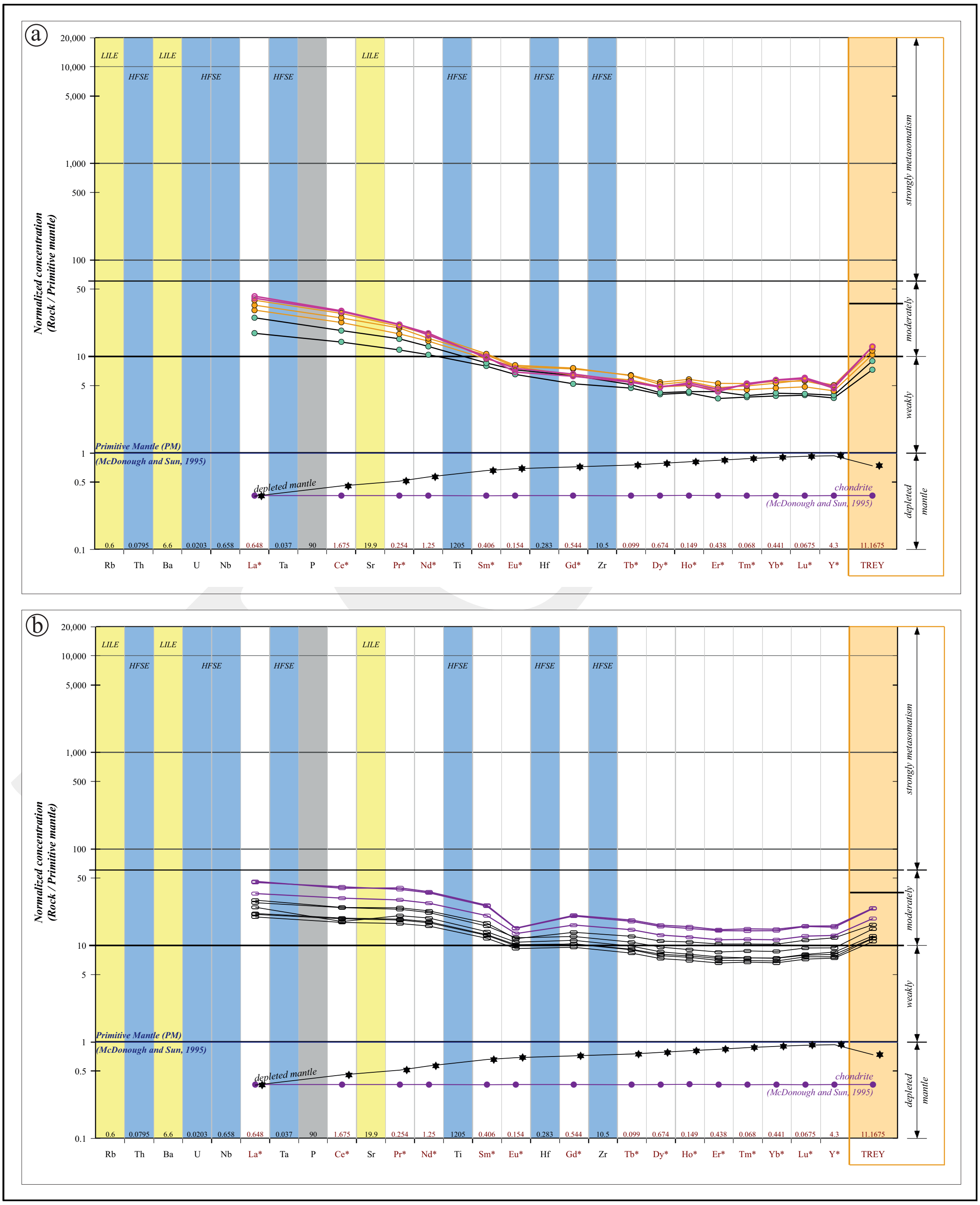


Figure 12. Incompatible to compatible Rare Earth Elements (REEs) diagram Normalized to Primitive Mantle. (a) Fossa delle Felci volcanics, (b) Salak volcanics. Primitive Mantle (PM) and Chondrite values are taken from McDonough and Sun (1995) and Depleted Mantle (DM) from Salters and Stracke (2004).

volcanics (Western Jawa) are ensured that each volcanic rock is a single cogenetic magma that undergoes the differentiation with minor potassic recycling.

