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Petrochemical Study on the Volcanic Rocks Related to Depth to the Benioff Zone and Crustal Thickness in the Kyongsang Basin, Korea: A Review

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ABSTRACT: Late Cretaceous to early Tertiary volcanic rocks in the Kyongsang basin exhibit high-K calc-alkaline characteristics, and originated from the magmatism related genetically to subduction of Kula-Pacific plate. They represent HFSE depletion and LILE enrichment characteristics as shown by magmas related to subduction. Early studies on the depth of magma generation has been estimated as 180~230 km based on K-h relation should be reevaluated, because the depth of peridotite partial melting with 0.4 wt.% water is 80~120 km at subduction zone, and subducting slab in premature arc can melted even lower than 70 km. Moreover the increase of potassium contents depends on either contamination of crustal material and fluids of subducting slab or low degree of partial melting. If the inclination of subduction zone is 30 degrees and the depth to the Benioff zone is 180~230 km, the calculated distance between the volcanic zone and trench axis would be 310~400 km. It is unlikely because the distance between the Kyongsang basin and trench during late Cretaceous to early Tertiary is closer than this value and not comparable with generally-accepted models in subduction zone magmatism. K_{55} of the volcanics in the Kyongsang basin is 0.3~2.3 wt.% and the average indicate that the depth ranges between 80~170 km on the diagram of Marsh, Carmichael (1974). Fractionation from garnet lherzolite, assumed the depth of 180~230 km, is not consistent with the REE patterns of the volcanoes in the Kyongsang basin. Futhermore, the range of depth suggested by many workers, who studied magmatism related to subduction, imply shallower than this depth. Crustal thickness calculated by the content of CaO and Na_2O is about 30 km and about 35 km, respectively. Paleo-crustal thickness during late Cretaceous to early Tertiary times in the Kyongsang basin inferred about 30 km calculated by La/Sm versus La/Yb data, which is also supported by many previous studies.

INTRODUCTION

Island arcs are regions of active volcanism and seismicity. One of the most important features of arc volcanism is the formation of the volcanic front, the trenchward boundary of the arc. It is well-known that the depth of seismic slab under the volcanic front is nearly constant about 100 km (Gill, 1981; Haukesson, 1985; Matsuzawa *et al.*, 1986; Tatsumi, 1986). Tatsumi (1986) proposed that aqueous fluids released by the dehydrations of amphiboles at 100 km depth migrate upward into the region with the solidus temperature of hydrous peridotite, where magma is generated. This magma migrates straight upward in the form of diapirs, and thus the volcanic front is formed just above the dehydration point. The frequency of volcanoes is greatest along a volcanic front and decreases toward the back arc (Sugimura *et al.*, 1963; see also Tatsumi, 1989, Fig. 1). The volume of magma produced in the mantle wedge is the greatest beneath a volcanic front (Tatsumi, 1989).

It is generally accepted that partial melting and volcanism result from lowering of the peridotite solidus by dehydration of aqueous fluids from the dehydrating oceanic crust (Boettcher, 1977; Davies, Bickle, 1991; Davies, Stevenson, 1992; Defant, Drummond, 1990; Fyte, McBirney, 1975; Hamilton, 1969; McBirney, 1969; Peacock, 1990; Sakuyama, Nesbitt, 1986; Tatsumi, 1989; Wyllie, 1973). In the subducting oceanic crust the termination of dehydration is essentially defined by the stability limit of hornblende, which is 100 km (Furukawa, 1993; Wyllie, 1973). The H_2O released from downgoing lithosphere reacts with the forearc mantle wedge to crystallize hydrous minerals (serpentine, talc, amphibole, chlorite and phlogopite).

