AN OVERVIEW OF ARC MAGMA PETROGENESIS

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Abstract

The petrogenesis of subducted-related magmas is complicated, and has been subject of controversy and widely discussed among petrologists, involving multi sources and multi processes. The source of arc magmas includes upper mantle with either MORB-like or OIB-like, the subducted slab which consists of an oceanic basaltic crust and possibly sediments, including material derived either through melting or release of fluid, and the arc crust. The process involves fractionation, assimilation or contamination and magma mixing. There are two types of contamination including source and crustal contaminations. Trace element and isotopic evidences suggest that most arc magmas are derived from melting of upper mantle induced by released fluids and incompatible elements from a subducted oceanic crust. Subsequent fractionation with or without assimilation or contamination and magma mixing would result in more acid magmas. However, crustal-derived magmas, resulted from melting of either subducted slab or lower crust, are also present in some arcs.

Keywords : arc magmas, petrogenesis, overview

S a r i

Petrogenesa magma di daerah penunjaman sangatlah rumit, dan menjadi bahan pertentangan dan diskusi yang sangat tajam di antara para ahli petrologi, melibatkan bermacam sumber dan proses. Magma di daerah ini dapat bersumber dari mantel yang bersifat MORB atau OIB, lempeng yang menunjam berupa kerak samudra basaltic dan mungkin juga sedimen, termasuk material berasal dari peleburan atau dari materil yang lepas bersama cairan, dan kerak busur kepulauan. Prosesnya melibatkan fraksinasi, asimilasi atau kontaminasi dan percampuran magma. Ada dua jenis kontaminasi, yaitu kontaminasi sumber dan kontaminasi kerak. Bukti kandungan unsur jejak dan nilai isotop menunjukkan bahwa magma busur umumnya berasal dari peleburan mantel atas yang diperkaya dengan cairan dan unsur inkompatibel dari kerak yang menunjam. Selanjutnya diikuti dengan fraksinasi dengan atau tanpa asimilasi atau kontaminasi dan percampuran magma akan menghasilkan magma yang lebih asam. Namun demikian magma sebagai hasil peleburan kerak, baik dari slab maupun dari kerak bawah juga terdapat di sejumlah busur.

Kata kunci : magma busur, petrogensis, gambaran umum

Introduction

Magmatism in island arc systems, both island arcs and active continental margins, is the most complex history compared to that in other tectonic settings, such as mid-ocean ridges and within plates both oceanic islands and continental rifts. The genesis of subduction zone magmas has been a subject of controversy and widely discussed for many years, but there is still no agreement about their origin. The controversial hypothesis of arc magma origin arises mostly because of their wide compositional variations. The rock suites in subduction zone environments vary from low-K tholeiitic through calc-alkaline basalt-andesite-dacite to leucitite and related ultrapotassic mafic volcanics. The causes of the compositional variation among island arc basalts and their differences from other basalts in mid-ocean ridges and oceanic islands are intensively debated in petrological literatures.

The subduction zone magmatism is a direct response to tectonic and chemical processes operating at convergent plate margins. In this area the magma generation, including sources and processes, is greatly influenced by geological conditions and tectonic developments. The phenomena of boninite (Crawford *et al*., 1981), high-Mg andesite (Yogodsinkski *et al*., 1994; Hartono *et al*., 1999; Danyushevsky *et al*., 2006; Hartono and Sulistyawan, 2010), and K-rich magmas which is not related to depth of the Benioff-Wadati Zone systematic in the Eastern Sunda arc (Varne and Foden, 1986; Stolz *et al*., 1988; Stolz *et al*., 1990) were suggested by these authors that how important

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tectonic and geological processes in the generation of the arc magmas.

An understanding of the process of the magma generation in orogenic environment not only could provide information on the relative roles played by subducted oceanic crust, overlying mantle wedge, and oceanic or continental crust above the slab, but also as important knowledge for further study on precious and base metal deposit formation. It has long been known that a close relationship occurred between magmatic activity in arc systems and mineral deposit formations. The interplay of several magmatic, tectonic and hydrothermal processes occurring at convergent plate margins result in precious and base metal-bearing epithermal and porphyry-copper deposits. A review on the petrogenesis of arc magma and its role in mineral deposit formation was presented by Hartono (2009).