Interpretation of Results

Three in one overlaid diagram is the overlay diagram constructed from three existing diagrams using the major oxides, *i.e.* Mg# *vs*. SiO_2 (Schilling *et al*., 1983), $FeO_{(t)}/\{FeO_{(t)}+MgO\}$ *vs*. SiO_2 (Frost and Frost, 2008), and $FeO_{(t)}/MgO$ *vs*. SiO_2 (Miyashiro, 1974). The diagram in Figure 13 shows a difference in discrimination between tholeiitic (Fe-series) and calc-alkaline (Mg-series). The interpretation of plot results is presented in Table 1.

The plot results in TAS diagram (after Le Bas, 1986) show RCVR, Fossa delle Felci, and Salak volcanics fall in sub-alkaline field (calc-alkaline series) (Figure 14), but the plot result in 'K_2O *vs*. SiO_2' diagram (after Peccerillo and Taylor, 1976; Figure 15) shows the magmatic alkalinity of RCVR and Fossa delle Felci evolved from medium-K to high-K (cross-castic); whereas the Salak volcanics (basaltic-andesite to andesite) has a trend of cross-castic evolution. The result of plotting in the overlay diagram between Ishihara and Murakami (2004) and Godang *et al*. (2016), Trapezoid model (Godang *et al*., 2016), and New ternary magmatic alkalinity evolution trend diagram that created in this study (Figures 16, 17, and 18) are presented in Table 2.

Discussion

There are differences in the results of the plot on the overlay diagram between the versions of Miyashiro (1974) and Frost and Frost (2008) (Figure 13). The difference between these two versions of discrimination will continue to be a considerable debate in the future. The case study

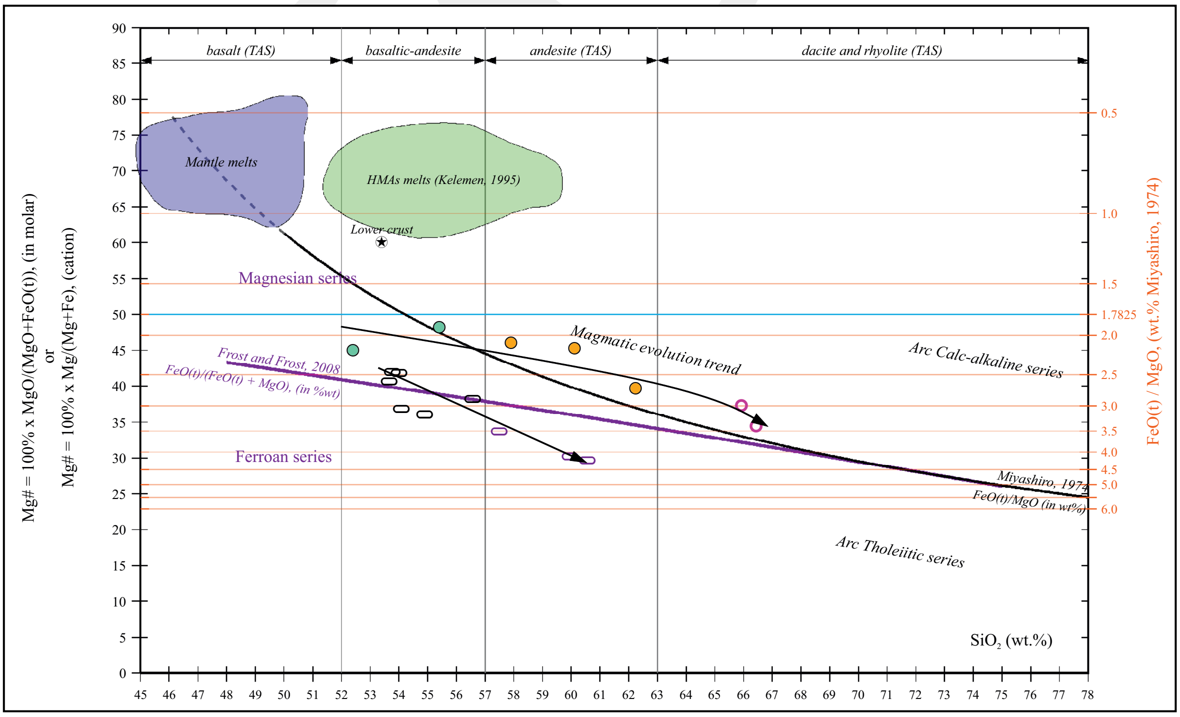


Figure 13. Three in one overlaid diagram. Index of differentiation diagram (Mg#; Schilling *et al*., 1983); Magnesian *vs*. Ferroan series (after Frost and Frost, 2008); Discriminates of Arc Tholeiites and Arc Calc-alkaline series (Miyashiro, 1974), Mantle-melts (after Kinzler, 1997). HMAs melts (High Magnesian Andesite; Kelemen, 1995), Lower crust (Rudnick and Gao, 2003).