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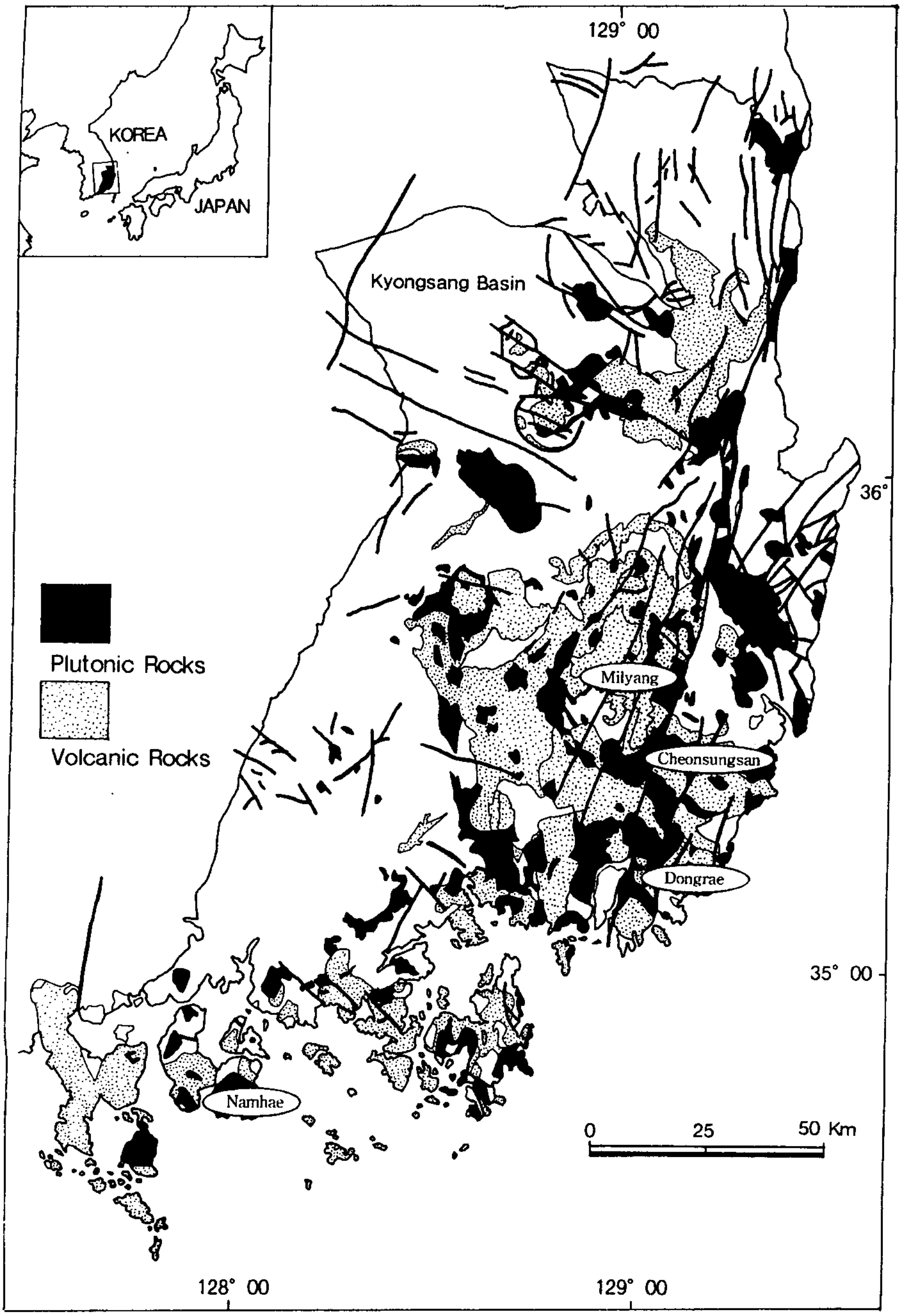

Fig. 1. Geologic map of the Kyongsang basin. Modified from Cha (1985), Kim, Sung (1996), Hwang, Kim (1994a, b), Yun (1988, 1993) and Yun *et al.* (1994).

This hydrated peridotite is dragged downward on the slabs toward higher PT regions and release H_2O to shallower potential magma source regions in the mantle wedge. Combining experimental data on the stability of serpentine and talc with the thermal structure in the mantle wedge, it is concluded that those minerals decompose beneath the forearc region (Tatsumi, 1989). On the other hand, high PT experimental and thermodynamic data suggest that dehydration of amphibole and chlorite

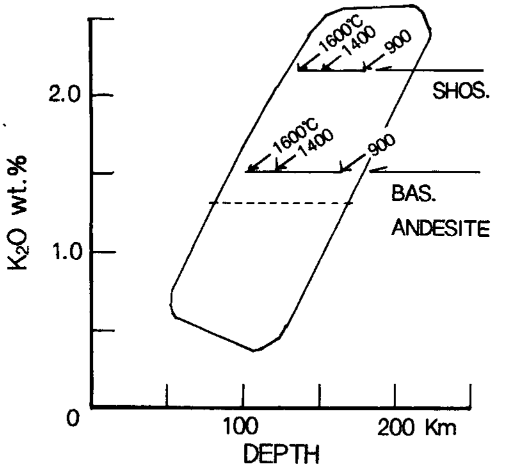

Fig. 2. Diagram of K_2O versus depth (at 55% SiO_2) to the top of the Benioff zone showing the position of calculated equilibrium with the subducted eclogite slab. The circle represents the observed field of points for present island arc suites (Dickinson, 1970). The temperature variation is only for one lava in each case and does not represent the variation for the field as a whole.

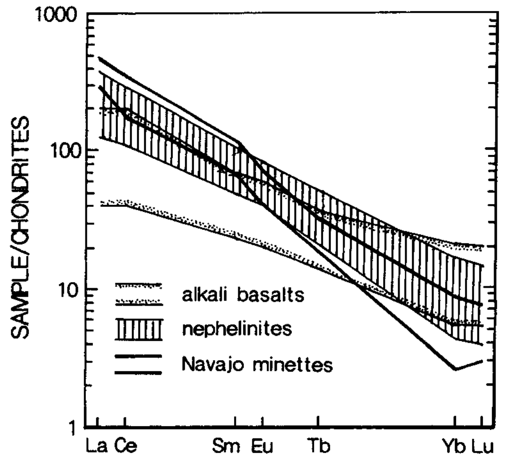

Fig. 3. Chondrite-normalized REE abundances in minettes of the Navajo volcanic filed, compared with ranges of REE contents of alkali basalts and nephelinites.

