CONTRIBUTION OF ARC MAGMATISM STUDIES IN EARLY STAGE MINERAL EXPLORATION

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ABSTRACT

Indonesia contains at least 15 volcano-plutonic arcs with total length of approximately 9,000 km. The eight arcs contain known mineral deposits, while the rest may have mineral deposit prospects. The discovery of new mineral resources depends on research into the genesis of ore deposits and improved methods of finding them. In order to reduce a high exploration cost, knowledge of arc magma genesis is very important in mineral exploration before further study on mineral deposit genesis. Review on a number literatures suggests there is no linear correlation between potential porphyry-Cu/ epithermal mineralization and a single petrological/ geological factor. Mineral deposit formation is a product of interplay of magmatism, tectonics, volcanism, and fluid processes.

Keywords : arc magma genesis, ore deposits, exploration

SARI

Indonesia mempunyai sekurangnya lima belas busur vulcano-plutonik dengan total panjang sekitar 9000 km. Delapan busur telah diketahui mengandung endapan mineral, sementara yang tujuh sisanya mungkin prospek. Ditemukannya sumber mineral baru bergantung pada penelitian terhadap genesis endapan dan peningkatan metode untuk menemukannya. Untuk mengurangi biaya eksplorasi yang tinggi, pengetahuan tentang magma di daerah penunjaman sangat penting di dalam eksplorasi mineral sebelum studi lanjutan terhadap genesis endapan mineral dilakukan. Kajian dari sejumlah literatur memperlihatkan bahwa, tidak ada korelasi linear antara mineralisasi yang potensial, baik porfiri-Cu atau epitermal dan satu faktor petrologi/ geologi. Pembentukan deposit mineral merupakan hasil kegiatan magmatisme, tektonik, vokanisme, dan proses larutan.

Kata kunci : genesis magma busur, endapan bijih, eksplorasi

INTRODUCTION

The Indonesian archipelago contains an appreciable extent of Earth's Cenozoic volcano-plutonic arcs. There are at least 15 volcano-plutonic arcs with total approximately 9,000 km length, and eight (8) of them contain known mineral deposits. The rest seven (7) arcs may contain gold and copper prospects, but no production or resource figures are available (Carlile and Mitchell, 1994). The present configuration of the archipelago was produced by a complex history of tectonic events and processes, including subduction and arc magmatism, back-arc spreading, arc migration and rotation, collision, strike-slip faulting, as well as possibly crustal extension. Katili (1975) and Hamilton (1979) suggested that these events accompanied the northward drift of Australia-New Guinea plate from Gondwana followed by the late Cenozoic collision of this plate and Sulawesi with the Sundaland.

The continued importance of the Indonesian mining industries depend on the discovery of new mineral resources, which in turn depends on research into the genesis of ore deposits and improved methods of finding them. However, most of mineral deposit studies in Indonesia were only focused on the system and type of mineralization and very rare, if not absent, studies on magma origin in relation to metal deposit formation.

It is generally known that ore mineral deposit formations are related to magmatism. The spatial relationship that exists between many hydrothermal deposits and igneous rocks suggests that consolidating magmas are the sources of hydrothermal solution. In mineralization processes magma is not only as a heat source to drive mineralization systems, but also as a source of the

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metals and water. The facts that many associated intrusion areas are barren and the others are fertile in mineral deposits indicate a complex history of ore mineral deposit formations. An integrated study on the key processes of magmatism, volcanism, tectonics, fluid processes and ore formation is necessary to better understand whether or not some particular deposits are economically significant for industrial purposes.

This paper presents a review on the magmatic origin and its genetic link to mineral deposit formation of porphyry-Cu/ epithermal mineralization, rather than rock types, based on previous published papers. As magma origins and processes are greatly influenced by a geodynamic evolution, a review study on geological condition, tectonic development, and magmatism as well as their role to mineral deposit formations are the focus of this study.