This paper presents a brief overview on the petrogenesis of arc magmas, including the source or sources and process or processes by which magma rise to the surface to produce various geochemical variation. A review of adakite, subducted related rocks with specific geochemical characteristics, is presented separately. In the last part of this reviewed paper a summarized review of the relation between arc magma petrogenesis and mineral deposit formation is also included.

Geochemical Characteristics of Arc Magmas

Lavas erupted in subduction zones frequently display geochemical characteristics which are different from that generated in other tectonic settings. The mafic to intermediate members of arc magma are characterized by low TiO_2 (≈1 wt%), high Al_2O_3 (16 – 19 wt%), low Ni and Cr concentrations. The K_2O concentrations display a wide range suggesting the magma composition varies from low-K tholeiite to ultrapotassic series (Fig. 1). The K_2O contents of continental margin arcs (*e.g.* the Andean arc) are higher compared to that of the oceanic island arcs (*e.g.* the Mariana arc). In many arcs there is an increase of K_2O content with increasing depth of the Benioff-Wadati zone (Dickinson and Hatherton, 1967; Hatherton and Dickinson, 1969). It is shown in Figure 1 that the K content in an active continental margin (the Andean arc) is higher than that in an oceanic island arc (the Mariana arc). The trace element characteristic of arc basalts from several subduction zones (*e.g.*, Hartono, 1997; Hartono *et al.*, 1999; Egins, 1993; Tatsumi *et al.*, 1991) is shown in Figure 2. The figure shows trace element abundance of arc basalts compared to that of normal mid oceanic ridge basalt (N-MORB) and oceanic island basalt (OIB). Arc lavas from many subduction zones are often chemically "depleted" relative to N-MORB. This is observed as depletions in the relative and absolute abundance of immobile trace elements such as the high field strength elements (HFSE: Nb, Ti, Zr) and heavy rare earth elements (HREE: Y, Yb). In contrast, the mobile elements, such as the large ion lithophyle elements (LILE: Ba, Rb, Th, K, Sr) and the light rare earth elements (LREE: La) are higher in arc lavas than in N-MORB. Compared to ocean island basalt (OIB), the arc basalts have comparable LILE abundance (for example Ba, K and Sr in Fig. 2), but the LREE (La, Ce, Nd) concentration are lower.

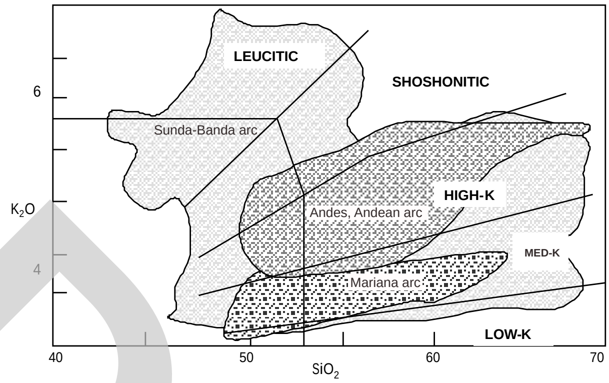

Figure 1. Distribution of arc magmas based on SiO_2 vs K_2O diagram showing fields of the Sunda-Banda volcanics, Mariana lavas represent oceanic island arc, and Andean volcanics, Central volcanic zone, Andes represents continental margin magmatic arcs (after Hartono, 2009). See Hartono (*op cit.*) for the references of each arcs.

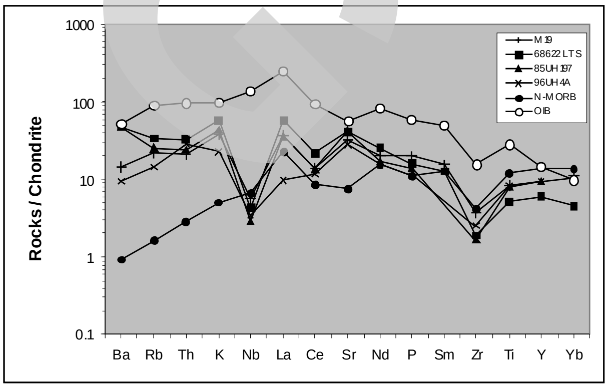

Figure 2. Condrite-normalized trace element concentrations of arc basalts compared to that of N-MORB and OIB. Samples of M 19 basalt from Tongokolo, NE Sulawesi (Tatsumi *et al.*, 1991), 68622 LTS picrite from Ambae, Vanuatu (Eggins, 1993), 85UH197 basalt from Wilis volcanics, Sunda arc (Hartono, 1997), 96UH 4 basalt from Cretaceous Haruyan volcanics, Kalimantan (Hartono, 1997 unpub. data).