Table 1. Interpretation of Magma Series (Mg-Fe series) during magmatic differentiation (in discontinuous branch of Bowen, 1922)

Location	**Three in one an overlaid diagram (Fig. 13 Diagram Mg# *vs*. SiO_2**	
	Miyashiro (1974)	**Frost and Frost (2008)**
Fossa delle Felci volcanics (Italy)	**cross-castic** magma evolution (from arc tholeiitic to arc calc-alkaline) (*)	castic magma evolution (Mg-series)
Salak volcanics (Western Jawa)	castic magma evolution (arc tholeiitic series)	**cross-castic** magma evolution (from Mg-series to arc Fe-series)

(*) Something that sounds pretty strange if it is said that the magma evolved from arc tholeiitic to arc calc-alkaline. It is due to the magma evolution in discontinuous branches, where Mg^{2+} will be substituted into Ca^{2+} and/or Fe^{2+}. After the formation of Fe^{2+}, where Fe^{2+} cannot be substituted into Ca^{2+}.

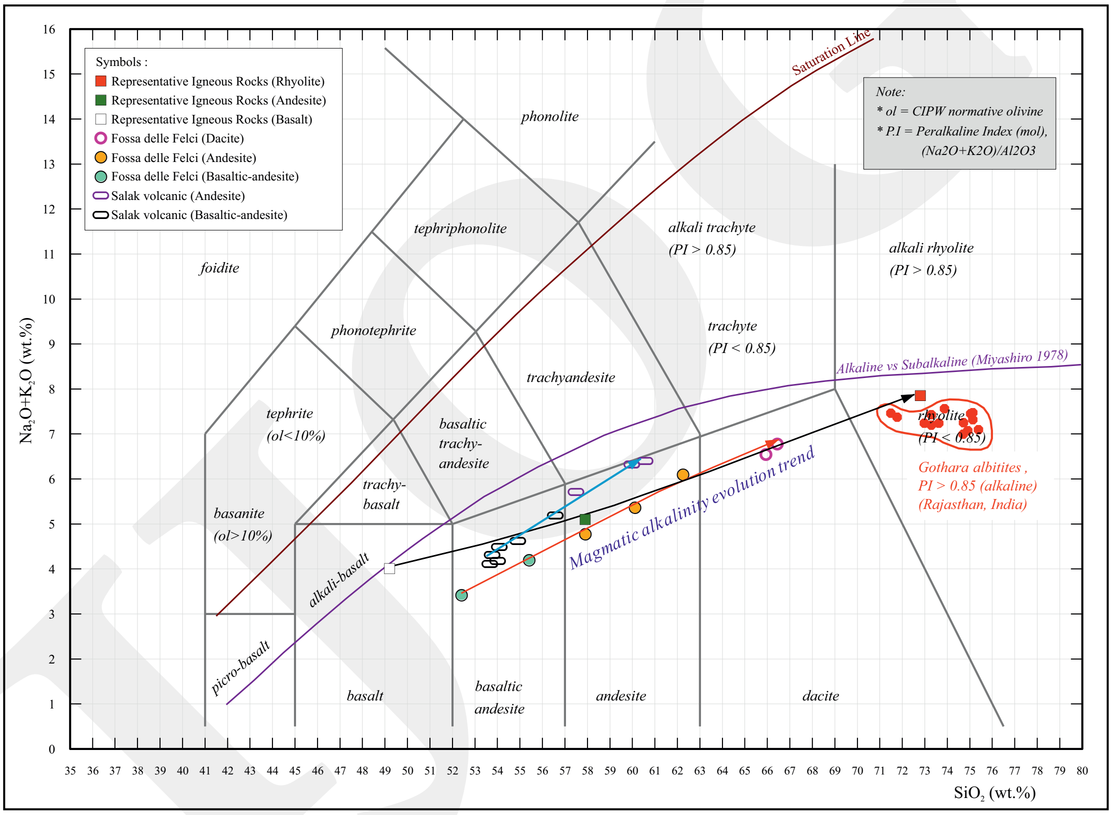


Figure 14. Discrimination of Igneous Rock Diagram (Le Bas *et al*., 1986) which overlaid by the discrimination between alkaline against sub-alkaline (Miysahiro, 1978). Plotting without LOI normalization.

of the Fossa delle Felci volcanics rock would be better if it is interpreted that magma evolved along the Mg-series, while Salak volcanic rock would be better if interpreted as a cross-castic magma evolution from Mg-series to Fe-series (referring to sub-discrimination from Frost and Frost, 2008).