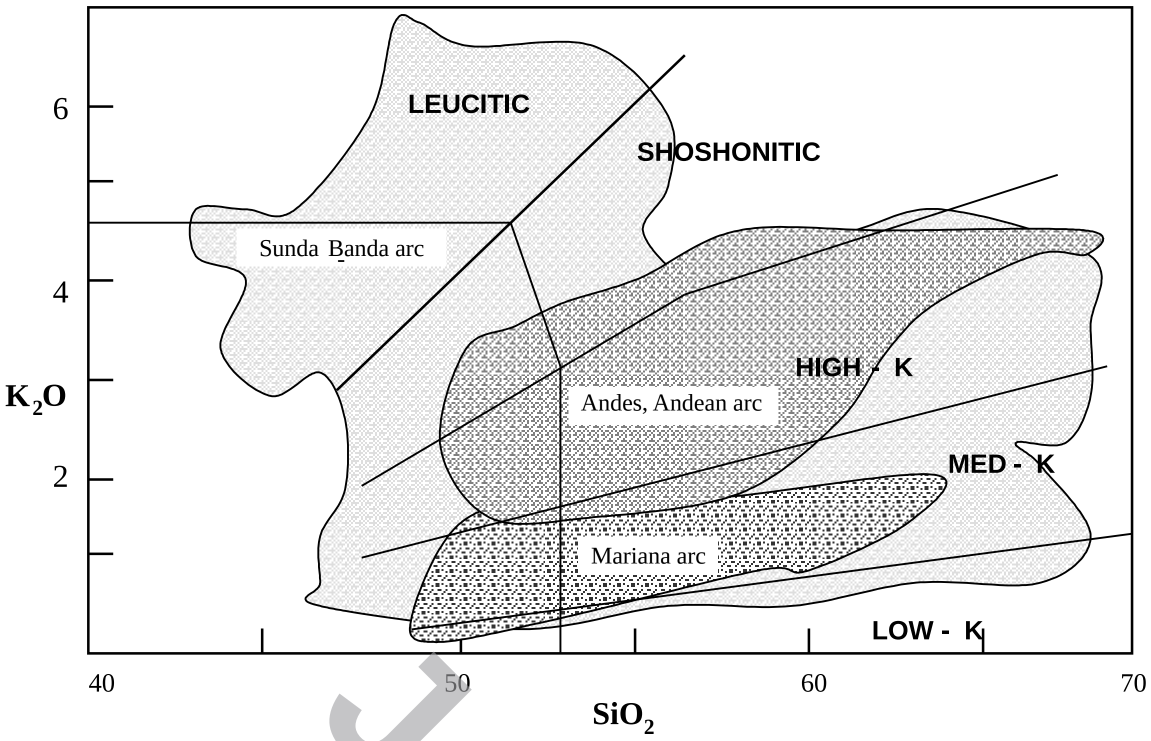
Geology, Tectonics and Magmatisms

Arc magmatism is a direct response to tectonic and chemical processes operating in subduction zones. It means the types and compositions of magmas resulted in this tectonic setting are strongly influenced by geological condition and tectonic developments of the area. The wide composition variation of arc magmas from low-K tholeiitite through calc alkaline basalt-andesite-dacite-rhyolite to leucitite and related ultrapotassic mafic volcanics (Figure 1) is an indicator of complex origins of the magma. The differences are mainly caused by their different in magmatic source or sources and processes by which magma ascends to the surface to form volcanic rocks.

Possible sources for convergent plate boundary magmas include subducted oceanic crust, the overlying mantle wedge and the arc crust. Early hypothesis (*e.g.*, Green and Ringwood, 1968; Marsh and Carmichael, 1974; Nicholls, 1974) postulated that partial melting of an eclogitic source (subducted oceanic crust) might be significantly important in the generation of magma of andesitic composition. Several petrologists (Brophy and Marsh, 1986; Myers *et al*., 1986; Johnstone, 1986) suggested that partial melting of the quartz eclogite source would produce high alumina basalt liquids. However, there are objections to this eclogitic source models on the basis of geochemical data (Gill, 1981; Crawford *et al*., 1987). Crawford *et al*. (1987) demonstrated experimentally that high-alumina basalt can be derived from fractionation of peridotite partial melts. Presently, following the works of *e.g.*, Woodhead (1988), Foden and Green (1992), and Eggins (1993), most petrologists believed that arc magmas were originated from melting of mantle wedge above the slab by hydrous fluid released during dehydration reaction in the subducted lithosphere or by pressure-release melting due to upwelling in the subarc mantle (Sisson and Bronto, 1998). Others (*e.g.*, Defant and Drummond, 1990; Peacock *et al*., 1994; Prouteau *et al*., 1996; Stern and Killian, 1996; Reich *et al*., 2003; Cosky *et al*., 2005; Hartono and Suyono, 2006) continued the debate on the role of slab melting in arc magmatism by suggesting that rocks with specific geochemical signatures, called adakite, present in some arcs.