Petrogenetic Models

Crustal or mantle sources, primary or secondary magmas

In general the petrogenetic hypothesis of arc magmas can be classified into two main groups, *i.e.*, primary magma as a result of melting of either lithospheric mantle or crust, and those of secondary origin in which felsic magmas are derivative products from a more primitive magma by a process of differentiation. The correlation between K_2O concentrations of arc magmas and the depth to the Benioff-Wadati zone (Hatherton and Dickinson, 1969) was originally interpreted within the plate tectonic concept to imply that arc magmatism was simply the result of melting of the subducting slab. Model which emphasized the role of subducted oceanic crust and treated andesite as primary magma resulted from melting of this crust had become popular by the 1970s.

Right after the birth of plate tectonic paradigm has been entranced firmly as a theory, a number of petrologists believed that melting of subducted oceanic lithosphere would produce arc magmas. Armstrong (1968) suggested that continental sediments being subducted at the margin of continents are the source of arc magmas. Green and Ringwood (1968) conducted experimental studies and suggested that either eclogite or amphibolite within subducted oceanic crust is the potential source for calc-alkaline magma produced in an orogenic environment. They proposed in the model that the calc-alkaline magma is produced in two stage magmatic processes. In the first stage, basaltic magmas, as a result of partial melting of mantle pyrolite (Ringwood, 1966) composition, rises to higher levels and undergoes fractional crystallization at depth less than 15 kilometers to produce quartz-normative basaltic piles. Due to dropping geotherm in the area of basaltic piles, when the basaltic pail remain dry and after basaltic volcanism has ceased, this quartz-normative basalt may transform to eclogite and sink to the mantle. The second stage occurs when the sinking of eclogite reaches depth 100 – 150 kilometers at which the temperature is sufficiently high to melt the eclogite, giving rise to members of calc-alkaline magmas. Ringwood (1974, 1975) proposed that hydrous partial melting of subducted oceanic crust would result in alkaline-rock silicic magmas which rise and react with overlying peridotite mantle producing olivine-pyroxene diapers. The diapers then partially melt and the resultant liquids consequently fractionate garnet, pyroxene and amphibole as they rise to the surface to produce island arc calc-alkaline magmas.

Subsequently the subducting slab melting hypotheses declined in popularity, and this idea had been largely discarded, especially for geochemical reasons. Many arc magmas are too magnesian (Green, 1973; Nicholls and Ringwood, 1973; Nicholls, 1974) and too high of K-Group element concentrations (Gill, 1981; Green, 1980; and see also Fig.2) to be partial melt of basaltic oceanic crust. The high-K group element (Rb, Ba, K) and Th content was argued by Gill (1981) and the literature therein to suggest that andesites could not be a result of melting of ocean floor basalt coexisting solely with a garnet and clinopyroxene residuum. Most other scientists believe that mantle peridotite above the Benioff zone is the potential source of the silicic calc-alkaline magmas. Kushiro (1972) and Mysen and Boettcher (1975) proposed that arc silica-rich magmas, *i.e.*, calc-alkaline andesite or dacite, may result from direct partial melting of uppermantle peridotite in the presence of excess water. However, others (Green, 1973; Nicholls and Ringwood, 1973) suggest that partial melting of upper mantle peridotie would result in basaltic magmas. Melting of water-saturated peridotitic mantel at depths about 30 km is capable of producing low-alkali andesitic magmas, but their Mg-numbers ($Mg^{\#} = 100Mg/Mg+Fe^{+2}$) are similar to those of basalts rather than andesites (Nicholls and Ringwood, 1973), such as boninite (Tatsumi and Ishizaki, 1982; Kuroda *et al*., 1978; Green, 1976). More recently Carrol and Wyllie (1990) show it is not possible to directly produce calc-alkaline magmas at 15 kilobars and over a range of water content by partial melting of tonalitic to gabbroic (eclogitic) lower crust.