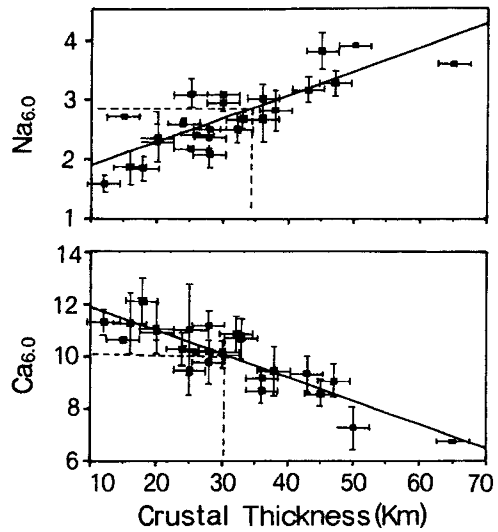

Fig. 4. Correlations between $Na_{6.0}$ and $Ca_{6.0}$ and crustal thickness. Each point represents an arc average, where vertical error bars are twice the standard deviation in the chemistry of each volcanic suite within each arc, and horizontal error bars are an arbitrary 5 km uncertainty in the seismic crustal thickness measurements. Where there is no vertical error bar, the data point is based on only one volcano. Data source are from Plank, Langmuir (1988). Dashed lines are represent the average value of $Na_{6.0}$ and $Ca_{6.0}$ of the volcanic rocks in the Kyongsang basin (see after Sung *et al.*, 1998).

in the downdragged peridotite can take place just beneath a volcanic front. Moreover, major hydrous minerals in the mantle wedge will break down at shallwer depths than 200 km, which is the stability limit of phlogopite (Tatsumi, 1989).

Furukawa (1993) suggested, through the modelling on magmatic processes under arcs, that temperature structure in the crust and the mantle wedge under arcs is insensitive to the angle and velocity of slab subduction. This information indicate that physical conditions such as temperature and pressure are similar under various arcs. It is thus inferred that primary magmas generated under various arcs should have similar chemical compositions. Recent experimental data (Liu *et al.*, 1996) suggested that subducted oceanic crust undergoes pressure-dependent amphibolite to eclogite dehydration reactions at around 70~80 km depth. In some models the resultant fluid flux occurs vertically into the wedge and the amphibole peridotite formed then migrates downwards with convection in the wedge until it crossed its solidus (1000; Green, 1973; Wyllie, 1979) and undergoes partial melting (Tatsumi, 1989). If the melt generation zone lies at 70~80 km depth, then, assuming that magma ascent is more or less vertical, it must lie 20~30 km out from the slab such that the arc volcanoes lie 100 km above the slab (Turner, Hawkesworth, 1997, see their Fig. 4).

The Cretaceous Kyongsang basin was filled with a 7 km thick sedimentary sequence below and an approximately 2 km thick volcanic sequence above (Choi, 1986). Kim (1986) and Lee *et al.* (1987) considered that Kula/Pacific plate subducted to 30 degrees beneath Eurasia continental plate and primary magmas of igneous rocks in the Kyongsang basin generated near the Benioff zone, and the generation depth of magma was about 180~230 km according to K-*h* relationships. This depth is much deeper than any other island and continental arcs. Wilson (1989) argued that it has become increasingly apparent that many arc systems do not follow this simple model, and K_2O contents could be changed due to such as crustal contamination, degree of partial melting, and compositional differences of primitive magma. Accordingly, it will be necessary to reconsider the generation depth of igneous rocks in the Kyongsang basin estimated from K-*h* relationship. This study will discuss the relations between geochemical data on the volcanics in the Kyongsang basin and K-*h* relationships, and will consider paleo-crustal thickness during late Cretaceous to early Tertiary.

Petrochemical characteristics and tectonic environment

The volcanic rocks in the Kyongsang basin are largely composed of alternations of lava flows and pyroclastic layers of air fall and ash flow in origin. The composition of those rocks generally changes upward from intermediate to acid (Reedman, Um, 1975). The variations of major elements show that contents of MgO, CaO, Al_2O_3, FeO^T, TiO_2 and P_2O_5 decrease with increasing of SiO_2, but K_2O contents increase slightly, and widely-dispersed pattern of Na_2O (Sung *et al.*, 1998; Yun, 1998). They exhibit calc-alkaline characteristics (Hwang and Kim, 1994b; Kim and Sung, 1996; Yun, 1998; e.g., Defant *et al.*, 1991): they are plagioclase phyric (Wilson, 1989), quartz and hyperthene normative (Ewart, 1982), display high large-ion lithophile element (LILE)/high-field strength element (HFSE) ratios (Hawkesworth, Ellam, 1989), low TiO_2 concentrations (Wilson, 1989), and do not show iron enrichment trends on the AFM diagram. They are believed to be originated from the magmatism related genetically to subduction of Kula-Pacific plate similar to the Cretaceous volcanic rocks in southwestern Japan (Kim, 1982; Miyashiro, 1974).