Arc magmas originated in a subduction zone with thicker crust, such as the Andean magmas, commonly have higher K_2O contents compared to the magma formed in a thinner crust (for example the Mariana lavas). The high K_2O and other K-group element (Ba, Rb, Th) contents supported by high concentration of other incompatible elements (LREE) and $^{87/86}Sr$ isotopic ratios might indicate of crustal contamination during the magmas ascent to the surface (*e.g.*, Hartono, 1994; Hickey-Vargas *et al*., 1989; Davidson, 1987). The positive correlation between the K2O contents of arc volcanoes, such as in Sunda arc Indonesia, Lesser Antilles and other island arcs and the depth of the underlyng Benioff-Wadati zone (Hatherton and Dickinson, 1969) was originally interpreted simply the result of melting of the subduting slab. However, more careful and intensive studies in arc mamgmatic origin (e.g., Varne, 1985; Varne and Foden, 1986; Stolz *et al*., 1988; Edward *et al*., 1994) show that the high K content of volcanoes of many arcs is caused by enrichment of this element in the source of the magma. Increasing the K-group elements, except Ba, and $^{87/86}Sr$ isotopic ratios of the volcanoes from East Java to West Java might also be an indication of crustal contamination (Hartono, 1997). In contrast, the concentration of Ba in the volcanoes gradually decreases from East Java to the West Java and was interpreted by the author as the richer Ba contents of the magmatic source in East Java.

In many localities, such as in the Piip volcano in the Aleutian arc (Yogodsinski *et al*. 1994), the Tonga arc (Falloon and Green, 1986), the Setouchi volcanic belt in Japan arc (Tatsumi, 1982; Tatsumi and Ishizaki, 1982), the West Philippine-Mariana regions



Gambar 1. Distribution of arc magmas based on SiO_2 vs K_2O. Field of the Sunda-Banda volcanics (Wheller *et al*., 1986); Mariana lavas represent oceanic island arcs (Woodhead, 1988); Andean volcanics, Central volcanic zone, Andes represents continental margin magmatic arcs (Harmon *et al*., 1984).

(Crawford *et al*., 1981), the Meratus Range Kalimantan (Hartono *et al*., 1999) and many others, unusual high-magnesian andesites (including boninites) are found. A number of studies in the origin of such magnesian andesites indicate the tectonic processes, in which the magma formed, play an important role. In the Piip volcano and the Meratus Range, the magnesian andesites were formed by a reaction between basaltic arc magma and a hot mantle peridotite at the base of the crust. Transpressional tectonics in the Piip volcano (Yogodsinski *et al*. 1994) and a collision between the Pastenoster microcontinent and Kalimantan continent (Hartono, 2003a) might cause the arc magma to pool immediately below the crust. These pooling magmas then reacted with a hot upper mantle peridotite to form the magnesian magma. An experimental study (Kelemen, 1995), based on the similar composition between the continental crust and the calc-alkaline magnesian andesite, support the reaction mechanism in producing arc magnesian magmas. In West Philippine-Mariana regions magnesian andesites (boninite) might be formed in an island arc-back arc basin system. The generation of the boninite series magma appears to occur at the point when arc volcanism ceases and back-arc spreading is initiated (Crawford *et al*., 1981). Several studies show that magnesian andesite magmas are not differentiated product, but they may represent a primary melt generated in upper mantle. A melting phase relation study at high pressure (Tatsumi, 1982) is capable of explaining the Setouchi magnesian andesite which was produced in the early stage of lithospheric subduction. Under this tectonic condition considerable amount of water and relatively high temperature were available in the uppermost mantle.