Although models involving andesite as primary magma resulted from melting of subducting slab declined in popularity in the middle 1970s, a number of petrologists (Brophy, 1986, Brophy and Marsh, 1986; Myers *et al*., 1986a,b) continued the debate by saying that the Aleutian high-alumina basalt (HAB) is primary origin resulted from melting of a subducted oceanic lithosphere. Brophy and coworkers (*op cit*.) conducted an experimental study of quartz eclogite melting and provide the major and trace element concentrations of the liquid produced has a HAB characters. In this model about 5% sediments are assumed to be incorporated into the process. Based on a mass balance approach on Sr, Nd and Pb isotopic data, Myers *et al*. (1986a,b) supported the quartz eclogite melting model. They believed that melting of mixing between eclogite melt, carbonate and pelagic sediments would result in primary HAB in the Aleutian arc. However, this opinion has been criticized by Crawford *et al*. (1987).

Crawford *et al*. (1987) argued that the Aleutian HAB studied experimentally is different from the HAB originally defined by Kuno (1960). While Kuno (1960) defined HAB as an aphyric lava, the Aleutian HAB is plagioclase-phyric with plagioclase phenocrysts vary from 24 to 45% (Myers *et al*., 1986b). They reasserted that the high Al_2O_3 content of many HAB described in the literature, including the Aleutian HAB, are due to the high content of plagioclase phenocrysts. In a compilation of hundreds of arc basalt from intra-oceanic arc volcanoes, they show a positive correlation between modal % plagioclase and whole rock % Al_2O_3. As a consequent, the presence of plagioclase phenocrysts would sift the data into plagioclase apex in the Di-Qtz-Pl ternary plot.

The inability to explain the chemistry of calc-alkaline magmas resulting from direct melting of either oceanic slab or mantle above the slab caused declining popularity of this hypothesis. The failure then drives petrologists and geochemists to turn their interest back to fractional crystallization of basaltic magma as possible process causing the geochemical variation within arc volcanic rocks. This model basically explains that hydrous partial melting of the peridotitic upper mantle would produce basaltic arc magmas, subsequently the magma will undergo crystal fractionation during its rise to the surface and result in acid calc-alkaline magmas (*e.g*., Grove and Kinzler, 1986; Crawford *et al*., 1987; McCulloh and Gamble, 1991).

The concept of fractional crystallization is one of the classic models of igneous petrology on which many modern petrologists founded their experimental work. Bowen (1928), the pioneer worker, proposed and developed this concept to explain the compositional change of igneous rocks as they evolved from basaltic magma precursor. He believed that acidic magmas (trachyte, rhyolite) are derivative liquids produced by differentiation processes involving Fe, Mg silicate and plagioclase from basaltic parental magmas. However, subsequent workers postulated that fractional crystallization models consider some other phases involved in the process. Osborn (1969) proposed that magnetite precipitation, rather just olivine and pyroxene, play a role in the calc-alkaline fractionation trend. More recently two contrasting fractionation trends, tholeiitic versus calc-alkaline trends, involving olivine, plagioclase and pyroxene from basaltic magmas were proposed (Grove and Baker, 1984; Grove and Kinzler, 1986). The tholeiitic trend develops when fractionation in low pressures involving olivine followed by plagioclase and pyroxene with plagioclase dominating the assemblage. In contrast, fractionation under condition of moderate pressures and undersaturated water with olivine, augite and/ or amphibole as dominant crystallizing phases in the early stage of differentiation would produce calc-alkaline trends.

Although it is widely believed that melting of the mantle wedge above the slab would produce basaltic magmas and subsequent fractionation of this basalt result in more acid members, the nature of the primary magma is poorly described. Depend on partition koefficient (K_D) between olivine and liquids used in the model, primary magmas in equilibrium with upper mantle olivine should have Mg number ($Mg^{\#}$) 69 – 75. This primary magma has concentrations of Ni 235-400 ppm (Sato, 1977), Cr 500-600 ppm (Perfit *et al*., 1980), and low FeO*/MgO (< 1, Tatsumi *et al*., 1983). If these criteria are adopted, there are only few primary magmas are known in arc environments.