The plot results using the discrimination of alkaline *vs*. sub-alkaline from Miyashiro (1978) in the TAS diagram, show the evolution of magmatic alkalinity of RCVR, Fossa delle Felci, and Salak volcanics are calc-alkaline series (sub-alkaline). Gothara albitites fall in the calc-alkaline field (sub-alkaline), but interpreted as alkaline (P.I > 0.85; P.I= Peralkaline Index). The discrimination of alkaline *vs*. sub-alkaline using Na_2O+K_2O (in wt.%) is not appropriate for discriminating the alkalinity in felsic rocks, because the magmatic in felsic phase is very dependent on the grade of sat-

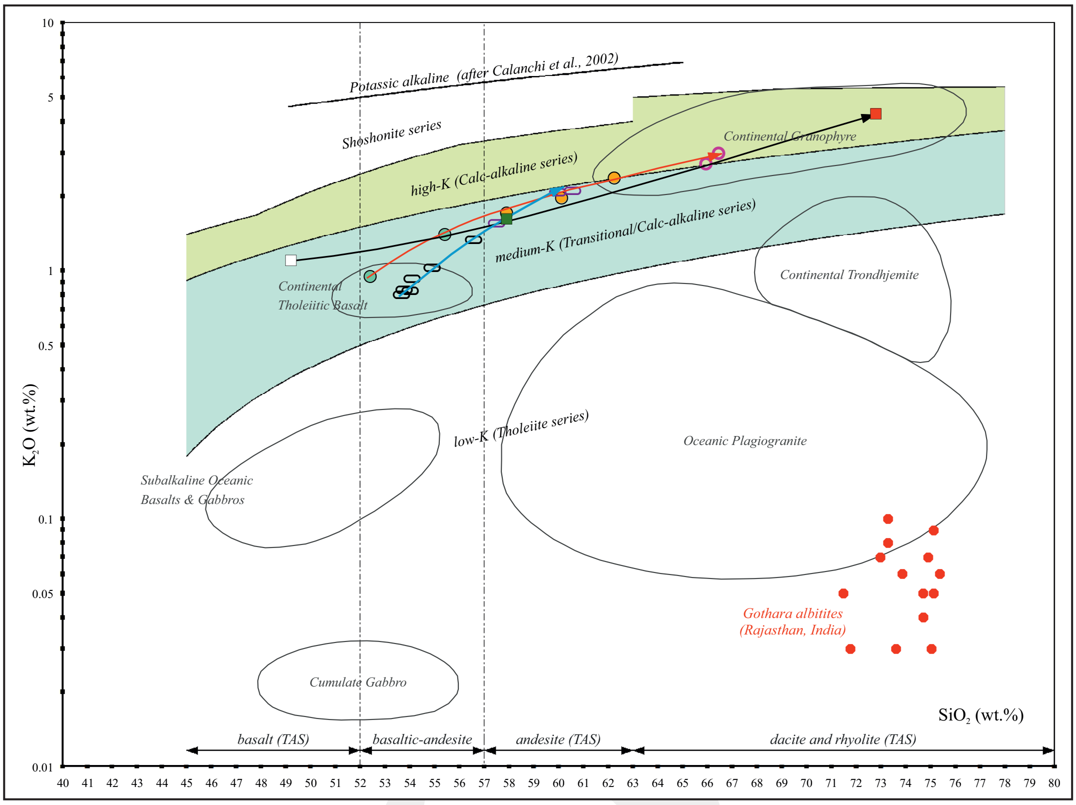


Figure 15. Overlaying of Volcanic Rocks Classification for Orogenic zone (Peccerillo and Taylor, 1976) into the discrimination diagram of Oceanic Plagiogranite (overlaid from Fadlin *et al*., 2017; Coleman and Peterman, 1975). Potassic alkaline (Calanchi *et al*., 2002). The discrimination for alkaline *vs*. sub-alkaline (Keith, 1983). Symbol in Figure 6