From the above discussion, it is clear that the arc magma generation is a complex origin with multi sources and multi processes. The geological conditions and tectonic development are two great factors that influence the chemical processes in magma generation. Furthermore, facing the fact that some volcanic rocks are barren and some others are fertile in mineral deposits, one important question is: "what is the relationship between magmatic origin and mineral deposit formation, especially the Cu-Au deposits?" The following section presents this particular discussion.

Arc Magmatism and Mineralization

It has long been known that a closely relationship occurred between magmatic activities in arc systems and mineral deposit formations. The interplay of several magmatic, tectonic and hydrothermal processes occurring at convergent plate margin resulted in precious metal-bearing epithermal and porphyry-copper deposits. The relationship between rock types and occurrences of the metal deposits has long been studied (*e.g*. Sillitoe, 2000; Tosdal and Richards, 2001 for recent review). They are genetically associated with broad range compositions of arc magmas from low-K- through high-K-calc-alkaline to alkaline, most are andesitic composition. Evolution of parental magma at shallow crustal levels is an essential step in the process conducive to porphyry-Cu and related deposits (Tosdal and Richards, 2001). Intrusion-related hydrothermal systems get their thermal energy and variable amounts of volatiles, metals and other components from subduction-related magmas emplaced at shallow levels of the Earth's crust (*e.g*., Sawkins, 1990).

Recently, more detailed studies on a relationship between tectonics, magma genesis and mineral deposit formation were done by several authors (for example: Table 1). Models for mineralization over a shallow subduction zone and thickened crust were proposed by, *e.g*., Kay and Mpodozis (1999) and Reich *et al*. (2003). The model of Kay and Mpodozis (1999) was based on a study of the Central Andean Miocene giant ore deposits (between 22°S and 33°S), the area in which some of the world's richest and largest Tertiary copper and gold deposits. Trace element data suggest that fluid for mineralization was derived from dehydration of the shallow subduction slab, but did not become available for mineralization until amphibole-bearing assemblage breakdown in tectonically thickened crust. In Los Pelambers porphyry copper deposits (Reich *et al*., 2003) mineralization occurs in association with adakite-type rocks. This type of rocks resulted from a slow-down W-E segment Juan Fernandez Ridge subduction of a previously rapid southward migration of a NE ridge-trench collision. This particular tectonic condition might cause melting of subduction of young hotspot rocks under flat condition producing an adakite magma.

A genetic link between adakite magma and porphyry copper deposit is also shown in huge Chuquicamata porphyry copper deposits (Oyarzun *et al*., 2001). A fast oblique subduction of the Farallon plate under South American plate led to flat subduction and direct melting of the subducting plate producing an adakite-type magma. Under prevailing compressional condition, volcanic activities might not be appear and prevent the escape of SiO_2 from adakite, sulphur-rich, highly oxidized magma (“closed porphyry system”), which allowed formation of huge mineral deposits. In contrast coeval volcanism during formation of the “normal calc-alkaline” rocks in Lomas Bayas, Northern Chille (Oyarzun *et al*., 2001) permit the development of “open porphyry system” causing outgassing, and small porphyry-Cu mineralization.

However, not all adakite-type rocks have genetic links with mineral deposit formation. The Late Miocene to Recent (LMR) adakite magma of the Ecuador continental arc (Chiaridia *et al*., 2004) does not associate with mineralization, except the epithermal high-sufidation mineralization of Quimsacocha. Different from common adakites that are originally derived from melting of the subducting slab, the LMR adakite was proposed by Chiaridia *et al*. (2004) as a product of an interaction between a mantle derived melt and residual garnet-bearing rocks at the base of the crust. The authors argued that the LMR rocks were formed during a period of tectonic compression, which caused trench-parallel structures were sealed and magmas were impended to rise by buoyancy. This condition causes the LMR magma could have pounded in the lower crust (at the depths around 40 – 50 km). The pounding magma partially melts and assimilates the lower crust and, at the same time, evolved, in a process similar to the MASH hypothesis of Hildreth and Moorbath (1988), producing adakite magma. Porphyry-Cu and epithermal mineralization could not be maintained in this scenario, because the pounding magma would overpressure and erupt violently without significant residence in upper crustal magma chamber.