MORB-Type or OIB-Type Sources

It is widely accepted that melting of mantle wedge above the slab would result in arc basalts, but the nature of this mantle is still unclear, either of MORB-like (Davidson, 1987; Woodhead *et al*., 1993; Eggins, 1993) or OIB-like sources (Morris and Hart, 1983; Arculus and Powel, 1986; Regan and Gill, 1989). The depletion of HFSE, and to some extend LILE (*e.g*. La of Moris and Hart, 1983) of arc basalts suggest an OIB source signature of the mantle wedge without any enrichment of LILE. This argument requires the presence of titanite phases (sphene, perovskite, ilmenite, rutile) to explain the depletion of HFSE and LILE. However, experimental works (*e.g*., Foley and Wheller, 1990; Kelemen *et al*., 1993; Mc Culloh and Gamble, 1991) have shown that titanite phases can not exist in the melt relevant to the arc magma source. In contrast, the mantle with MORB characters believed that depletion in HFSE due to extraction of MORB before being remelted to produce arc magmas (Woodhead *et al*., 1993). Melting is believed to be initiated in the mantle wedge above the slab caused by the release of H_2O and other volatiles (which lower the mantle solidus) and LILEs from downgoing slab producing enrichment in these elements in arc basalts relative to MORB. The work of Tatsumi *et al*. (1986) on relative mobility of trace elements in the fluid phase released from subducted slab support the mantle melting hypothesis. Tatsumi *et al*. (*op. cit*.) suggested that enrichment of LILE and LREE concentrations in arc basalts was caused by tranfering those elements by fluid released from downgoing slab into their source or sources. Fractional crystallization of this primary basaltic magma, with or without assimilation and magma mixing, would produce more evolved magmas (andesitic and more silicic magmas).

Isotopic data, both radiogenic and non-radiogenic, are very useful tool for better understand petrogenesis of arc magmas. Figure 3 shows plot of Sr and Nd isotope values of rocks from several arcs compared to that from mid-ocean ridge (for example the Indian MORB) and ocean island (for example the Cristmas Island). The Sr and Nd isotopic characteristics of the arc rocks are sitting within the mantle array suggesting arc magma could be generated from either depleted asthenospheric mantle sources (MORB characters) or enriched

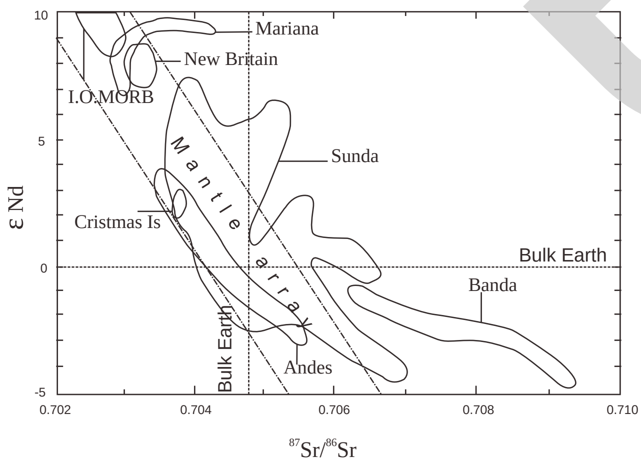

Figure 3. Sr and Nd isotopic composition of some arc rocks plotted on εNd vs $^{87}Sr/^{86}Sr$. Thes compostion of Indian ocean (IO) MORB and OIB (Cristmas Is) are shown for comparison. Data sources: Sunda arc (Whitford, 1975; Whitford *et al*., 1978; Whitford *et al*.,1981; Edward *et al*., 1991; Foden, 1979; Foden and Varne, 1980; Varne and Foden, 1986; Wheller and Varne, unpub.data; Stolz *et al*., 1990; Hartono, 1997), Banda arc (Whitford and Jezek, 1979; Whitford *et al*.,1981), Mariana arc (De Paolo and Wesserberg, 1977), New Britain arc (De Paolo and Johnson, 1979), Andes, Central Chile (Hildred and Moorbath, 1988), Indian Ocean MORB (Ito *et al*., 1987), and Cristmas Island (Hart, 1988).