The Kula-Pacific ridge subduction during Cretaceous resulted in extensional tectonism (Hilde *et al.*, 1976). As the coastal zone was separated from the rest of the continent, the East Sea was opened (Uyada, Miyashiro, 1974) during post-Cretaceous times. The sea has progressively developed as a back-arc basin (Karig, 1971) by crustal rifting either along many short-lived micro-spreading centers (Matsuda, Uyeda, 1971) or along two major NE-SE trending centers of late Cretaceous and early Neogene age (Hilde, Wageman, 1973). Sung *et al.* (1998) suggested that the volcanics in the Kyongsang basin divided into two different series, BAV (basaltic to andesitic series) and DRV (dacitic to rhyolitic series) during 79 to 62 Ma and 71 to 58 Ma, respectively. The phenocrysts of BAV are mainly olivine and clinopyroxene, and those of DRV are plagioclase, quartz and potassium feldspar. In diagrams of Eu and Sr vs. SiO_2, MgO and CaO vs. Al_2O_3, it is shown that fractionation of olivine and clinopyroxene is characteristic in BAV and plagioclase fractionation is predominent in DRV (Sung *et al.*, 1997, Fig. 1e, f, g, h). The concentration of Sr decrease from about 500 to 18 ppm with increasing SiO_2, up to 55 wt.% and decreasing MgO down to ~4 wt.% for rocks from Kyongsang basin, suggesting a major role of plagioclase crystallization in determining bulk compositions of these rocks.

The volcanics of the Kyongsang basin are characterized by selective enrichment of incompatible elements of low ionic potential (K, Rb, Ba$\pm$Th) and low abundances of elements of high ionic potential (Ta, Nb, Zr, Hf) relative to N-type MORB (Basaltic Volcanism Study Project, 1981; Pearce, 1982; Sung *et al.*, 1998, Fig. 6a). In the similar pattern, magmas related to subduction show characteristics of HFSE depletion relative to LREE and strong LILE enrichment (e.g., Bacon, 1990; Ewart, 1982; Ewart, Hawkesworth, 1987; Hawkesworth, Ellam, 1989; Hawkesworth *et al.*, 1979; McCulloch, Gamble, 1991; McDermott *et al.*, 1993; Morris, Hart, 1983; Münker, Cooper, 1995; Pearce, 1982; Pearce, Cann, 1973; Saunders, Weaver, 1980; Saunders *et al.*, 1991; Wood *et al.*, 1979). Typically, the HFS element depletion of arc lavas is attributed to either (1) previous depletion of HFS elements in the source region for arc lavas

(Hickey, Frey, 1982; Sun, Nesbitt, 1978) or (2) residual phases in the source region which retain the high-field-strength elements (Green, 1980, 1981). Large-ion lithophile elements (LILE) such as K, Ba, Rb and Cs are probably mobilized in subduction zone fluids and melts (Sorensen *et al.*, 1997). Previous estimates of chemical fluxes assumed that the relative enrichment in large ion lithophile elements (LILE) in destructive margin magmas, i. e., LILE/HFSE ratios greater than those in unaltered mid-ocean ridge basalt (MORB) and undepleted mantle, are due largely to the introduction of LILE from subducted oceanic crust (Kay, 1980; White, Patchett, 1984).

The volcanics in the Kyongsang basin showed that minor and trace elements charcaterized consistently discriminating ratio of island arc in orogenic belts, and tectonic setting represents plate margin that magma generated from subduction zone (Hwang, 1991; Kim, Sung, 1996; Kim *et al.*, 1997; Park, 1990; Yun *et al.*, 1994). On plots of Sr/Y versus Y (Sung *et al.*, 1997; Sung *et al.*, 1998, Fig. 7b), DRV are ploted in island arc andesite-dacite-rhyolite fields and BAV in fields defined for MORB slab-melts (Defant, Drummond, 1993; Feeley, Harker, 1995). Defant, Drummond (1990) have shown that partial melting of metamorphosed basalt will generate dacitic melts with high Sr/Y and low Y.

On the discriminant diagram such as Ba/Th and La/Th ratios, BAV and DRV belong to orogenic high-K suites. In the diagram of La/Yb vs. Th/Yb, BAV are plotted widely in the area of oceanic arc, continental margin arc and Andean arc. DRV are located in more matured environment than BAV. They fall in the oceanic arc within the destructive plate margins in the tectonic discriminant diagrams such as Rb vs. (Y+Nb) and Zr-Th-Nb diagram (Pearce *et al.*, 1984; and Wood, 1980, respectively; Sung *et al.*, 1997, Fig. 2c, d; Sung *et al.*, 1998, Fig. 7c). Moreover, BAV are plotted from pre-collision uplift to post collision region, while DRV fall under late orogenic (Batcheler, Bowden, 1985; Sung *et al.*, 1997, Fig. 2f). These results represent that magma generation of BAV had been occurred in the early stages of arc formation and those of DRV had been produced in more matured arc. DRV magmas are separated from the upper mantle at deeper levels and by smaller degrees of partial melting than BAV magmas (Sung *et al.*, 1998). Most backarc-side magmas are derived from a greater depth by a smaller degree of partial melting than more trench-side magmas (Tatsumi *et al.*, 1995).

K-*h* relation and the depth to the Benioff zone

Early models for island-arc magmatism, based on studies of Japan arc, suggested that the erupted magmas should increase in alkalinity away from the trench (Dickinson, Hatherton, 1967; Keith, 1978; Kuno, 1959; Sugimura, 1973). Moore (1959, 1962) first formalized this notion when he established the quartz diorite line in the western United States. Convincing evidence that the trend is real is provided by a detailed study of the Sierra Nevada batholith by Bateman, Dodge (1970). Dickinson (1970) and Hatherton, Dickinson (1969) have found the increase in K_2O in the continental direction to be directly proportional to the depth of the underlying Benioff zone. This led to the development of the so-called K-*h* relationship, whereby the K_2O content (K) of the magmas at a fixed SiO_2 value was apparently correlated with the depth to the Benioff zone (*h*) (Dickinson, 1975).