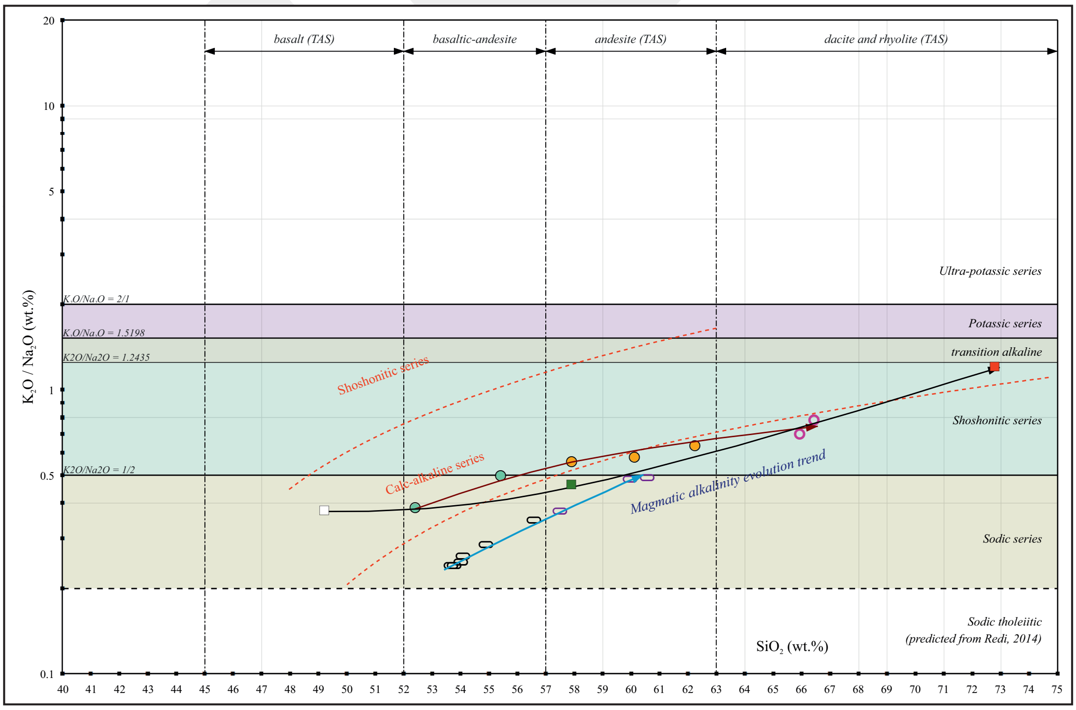


Figure 16. Magmatic alkalinity evolution by fractional crystallization diagram. The ratio of K_2O/Na_2O is adopted from Godang *et al*. (2016). The red dash-line is converted from Ishihara and Murakami (2004) which clearly explained the cross-castic magma alkalinity evolution.