mantle source unmodified by subduction zone components (OIB characters). The sift to higher values of $^{87}Sr/^{86}Sr$ and lower $^{143}Nd/^{144}Nd$ may due to crustal contribution in the magma source (*e.g*., Central Andes of Hildreth and Moorbath, 1988), crustal contamination during magma ascend (*e.g*., Lesser Antilles arc of Davidson, 1985: not in the figure, the Wilis volcanics, Sunda arc of Hartono, 1997), or involvement of terrigenous sedimentary components (*e.g*. Banda arc of Whitford and Jezek, 1982). The sift to higher values of $^{87}Sr/^{86}Sr$ with relatively constant value of $^{143}Nd/^{144}Nd$ of some rocks from New Britain (De Paolo and Johnson, 1979) and Mariana (De Paolo and Wasserberg, 1977) arcs is believed to be sea water involvement in magma generation.

Sr and Nd isotopic data are useful to identify whether or not an arc magma has been contaminated by crustal components. There are two types of contaminataion, *i.e*., crustal contamination and source contamination. Crustal contamination is contamination of mantle-derived magmas through direct assimilation of the crust when the magma ascends through it. Source contamination, on the other end, involves enrichment of crustal components, via either bulk mixing or subducted slab-derived melt, into the mantle. A combination between radiogenic (*e.g*., $^{87}Sr/^{86}Sr$) and non-radiogenic (*e.g*., $\delta^{18}O$) isotopes is potential tool to distinguish between source contamination and crustal contamination (Davidson, 1985; Chen *et al*., 1990; Hartono, 1994).

From the above discussion it can be summarized that the petrogenesis of arc magmas is complex problem, involving multisources and multiprocesses. Most petrologists believed that melting of the upper mantle would produce primary arc magmas. Melting is believed to be initiated in the mantle wedge above the slab caused by the release of H_2O and other volatiles (which lower the mantle solidus) and LILEs from downgoing slab producing enrichment in these elements in arc basalts relative to MORB (*e.g*., Nicholls and Ringwood, 1973, Ringwood, 1977; Arculus and Powel, 1986; Davidson, 1987). The work of Tatsumi *et al*. (1986) on relative mobility of trace elements in the fluid phase released from subducted slab support the mantle melting hypothesis. Tatsumi *et al*. (*op. cit*.) suggested that enrichment of LILE and LREE concentrations in arc basalts was caused by tranfering those elements by fluid released from downgoing slab into their source/

or sources. Fractional crystallization of this primary basaltic magma, with or without assimilation and magma mixing, would produce more evolved magmas (andesitic and more silicic magmas).

Adakite Phenomena

It is widely accepted that most arc magmas generated by melting of the mantle wedge above the slab induced by hydrous fluids released during dehydration reaction in the subducted lithosphere. However, a number of petrologists (*e.g.*, Defant and Drummond, 1990; Defant and Kepezhinskas, 2001; Reich *et al*., 2003) continues the debate that in some arcs rock with specific geochemical characteristics might be a result of melting of subducted oceanic crust. A petrological term of adakite comes from the island of Adak in the Aleutian Islands, Alaska, and was firstly introduced by Defant and Drummond (1990) to define volcanic and intrusive rocks in Cenozoic arcs associated with subduction of hot, young ($\leq$25 my) oceanic lithosphere. The significant characteristics of adakite are high Sr ($\geq$400 ppm) and low HREE (Y $\leq$18 ppm, Yb 1.9 ppm) concentrations, and consequently high Sr/Y ratios and low Y contents (Fig. 4). The rocks are also characterized by $\geq$56% SiO_2, $\geq$15% Al_2O_3, < 3% MgO. The high Sr concentration indicate melting of plagioclase or absence of plagioclase in the residue, while the low Y is an indicative of garnet (to a lesser extent, of hornblende or clinopyroxene) as aresidual or liquidus phase. The higher Sr/Y compared to that produced by crystal fractionation suggests of garnet and amphibole as residual or liquidus phases.