Concentrations of incompatible elements from volcanic rocks in the Kyongsang basin show clear across-arc variations (Min *et al.*, 1988). The across-arc variation in K_2O have been documented in the Kyongsang basin especially for basaltic to andesitic compositions (BAV). An up-dated compilation of across-arc variation in K_2O contents (Tatsumi, Eggins, 1995), which show marked increase of K_2O, is observed in the various arcs, such as Kurile, NE Japan, Luzon, Sunda, Sangihe, New Zealand, and Chile. Several mechanisms have been proposed to interpret the across-arc variation: (1) the depth of magma separation from the source mantle (Green *et al.*, 1967; Tatsumi *et al.*, 1983), (2) the degree of crustal contamination (Best, 1975), (3) the degree of crystallization differentiation (O'Hara, 1973), (4) the residual K-bearing phases in the magma source region (Jakes, White, 1970), and (5) the degree of partial melting controlled by the amount of slab-derived fluids to the magma source region (Gill, 1981).

Although the relationships between abundance of K_2O and depth to the Benioff zone are described elsewhere (e.g., Dickinson, 1968, 1970, 1975; Johnson, 1976; Nielson, Stoiber, 1973), many workers, however, have argued the K_2O-depth plots either show a poor relation (Kienle *et al.*, 1983; Nielson, Stoiber, 1973) or no relation at all (Carr *et al.*, 1979). Futhermore, Kussmaul *et al.* (1977) considered that K-*h* relationships correlate to crustal thickness and compositons. In the Lesser Antilles the erupted magmas change in composition from tholeiitic to calc-alkaline to alkaline from north to south along the arc, at an approximately constant depth at 100 km to the Benioff zone (Brown *et al.*, 1977; Davidson, 1986). Furthermore, in the New Hebrides, Barsdell *et al.* (1982) have reported a reversed K-*h* relationship with K_2O contents decreasing with increasing depth to the Benioff zone. Hodder (1985) suggested that the subducted oceanic crust is not always directly involved in magma genesis, implying that the inference of paleo-subduction zone by the K_2O-depth relationships may be invalid for much of the life of an island arc. There are regions that systematic changes found from LILE not accord with radiogenic changes (Stern *et al.*, 1993). In Japan, for example, the distance is longer from the trench, then Sr is more radiogenic but Nb is less ragiogenic, whereas there are some regions showing the opposite trends (Nohda, Wasserburg, 1981; Notsu, 1983). Based on vast database, Gill (1981) suggested that isotopic variations showed not constant patterns across arcs.

Lee *et al.* (1987) mentioned that depth of primitive magma which generated igneous rocks in the Kyongsang basin is 180~230 km according to K-*h* relationship. In the study on petrogenesis of Cretaceous volcanic rocks in the Yucheon minor basin, the depth of magma generation has been reported as 220 km and 180 km, in the Milyang and Dongrae region, respectively (Hwang, 1979; Kim, 1982; Kim, 1986, Fig. 15). The volcanics of Andean Cordillera shows not only similar tectonic setting (Hwang, 1994a), but also similar K_2O contents variation to those of the Kyongsang basin. Avila-Salinas (1991) showed a strikingly high-potassium character from Cenozoic western Andean Cordillera of Bolivia and argued that these K_2O contents probably do not correlate with the depth of the underlying Benioff zone of the Nazca plate, as suggested Dickinson (1970). Instead, he suggested that this potassium enrichment can be explained in terms of the crustal thickening caused by development of the Bolivian orocline.

Ewart *et al.* (1977) proposed that the K_2O status of island-arc volcanics was due to the interaction of mantle-derived basalts with overlying continental crust. There are considerble debates on the components such as K_2O derived from either mantle wedge or recycled materials within subducted slab (Kay, 1980; Hawkesworth, Ellam, 1989). Moreover, the excess of K_2O over those values expected from fractional crystallization processes may be due either to low degrees of melting in the mantle source (Tatsumi *et al.*, 1995), as a result of thickening of the continental crust or the thinning of the lithospheric mantle (Hawkesworth, Ellam, 1989), or to a higher degree of contamination at crustal levels. Although the K-*h* relationship has been applied generally in Japan arc, slab fluids involved in the magma which produced BAV in the Kyongsang basin would raised K_2O contents in the primary magma. (Sung *et al.*, 1997; Sung *et al.*, 1998, Fig. 5d; Tatsumi, Kogiso, 1997).