In contrast, the Eocene-Late Miocene (ELM) “normal calc-alkaline” rocks are spatially and temporally associated with the major districs of porphyry-Cu and epithermal deposits of Ecuador. The deposit is relatively small in size (<<200 Mt), when compared to other Central Andean deposits. Chiaridia *et al*. (2004) envisaged that the ELM magma originated from mantle-derived calc-alkaline magmas that had evolved at the shallow crustal magma chamber through plagioclase-dominated fractionation and assimilation (an AFC process). The emplacement of

Table 1. A Correlation Between Type of Mineral Deposits, Rock Association, Magma Genesis, and Tectonic Significances

Location	Type of Deposits	Rock Association	Petrogenesis Related to Mineralization Processes	Geology/ Tectonics
Central Andean ($22^{O}S – 33^{O}S$) 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.

magma to upper crustal levels happened during transpressional ± extensional tectonics.

DISCUSSION

From the above review study, it is clear that there is no linear correlation of mineral deposit formation with a single factor of petrological/geological phenomena (rock-type association, geological condition and tectonic evolution). The two locations with the same rock-types, or similar tectonic development, may have different metallogenic potential, the one is barren and the other is fertile in mineral deposits. The fact that the same rock-type have different petrogenetic processes (including the magmatic source or sources) may explain the different in metallogenesis. The adakite-type rock from Los Pelambers, Central Chile (Reich *et al*., 2003) and that from Ecuador (the LMR adakite of Chiaradia *et al*., 2004) are good examples. The Los Pelambers adakite was originally from a young oceanic crust source and was formed when shallowing angel of subduction and thickening crust occurred. While the LMR adakite was a result of an interaction between mantle-derived magma and lower crust during a period of dominant tectonic compression. This different origin might cause different in metallogenic processes.

In principle, the concentration of gold in hydrothermal fluids is low, because gold-sulphide is not very soluble. However, hydrothermal systems are usually large and long-lived. High-grade deposits are formed when the boiling of hydrothermal fluid is long-lived, localized and abrupt rather than distributed. The origin of LMR adakite, which is similar process with MASH hypothesis suggests that a long-lived hydrothermal system might not be maintained. The pounding LMR magma and at the same time evolved at the lower crust or subcrustal level (caused by tectonic compression) would erupt violently without significant residence in upper crustal magma chambers. Since evolution of parental magmas at upper crustal levels is an essential step in the process conducive for porphyry-Cu and related deposits (Tosdal and Richards, 2001), the scenario of the LMR magmatism would unfavorable for porphyry-Cu or epithermal mineralization. Alternatively, as suggested by Chiaradia *et al*. (2004), the paucity of porphyry-Cu/ epithermal deposits associated with LMR magmatism might be simply the deposits concealed under the thick recent volcanic cover. The volcanics distribute in the central and northern Ecuador, where the majority of LMR rocks occur. In contrast, such recent volcanic cover is absent in southern Ecuador, where ELM magmatism occur.

A short-lived hydrothermal system is also indicated in the Tertiary magmatism in South Kalimantan (Figure 2; Hartono, 2003a). The Tertiary volcanic and subvolcanic rocks in South Kalimantan are anomalously high-magnesian contents, which were interpreted as the result of a reaction between the Cretaceous subducted mantle-derived magma and hot mantle peridotite. The reaction occured when the magma pounded in the lower crust-upper mantle during tectonic compression from late Paleocene (60 my) to late Lower Eocene (50my). Tectonic extension during late Lower Eocene - late Middle Eocene resulted in horst and graben in the southern part of the Meratus High (Sanyoto and Sukamto, 2000) and allowed the pounding magma ascended to shallow crustal magma chamber. There might be a hydrothermal system related to andesitic magma evolution in a magma chamber producing epithermal (?) gold that may have been eroded and resulted in a wide distribution alluvial gold in South Kalimantan. However, the hydrothermal system probably would not be long-lived, because there was no new magma produced to feed the crustal chamber.