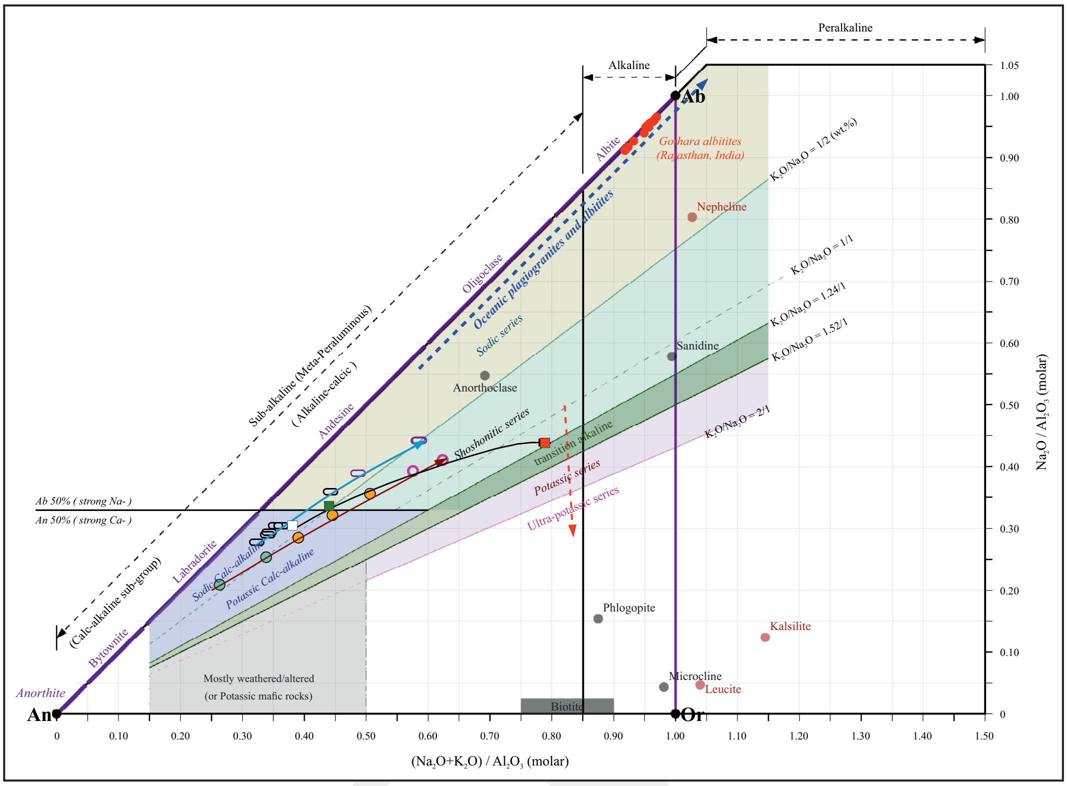


Figure 17. Trapezoid Magmatic Alkalinity Classification (Godang *et al*., 2016). Discrimination of Alkaline type of Igneous rocks for Ultra-potassic – Potassic – Shoshonitic – Sodic – Calc-alkaline rocks. Calc-alkaline sub-group: Calc-alkaline (Sodic, Potassic) and Tholeiitic. Red dashed line arrow reveals the cross-castic alkalinity evolution of S-type granites {from shoshonitic to potassic/ultrapotassic alkaline-calcic (cross-castic in sub-alkaline)}. Symbol in Figure 6

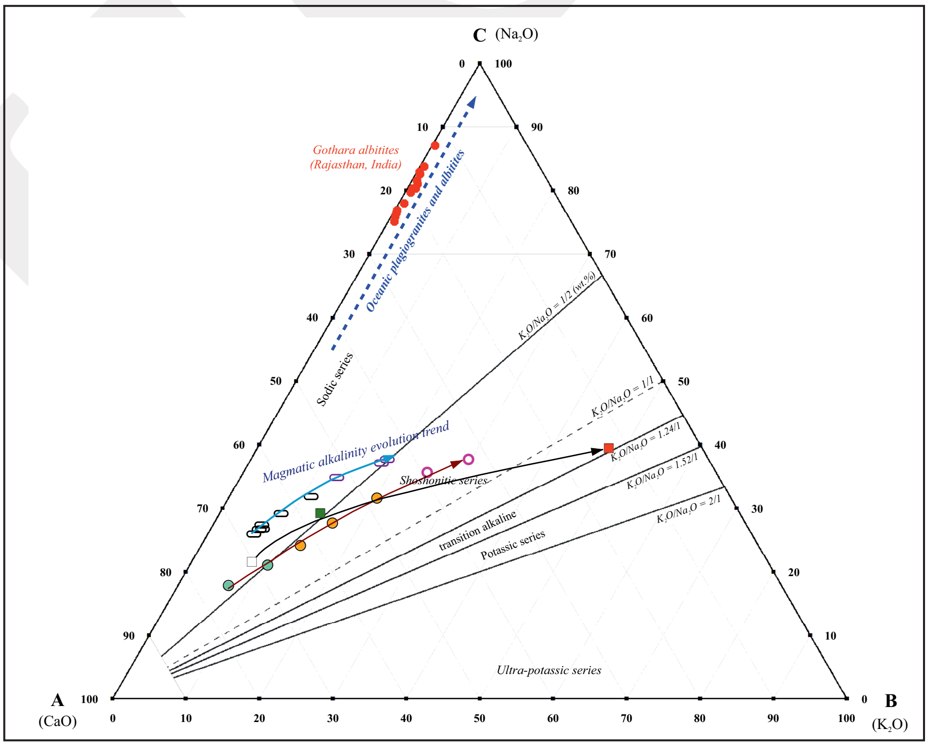


Figure 18. Ternary Magmatic Alkalinity Evolution Trend for Non-alkaline/peralkaline Diagram (CaO-K_2O-Na_2O, in wt.%), mathematically converted from Turner *et al*. (1996) and Godang *et al*. (2016)

Table 2. Interpretation Results of Magmatic Alkalinity Evolution from Several Model Diagrams (in continuous branch of Bowen, 1922)