K_2O contents on DRV in the Kyongsang basin are influenced by contamination or assimilation of crustal components (Sung *et al.*, 1997, 1998). Watson (1982) has shown that selective contamination of some elements, such as potassium, can occur during dissolution of minerals or rocks into basaltic magma. Selectivity is caused because alkali elements have much higher chemical diffusivities than silica, and thus can attain transient chemical equilibrium with the host magma long before dissolution and homogenization is complete (Huppert, Sparks, 1985). In some cases, notably in continental areas, more enriched materials may contaminate magmas (Saunders *et al.*, 1991). Hildreth, Moorbath (1988) reported that the amount of K_2O is irrespective of the depths to which partial melting might extend in the mantle since increasing K_2O values across arcs may in large part be caused by progressively greater contributions from the crust and subcrustal lithosphere. Because of these reasons, the depth value of the previous studies, based on K-*h* relationships, should be rechecked. We consider the depth of magma generation is shallower than those in the previous studies. K_{55} (wt.% K_2O at 55 wt.% SiO_2)

of the volcanics in the Kyongsang basin ranges 0.3~2.3 wt.%, thus, we take 1.3 wt.% for the average values in order to calculate the depth of magma generation, it ranges 80~170 km on the diagram of Marsh, Carmichael (1974; Fig. 2). The mean of K_{60} in Kyongsang basin is 1.85 wt.% which is similar to the K_{60} of andesites of the Tongariro volcanic center, New Zealand (Cole, 1978). Partial melting of phlogopite eclogite beneath the Tongariro volcanic center lies at 150~200 km depth, and this depth is also shallower in comparison with the depth in the Kyongsang basin suggested in previous study. K_{60} of Paricution volcano, Mexico and Tokati and Daisetsu volcanoes, in Hokkaido is also resembling with the Kyongsang basin, and the depth to the Benioff zone is estimated to 125 km and 135 km, respectively (Dickinson, Hatherton, 1967). Especially, the K_{55} and K_{60} of Paramushir I., NE Kuriles (K_{55}=1.4, K_{60}=1.9) is very similar to those of the Kyongsang basin (K_{55}=1.3, K_{60}=1.85), and their depth to the Benioff zone is 105 km (Dickinson, Hatherton, 1967).

Nearly constant the depth to the Benioff zone *(h)* beneath volcanic front is one of the striking characteristics of destructive margin volcanic activity (Plank, Langmuir, 1988). The mineralogy of the rocks from the oceanic crust varies during subduction as a function of pressure, temperature and vapour phase composition, changing from zeolite through blueschist or amphibolite facies to eclogite. This prograde metamorphism is accompanied by dehydration, which is thought to occur principally in the 80~125 km depth range (Wilson, 1989). Serpentine and talc, if present in the cooler centers of the subducting slabs, may be carried deeper. According to the model on subducted slab of Toksöz *et al.* (1971), serpentine cannot reach a depth of 100 km, but talc could persist to about 120 km. Upward migration of water following dehydration of talc would bring the water into the oceanic crust of a maximum depth of about 100 km. Assuming that water released rises virtually through the slab, water from serpentine and talc reaches oceanic crust at a maximum depth of 100 km and 125 km, respectively. Furukawa (1993) considered that the volcanic front is inferred to be formed through the stress-controlled propagation of magma-filled cracks. In his model, magma will migrate vertically upward in the crust due to the vertical compressional stress. In this zone of large magma supply, a volcanic belt will be formed. The stress transition occurs at the depth of 100 km.

A recent seismic study in the northeastern Japan arc shows that subcrustal microearthquakes are observed under volcanoes to a depth of 40~50 km, which is the depth of the partially molten region (Hasegawa *et al.*, 1991). But in this depth, only tholeiitic series rocks are generated frequently, and segregated magma cannot accumulate and rise to the surface as shown by Furukawa (1993). Partial melting of subducting slab and dehydration in premature arc can occur even at depth lower than 70 km (Liu *et al.*, 1996). Tatsumi, Kogiso (1997) considered, in their experimantal study, that fundmental aqueous facies in subducted oceanic crust are broken down at shallower depth than 100 km, and there are transform of subducted slab from amphibolite to eclogite at 70~100 km depth. Depth of partial melting of peridotite with 0.4 wt.% water at subduction zone is 80~120 km (Wilson, 1989; Wyllie, 1981).

The depth of a dipping seismic zone beneath a volcanic front is constant in most subduction zones (124 $\pm$ 38 km; Gill, 1981). The depth range becomes narrower (112 $\pm$ 19 km; Tatsumi, 1982) when seismic data from arcs with high angle of subduction (>70°) and with a slow rate of subduction (<1 cm/yr; Tatsumi, 1981) are eliminated. Hildreth, Moorbath (1988) showed that fifteen andesite-dacite stratovolcanoes on the volcanic front of a single segment of the Andean arc lie 90 km above the Benioff zone and 280 $\pm$ 20 km away from the trench axis. Hypocentral trend surface analysis applied by Bevis, Isacks (1984) to intermediate-depth teleseismic data suggested a depth of about 115 $\pm$ 15 km to the "middle" of the Benioff zone (or ~100 km to its upper surface) along most of the volcanic front. Kim (1982) postulated that the inclination of subduction zone during Cretaceous, which produced the volcanics in the Kyongsang basin, is 30 degrees. If the inclination of subduction zone was not changed in addition to this gradient, it is calculated that the vertical depth of 180~230 km correspond to the horizontal distance of 310~400 km from trench. The distance between the Kyongsang basin and trench axis during late Cretaceous to early Tertiary is closer than this value (Choi, 1986). Melting may occur in rocks just above the hanging wall of the Benioff zone as the result of incorporation of water released by dehydration of the descending slab (Boettcher, 1973). Consequently, the depth to the Benioff zone concluded from Kim (1986) and Lee *et al.* (1987), approximately 180~230 km, is not harmonized with generally accepted model.