In contrast, a long-lived hydrothermal system might be maintained during the formation of porphyry-Cu and epithermal deposits associated with the Ecuador ELM magmatic rocks. These rocks originated from mantle-derived magmas that have evolved by AFC process in the upper crustal magma chamber. The evolution of ELM magma occurred during prolonged period of dominant transpression ± extension tectonics, which allowed producing new magma to feed the magma chamber. This scenario could cause a long-lived hydrothermal system.

A long-lived hydrothermal system might also be suggested in the Kelian gold deposists (Figure 3; Hartono, 2003b). Hartono (*op cit*.) proposed that the feeding a deep mantle source magma (OIB-type magma) into the Tertiary Kelian magma chamber would extend the life of hydrothermal system to be longer. This argument was based on a mixing model between OIB-type magma and the Tertiary Kelian magma. The model shows that the Magerang, East Prampus and the Plio-Pleistocene Matulang volcanics (Mt. Acau) are sitting on the mixing line, suggesting the rocks from those three areas were derived from mixing of the OIB-type and Tertiary Kelian magma.

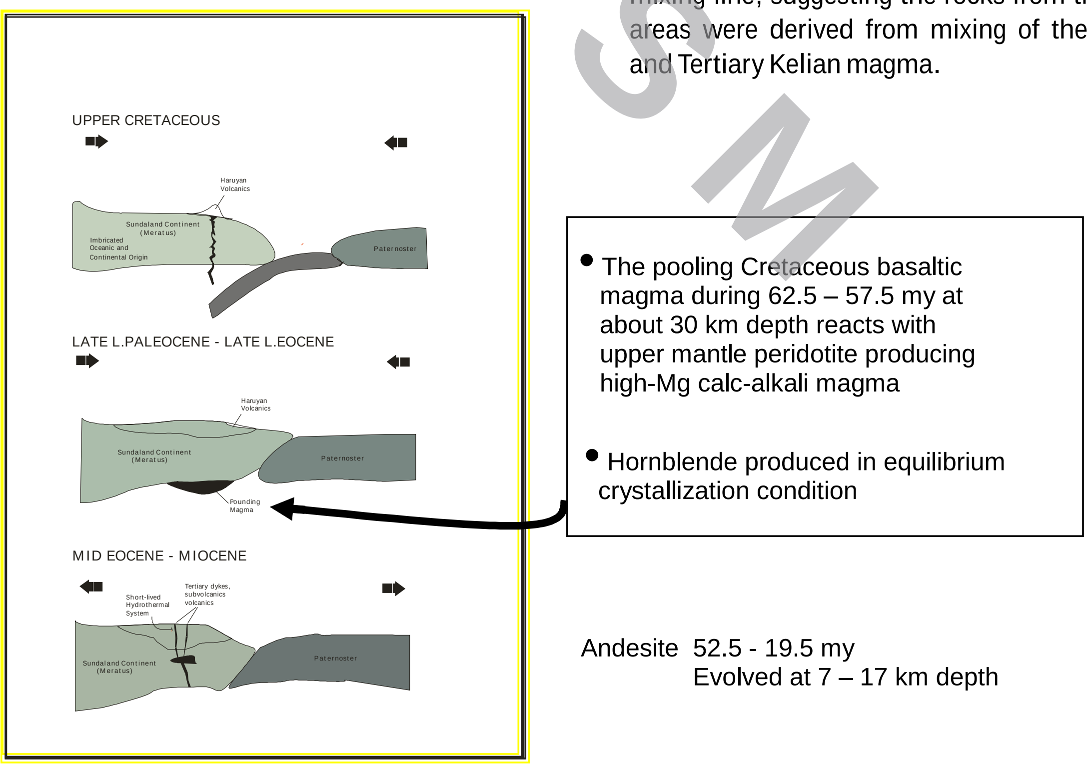


Figure 2. Schematic diagram showing the tectonic development of South Kalimantan area related to the origin of the magnesian Tertiary volcanics formation. A long-lived hydrothermal system could not be maintained because there was no new magma fed the magma chamber (After Hartono, 2003a)