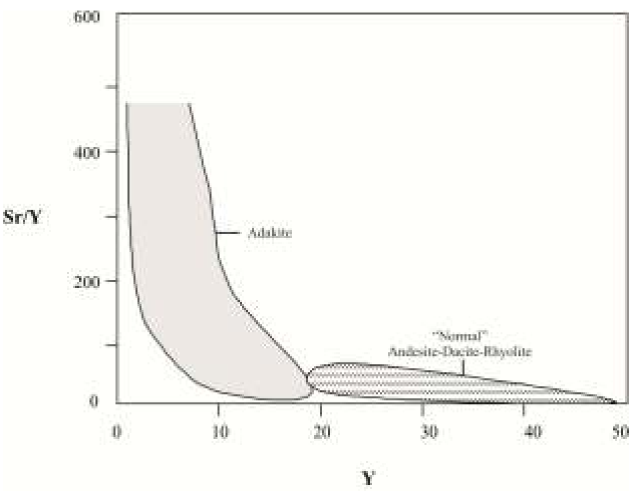

Figure 4. Field of adakite compared to that of "normal" andesite-dacite rhyolite (After Defant and Drummond, 1990).

However, subsequent literatures on adakite become confusing, because many igneous rocks with geochemical characteristics (particularly the high Sr low Y and Yb contents, and high Sr/Y) similar to adakite, but they are not related to subduction of a young oceanic lithosphere. This type of rocks was called "adakitic rocks" by Castillo (2006). They might be a melting product of thickened lower crust (Peacock *et al*., 1994; Kay and Kay, 1993; Chung *et al*., 2003), dead slab (Peacock *et al*., 1994; Hartono and Suyono, 2006) or even mantle (Chiarida *et al*., 2004; Cosky *et al*., 2005). Unlike the adakite originally defined by Defant and Drummond (1990) which is characterized by low $Mg^{\#}$, adakite from a number of arcs, for examples, the Northern Oregon Cascadia Subduction Zone (Cosky *et al*., 2005), Dexing, South China (Wang *et al*., 2006), the Certaceous Haruyan adakitic rock (Hartono and Sulistyawan, 2010) has high $Mg^{\#}$. This high $Mg^{\#}$ suggests involvement of mantle peridotite, either directly or indirectly. The adakite or adakitic rock now has a broad magmatic origin (the readers are suggested to have more reading of Castillo, 2006) for comprehensive review on the adakite petrogenesis). They might be generated by the equilibration of subducted oceanic crust melt with mantle peridotite (*e.g*., Kay, 1978; Bourdon *et al*., 2002; Cosky *et al*., 2005), reaction between lower crust melts and mantle peridotite (Xu *et al*., 2002; Wang *et al*., 2006; Hartono and Sulistyawan, 2010), or mantle metazomatism derived melts (Castillo *et al*., 1999; Chiarida *et al*., 2004).

Relation to Mineral Deposit Formation

The study on petrogenesis of arc magma to better understand the process of mineral deposit formation has been conducted by a number of scientists (*e.g*., Kay and Mpodozis, 1999; Oyarzun *et al*., 2001; Reich *et al*., 2003; Chiaridia *et al*., 2004) and has been reviewed by Hartono (2009). This section presents only a summarized reviewed of Hartono (*op.cit*.), and would not discuss in detailed on petrogenetic models cause the mineralization.

From the work of Hartono (2009.), it is clear that the occurrence of mineral deposit is not simply related to single geological phenomenon or process. The fact that, two locations with the same rock-types or similar tectonic development have different metallogenic potential (the one is barren and the other is fertile) indicates the formation of the deposits is not simple. Subsequently the phenomena suggest the important of arc magma petrogenetic studies before a detailed exploration research on mineral deposit occurrences is conducted. Table 1 shows an example of the relationship between type of mineral deposits, rocks association, magma genesis, and tectonic significant for some deposits compiled by Hartono (2009).

Overall the petrogenetic study would give a better understand of whether the hydrothermal system is long-live or short-live. High grade deposits are formed when the boiling hydrothermal fluid is long-lived, localized and abrupt rather than distributed. The work of Chiaradia *et al*. (2004) on Cenozoic mgmatism in Ecuador, Chile (see Table 1) is a good example. A long-lived hydrothermal system is not maintained in the generation of the Lower Miocene to Recent adakite in Equador. Chiaradia *et al*. (*op.cit*) suggested this adakite is produced by mantle-derived magmas assimilated residual garnet-bearing rocks (possibly underplated metabasalt as result of compressional initiated 9 my ago) at sub-crustal level. Subsquently the magma evolved through plagioclase free and amphibole fractionation, a similar process with MASH (melt, assimilation, storage, and homogenization) in sub-crustal level. The magma then would erupt violently without significant residence in an upper crustal magma chamber, a process conducive for porphyry-Cu and related deposits (Tosdal and Richards, 2001).