	Model diagram	Figure	Representative calc-alkaline volcanic rocks (RCVR; basalt to rhyolite; Winter 2014)	Fossa delle Felci volcanics (basaltic-andeste to dacite; Salina Italy)	Salak volcanics (basaltic-andeste to andesite; Western Jawa)	Gothara albitites (Rajasthan, India)
(a)	Discrimination Alkaline *vs*. Sub-alkaline (Miysahiro, 1978) in TAS diagram.	Fig. 14	calc-alkaline (sub-alkaline series)	calc-alkaline (sub-alkaline series)	calc-alkaline (sub-alkaline series)	Alkaline (P.I > 0.85) {see also in Fig. 6 and Fig. 17}
(b)	after Peccerillo & Taylor, 1976 (in K_2O *vs*. SiO_2 diagram)	Fig. 15	magmatic alkalinity evolution from medium-K to high-K (**cross-castic**)	magmatic alkalinity evolution from medium-K to high-K (**cross-castic**)	has a trend of **cross-castic** evolution.	Alkaline (P.I > 0.85); Na_2O-rich (very low K_2O)
(c)	Overlaid between Ishihara and Murakami (2004) and Turner *et al.* (1996) & Godang *et al.* (2016)	Fig. 16	magmatic alkalinity evolution from sodic series to shoshonitic series (**cross-castic**)	magmatic alkalinity evolution from sodic series to shoshonitic series (**cross-castic**)	has a trend of **cross-castic** evolution (from sodic to shoshonitic series).	not plotted in the diagram, because the ratio of K_2O/Na_2O is very low (~ 0.0040 - 0.0136)
(d)	Trapezoid model (Godang *et al.,* 2016)	Fig. 17	magmatic alkalinity evolution from sodic calc-alkaline to shoshonitic alkaline-calcic (**cross-castic**)	magmatic alkalinity evolution from sodic calc-alkaline to shoshonitic alkaline-calcic (**cross-castic**)	magmatic alkalinity evolution from sodic calc-alkaline to alkaline-calcic (**cross-castic**)	Sodic alkaline (albite-rich). Magmatic alkalinity evolution from alkaline-calcic to alkaline (**cross-castic**)
(e)	New ternary magmatic alkalinity evolution trend (created in this study)	Fig. 18	magmatic alkalinity evolution from sodic series to shoshonitic series (**cross-castic**)	magmatic alkalinity evolution from sodic series to shoshonitic series (**cross-castic**)	has a trend of **cross-castic** evolution (from sodic to shoshonitic series).	Sodic series

*P.I = Peralkaline Index $(Na_2O+K_2O)/Al_2O_3$ (in molar)

uration of alumina as proposed by Shand (1927) and exposed in the Trapezoid model (Godang *et al*., 2016) (Figure 6 and Figure 17). In general, S-type granitoids from sedimentary protoliths or plagiogranite (or albitites/peralkaline granites/peralkaline rhyolites) from igneous protoliths are not suitable in the plot using the TAS diagram.

Plotting using 'K_2O *vs*. SiO_2' diagram (Figure 15), where RCVR and Fossa delle Felci showed cross-castic magma alkalinity evolution from medium-K to high-K, Salak volcanic rock has a trend of cross-castic evolution. In this study, the authors do not really like using the term like 'magma affinity' or 'coexistence' of medium-K and high-K, because each originates from the evolution of its own single magma.

The plot results on Figure 16 show RCVR and Fossa delle Felci volcanics reveal the cross-castic magma alkalinity evolution from sodic series to shoshonitic series; whereas Salak volcanic rock has a trend of cross-castic evolution. The discrimination line (dash lines), proposed by Ishihara and Murakami (2004), is only used as a reference which in principle explains about the cross-castic alkalinity evolution.

Plotting in the Trapezoid model (Figure 17) provides the detailed output of magmatic alkalinity evolution, in which RCVR and Fossa delle Felci volcanics show the cross-castic from 'sodic calc-alkaline' to 'shoshonitic alkaline-calcic', whereas Salak volcanic rock shows the cross-castic from 'sodic calc-alkaline' to 'sodic alkaline-calcic'. The Gothara albitites (India) clearly confirmed as sodic-rich alkaline (see also Figure 6); furthermore, Trapezoid model also displays the evolutionary trend of plagiogranites/albitites in the form of cross-castic from sodic alkaline-calcic to sodic alkaline/peralkaline without the presence of potassic. The plot results of the Gothara albitites in the new ternary CaO-K_2O-Na_2O diagram are interpreted as a sodic-rich series (Figure 18). The ternary diagram is a crosscheck for the Trapezoid model, which has the same expression in discrimination of alkalinity series. This ternary diagram is just a simple diagram only used for discriminating alkalinity series. It couldn't further define such as calc-alkaline, alkaline-calcic, alkaline or peralkaline, because it does not involve the variable of alumina.

The magmatic evolution of (Mg, Fe)-series in discontinuous branches do not have a direct relationship with the evolution of alkalinity in continuous branches (*e.g*. sodic, shoshonitic, potassic, alkaline/peralkaline), because each branch is on its own.