It is assumed that rock compositions in the depth of 180~230 km is garnet lherzolite (Wilson, 1989). If primitive magma is generated in this depth, it must show comparable geochemical data. However, garnet is not found as phenocryst of the volcanics in the Kyongsang basin and garnet fractionation is not important in their petrogenesis (Sung *et al.*, 1998). Major mineralogical evidence, the volcanics of andesitic to basaltic composition range composed of olivine, clinopyroxene, plagioclase, and rarely amphibole as major phenocrysts do not support this depth (Green, 1982). Especially, amphibole, although only found in early stage of the volcanics in the Kyongsang basin (Cha, M.S., 1998, personal communication), indicated shallower depth of magma generation. Futhermore, the source of volcanic rocks in the northern part of the Kyongsang basin is plagioclase lherzolite which reveals also shallower depth than garnet lherzolite suggested by Kim *et al.* (1998).

If garnet fractionated in large quantities at early stage, HREE was depleted extremely in the pattern of REE. Flat pattern of HREE implys that partial melting or fractionation generated at the condition of no residual garnet (e.g., Takahashi, 1986). It can be argued that fractionation of garnet in primitive magma was too little and/or absent because partial melting of garnet lherzolite was too little. Kay, Gast (1973) showed that Navajo minettes produced from 0.8~0.3% partial melting of garnet lherzolite parent, and the REE abundance variation diagrams normalized to chondrite of which alkali basalt or nephelinite fractionated from garnet lherzolite, and showed HREE depletion extremely relative to LREE (Fig. 3). Therefore, the fact that the garnet lherzolite partially melted at about 200 km depth cannot be the genesis of the Kyongsang basin igneous volcanics. Moreover, Green, Ringwood (1968) noted that garnet and clinopyroxene are a near-liquidus crystalline assemblage for this composition at pressure of 27~36 kbars (corresponding to 100~150 km).

Crustal thickness

Crustal thickness plays an important role in constraining low-pressure fractionation of ascending magmas (Leeman, 1983). In general, in regions of thin crust mantle-derived magmas can ascend rapidly to the surface and can maintain near-primary characteristics. However, in more mature arcs with thickened crust, the low-density crustal rocks as a filter impeding the ascent of primary magmas and causing extensive low-pressure crystal fractionation in high-level magma chambers (Herzberg *et al.*, 1983; Feeley, Hacker, 1995).

Gill (1981) suggested that shallow magma chambers (<20 km deep) usually underlie volcanoes with historic eruptions of andesite or dacite where they exist. More acidic magma chamber, which produced by fractionation of mafic minerals such as olivine, clinopyroxene from primary magma, normally occur at depths less than 20~30 km and may extend to within a few hundred meters of the surface (Iyer, 1984). The presence of plagioclase feldspar constrains their depth of crystallization to less than about 30 km, as plagioclase does not readily crystallize from basic melts at great depths (Powell, 1978). It is possible that high-level storage systems are not present in very young island arcs and only become established once a certain crustal thickness has been reached (Wilson, 1989). Based on the geochemical evidence, from the volcanic rocks in the Kyongsang basin indicate that the tectonic setting is mature continental arc. Fractional crystallization at volcanic arc is predominantly in high-level magma chambers shallower than 30 km (Gamble *et al.*, 1990; Gill, 1981; Iyer, 1984). As arc develops, the basalt pile will be thickened downwards by underplating of basaltic magma. Once the crust has thickened to some 20~25 km, it may start to act as a density filter, arresting the ascent of primary magmas which will then pond in high-level magma chambers. Subsequent crystal fractionation will result in the generation of low-density andesitic derivates (Wilson, 1989), which can rise more easily towards the surface. This may explain the predominance of intermediate magma compositions in mature island arcs. Eruptions of large volumes of magma from

Table 1. REE data (La, Sm, and Yb) in Namhae area (Jung, 1998).

Sample	N346	N308	N316	N344	N343	N330	N303	N324	N369	N323	N305	N368	N361
rock type	basalt	basalt	basalt	basalt	basalt	basalt	basaltic andesite	basaltic andesite	andesite	andesite	andesite	andesite	basaltic andesite
La	14.93	22.84	12.56	16.55	17.55	12.80	23.23	26.29	17.25	20.41	24.00	22.16	21.43
Sm	4.11	5.30	3.94	4.19	4.35	3.54	4.39	5.61	4.28	4.25	4.39	4.85	5.65
Yb	1.85	2.27	2.04	1.80	1.87	2.12	1.76	2.45	2.13	1.64	1.69	1.97	2.21
La/Sm	3.63	4.31	3.19	3.95	4.03	3.62	5.29	4.69	4.03	4.80	5.47	4.57	3.79
La/Yb	8.07	10.06	6.16	8.85	9.39	6.04	9.48	12.34	8.10	12.45	14.20	11.25	9.70

Table 2. REE data (La, Sm, and Yb) in Cheonsungsan area (Kim and Sung, 1996).