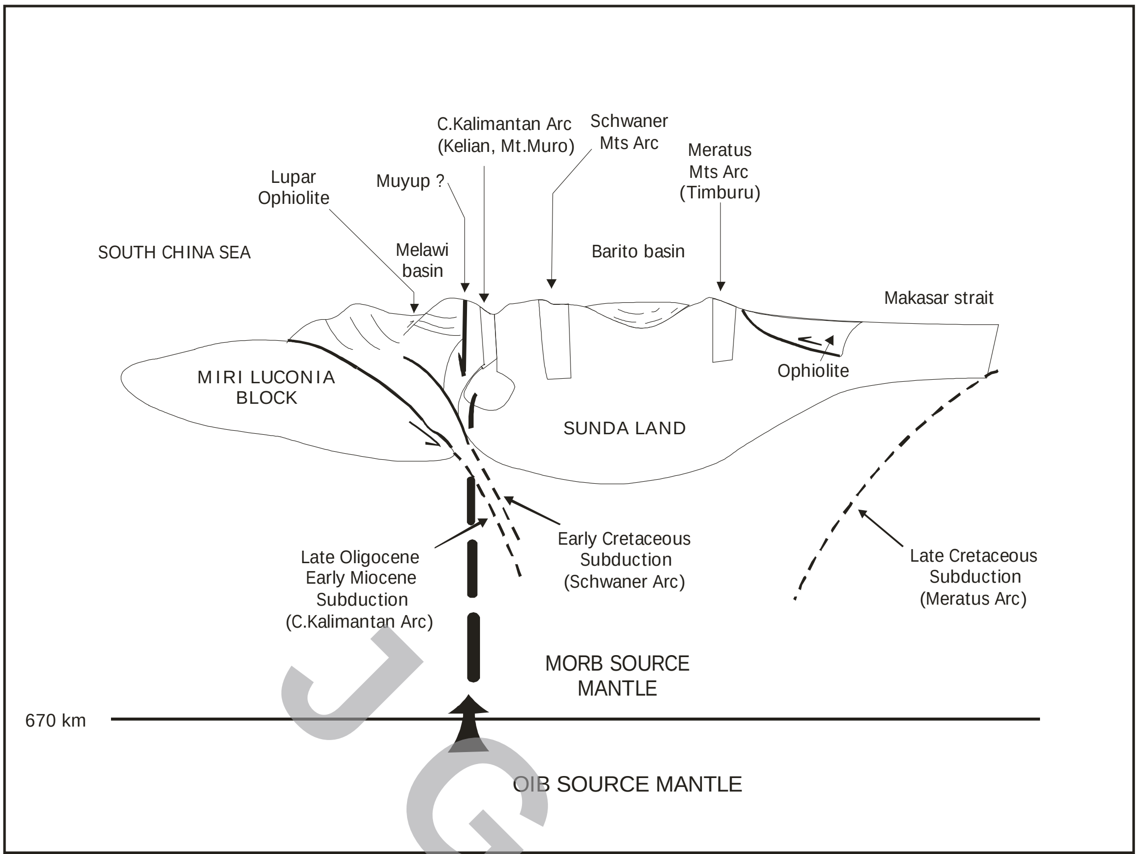


Figure 2. Schematic diagram showing the paleosubduction and the related arc in the Kalimantan Sunda Land and the origin of the Plio-Pleistosen magma by mixing of The Tertiary Kelian with OIB source magmas (After Hartono, 2003b).

CONCLUSION

The above discussion suggests that origin of arc magma is multi-sources and multi-processes. The composition of arc magmas is greatly influenced by geological condition, tectonic development, and chemical processes operating in subduction zone environments. Magmatic and metallogenic studies show that there is a tight link between magma origins and potential porphyry-Cu and epithermal mineralization. The metallogenic process in arc systems is controlled by the interplay of various factors, including magmatisms, tectonics, geological conditions, and hydrothermal processes. An integrated study on the key processes of magmatism, volcanism, tectonics, and fluid processes is necessary to better understand the metallogenic processes. An understanding of tectonic and magmatic processes, including magma types and sources will provide useful information for further strategic exploration. Knowledge of arc magma origin, in term of magma source or sources and processes, is particularly important in the beginning mineral exploration to reduce the high exploration cost.

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