Finally, after going through the comprehensive studies above, it is proposed that the magmatic evolution of the Mg-Fe series such as the discontinuous branch of Bowen (1922) is different from the magmatic alkalinity evolution (continuous branch). The magmatic evolution (Mg-Fe series, tholeiitic *vs*. calc-alkaline series) can take place the castic and cross-castic (Table 3, see also Figure 13), as well as the evolution of magmatic alkalinity can also occur in castic and cross-castic. The evolutionary of magmatic alkalinity which refers to the TAS diagram (such as Rittmann, 1957; Miyashiro, 1978) or the diagram of K_2O *vs*. SiO_2 (Peccerillo and Taylor, 1976) takes place in castic, the New Ternary Magmatic Alkalinity Evolution diagram can take place in castic and cross-castic, whereas the Trapezoid model generally occurs in cross-castic (Table 4, see also Figures 2 and 5).

Table 3. Summary of the Magmatic Evolution in Bowen's Discontinuous Branch

Model diagram		Castic magma evolution		Cross-castic magma evolution	
Three in one an overlaid diagram (Fig. 13)	Frost and Frost (2008)	Mg-series to Mg-series	Fe-series to Fe-series	Mg-series to Fe-series	
	Miyashiro (1974)	Calc-alkaline to Calc-alkaline.	Tholeiitic to tholeiitic series.	-	

Table 4. Summary of the Magmatic Alkalinity Evolution in Bowen's Continuous Branch

	Model diagram	Castic magma alkalinity evolution		Cross-castic magma alkalinity evolution	
(1)	Discrimination Alkaline *vs*. Sub-alkaline (Miysahiro, 1978) in TAS diagram.	* Tholeiitic to tholeiitic; * Calc-alkaline to calc-alkaline;	* Alkaline to alkaline; * Peralkaline to peralkaline.		
(2)	After Peccerillo & Taylor, 1976 (in K_2O vs. SiO_2 diagram)	* low-K tholeiitic to low-K tholeiitic; * medium-K to medium-K;	* high-K calc-alkaline to high-K calc-alkaline.		
(3)	Trapezoid model (Godang *et al.,* 2016); see in Fig. 5			* sodic calc-alkaline to sodic alkaline-calcic; * sodic alkaline-calcic to sodic alkaline/ peralkaline; * sodic calc-alkaline to shoshonitic alkaline-calcic; * sodic calc-alkaline to potassic calc-alkaline.	* potassic calc-alkaline to shoshonitic alkaline-calcic; * shoshonitic alkaline-calcic to shoshonitic alkaline/peralkaline; * shoshonitic alkaline-calcic to potassic/ ultrapotassic alkaline-calcic.
(4)	New ternary magmatic alkalinity evolution trend (created in this study), see also in Fig. 18	* sodic series to sodic series;	* shoshonitic series to shoshonitic series.	* sodic series to shoshonitic series;	* shoshonitic series to potassic/ultrapotassic.

Conclusion

The comprehensive studies of the geochemistry (major oxides, trace elements, and REE) and isotopic on the magma differentiation from the volcanics and albitites have obtained the following conclusions:

(1). The magmatic differentiation based on the evolution of Mg-series to Fe-series in a discontinuous branch of Bowen (1922) can take place the castic or cross-castic, *i.e.*:
   (a). from Mg-series to Mg-series (castic; calc-alkaline to calc-alkaline series), *e.g.* Fossa delle Felci volcanics (Italy)
   (b) from Mg-series to Fe-series (cross-castic), *e.g.* Salak volcanics (western Jawa)
   (c) from high-Mg tholeiitic basalt to calc-alkaline series (cross-castic; refer to Jensen, 1976)
   (d) from Fe-series to Fe-series (castic; tholeiitic to tholeiitic series)

(2). The magmatic alkalinity evolution is based on the continuous branch of Bowen (1922) and refers to Trapezoid model generally occurring a cross-castic, *i.e.*:
   (A) from sodic calc-alkaline to sodic alkaline-calcic, *e.g.* Salak volcanics (western Jawa)
   (B) from sodic calc-alkaline to shoshonitic alkaline-calcic, *e.g.* Fossa delle Felci volcanics (Italy)
   (C) from sodic calc-alkaline to potassic calc-alkaline
   (D) from potassic calc-alkaline to shoshonitic alkaline-calcic
   (E) from sodic alkaline-calcic to sodic alkaline/peralkaline, *e.g.* Gothara albitites (Rajasthan, India)
   (F) from shoshonitic alkaline-calcic to potassic/ultrapotassic alkaline-calcic (cross-castic in sub-alkaline), *e.g.* S-type granites
   (G) from shoshonitic/potassic alkaline-calcic to shoshonitic/potassic alkaline/peralkaline, *e.g.* A-type granites.

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