Conclusion

The petrogenesis of arc magmas is not simple, involving multi sources and multi processes. The magma generation in subduction zone environment is subject of controversy and widely discussed among petrologists. The different is mainly because of the wide compositional variation among island arc basalts and their differences from mid-ocean ridge and oceanic island basalts. As subducted-related magmatism is direct response to tectonic and chemical processes operating at convergent plate margins, petrogenetic studies on arc magmas not only focus on chemical composition of the magma, but also consider its tectonic or geological history. Since there is a contrasting different isotopic values between mantle and crust, the isotopic data, both radiogenic and non-radiogenic are very useful tool for better understand the petrogenesis of arc magma.

It has long been known that a closely relationship occurred between magmatic activities in convergent plate margins and mineral deposit formations. A study on arc magma generation might give significant contribution for exploration studies on mineral deposit formations. More specifically the knowledge of arc magma petrogenesis may be useful for better understand of whether the hydrothermal system could be long-live or short-live.

Table 1. A Correlation Between Type of Mineral Deposits, Rock Association, Magma Genesis, and Tectonic Significances (After Hartono, 2009)

Location	Type of Deposits	Rock Association	Petrogenesis Related to Mineralization Processes	Geology/ Tectonics
Central Andean (22°S – 33°S) Kay & Mpodozis (1999)	Giant porphyry copper	Miocene "normal" calc-alkaline andesitic rocks	Early process of subduction resulted in calc-alkaline andesitic magma. Fluid released from dehydration of subducting slab promoted amphibole crystallization that underplated or intruded the lower crust. Continuous subduction with low angle followed by thickened crust capable of changing residual mineralogy from amphibole to garnet-bearing. Mineralization occur when amphibole breakdown to produce fluid.	Shallow subduction followed by thickened crust. Fluid released from dehydration of subducting slab, but did not become available for mineralization.
Los Pelambres, Central Chile (Reich *et al*., 2003).	Porphyry copper	Late Miocene Adakite	A garnet-amphibole magmatic source of young hotspot rocks. The deposits were formed when both shallowing of the subduction angle and crustal thickening occurred in the Miocene-Pliocene.	Low-angle, slow down subduction. Crustal thickening.
Chuquicamata, Northern Chile (Oyarzun *et al*., 2001).	Huge porphyry copper deposits	Late Eocene – Early Oligocene adakite	Adakite produced by fast, oblique flat subdcution. Absence of volcanicsm, under prevailing compressional condition, prevented the escape of SiO_2 from adakite, S-rich, highly oxidezed magma ("closed porphyry system"), which allowed formation of huge mineral deposits	Fast, oblique convergence led to flat subduction and direct melting of subducting plate. Absence of volcanism during compression
Lomas Bayas, Northern Chile (Oyarzun *et al*., 2001)	Small Porphyry copper	Paleocene – Early Eocene normal calc-alkaline	Coeval volcanic activity during formation of calc-alkaline porphyries allowed development of "open system", hence to outgassing, resulted in small mineral deposits	Coeval volcanism during mineral deposit formation.
Ecuador (Chiaradia *et al*., 2004)	a. No minerali-zation b. Porphyry copper and epithermal	a. Late Miocene – Recent (LMR) adakite b. Eocene-Late Miocene (ELM) normal calc-alkaline	a. Mantle-derived magma interacts with residual garnet-bearing rocks at the base of the crust, evolved at the same time through plagioclase-free and amphibole fractionation (similar process to MASH) producing an adakite-type magma. Under this condition magma ascent to the surface may be restricted to overpressured magmas that would erupt violently without significant residence in upper crustal magma chamber. This scenario is unfavorable for porphyry-Cu and epithermal mineralization. b. AFC process at shallow crustal levels (< 20 km). The tectonic history allow the ELM magma ascent continuously to shallow crustal levels.	a. Tectonic compression following subduction cause the LMR magma pounded at the mantle-crust interface yielding adakite-type signatures b. Transpressional tectonic ± extension.

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