Sample	w27	w43	w21	w36	w48	w42	w41	w28	w6	w7	w19
rock type	rhyolite	dacite	dacite	dacite	dacite	dacite	dacite	rhyolite	rhyolite	rhyolite	rhyolite
La	8.38	25.59	25.16	22.46	24.47	11.67	28.65	25.57	17.50	7.90	17.47
Sm	2.59	3.64	4.96	3.94	4.92	2.60	4.26	5.16	2.83	1.33	2.14
Yb	2.25	2.64	3.64	2.03	3.45	1.91	3.27	3.86	2.68	1.04	1.64
La/Sm	3.26	7.03	5.07	5.70	4.97	4.49	6.73	4.96	6.18	5.94	8.16
La/Yb	3.72	9.69	6.91	11.06	7.09	6.11	8.76	6.62	6.53	7.60	10.65

high-level magma chambers may be sufficient to cause collapse of the roof into the void, producing a caldera. These are a common feature of island-arc volcanoes and provide further evidence for the existence of high-level magma chambers. It is consider that the volcanic caul- drons (Yun, 1998) related to DRV (Sung *et al.*, 1998) are evidence of high-level magma chambers. Jin (1985) inferred a conclusion that the crustal thickness of the Kyongsang basin during Cretaceous to Tertiary was about 30 km, and Choi *et al.* (1993) corroborated that the crustal thickness of present-day is 33 km calculated by investigation on gravity data. Plank, Langmuir (1988, Fig. 4) calculated the crustal thickness at subduction zone through the relations of CaO and Na_2O contents with 6.0 wt.% MgO. In views of these facts, crustal thickness calculated by CaO and Na_2O contents ($Ca_{6.0}$=1.0, $Na_{6.0}$=2.8) is about 30 km and 35 km, respectively. La/Sm and La/Yb are correlated to crustal thickness according to the geochemical study on Andean Cordillera (Kay *et al.*, 1991, Fig. 7), whose tectonic environments is similar to those of the Kyongsang baisn and the crustal thickness was studied more in detail. Among the volcanics in the Kyongsang basin, basaltic to basaltic andesite in Namhae area (Table 1; Jung, 1998) plotted to the area of about 30~35 km, acid volcanic rocks in Cheonsungsan area (Table 2; Kim, Sung, 1996) plotted show elongate higher La/Sm regions (Fig. 5). It may be due to the effect of contamination which pronounced in acid volcanic rocks in the Kyongsang basin (DRV).

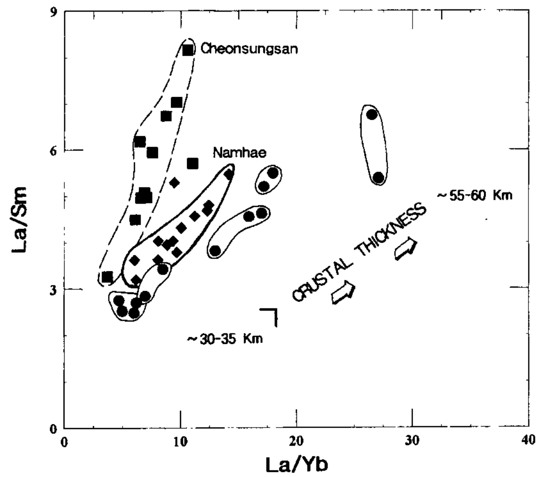

Fig. 5. La/Sm versus La/Yb ratios for samples from the Namhae (A; filled square) and Cheonsungsan area (B; filled diamond) compared to those from the "flat-slab" and SVZ in the Andean Volcanic Zone (filled circle) to examine the relation between the REE pattern and crustal thickness. Data sources are from Hickey *et al.*, (1986) and Futa, Stern (1988). Crustal thickness are estimates by Hildreth, Moorbath (1988).

CONCLUSION

The depth of peridotite partial melting with 0.4

wt.% water at subduction zone is known as 80~120 km, and subducting slab in premature arc can melted even lower than 70 km. Moreover the increase of potassium contents on either contamination of crustal material and fluids of subducting slab or low degree of partial melting. If we support the inclination of subduction zone is 30 degrees and the depth to the Benioff zone is 180~230 km which mentioned early studies, the calculated distance between the volcanic zone and their related trench axis would be 310~410 km. It is much higher value relative to generation depth of primary magma at any other island-arcs or continental arcs, and not harmonize with distribution of the volcanics derived from subduction. Although the relationships between abundance of K_2O and depth to the Benioff zone are described elsewhere, in the Lesser Antilles where the erupted magmas change in composition from tholeiitic to calc-alkaline to alkaline from north to south along the arc, at an approximately constant depth at 100 km to the Benioff zone. In the New Hebrides, the reversed K-*h* relationship with K_2O contents decreasing with increasing depth to the Benioff zone had been reported. The primary magmas in the Kyongsang basin volcanics are strongly affected by subducted slab fluids. Magmas of more acidic volcanics correlated with smaller degrees of partial melting relative to basic to intermediate magma and had undergone crustal contamination. These are all factors to elevate K_2O contents in primary mamas. Accordingly, early study which mentioned the depth of generated magma is 180~230 km according to K-*h* relation should be rechecked, and we suggest the depth to the Benioff zone is about 80~170 km calculated from average K_2O contents. Paleo-crustal thickness during late Cretaceous to early Tertiary inferred about 30 km, through the mineralogical assemblage, geochemical data, such as La/Sm versus La/Yb, and crustal thickness of present-day estimated from gravity study.

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경상분지 화산암류의 지화학적 연구: 섭입대(베니오프대)의 깊이와 지각의 두께

성종규 · 김진섭 · 양경희

요 약 : 경상분지의 후기 백악기~고 제 3기의 화산암류는 high-K 칼크 알칼리의 특성을 나타내며, 쿨라-태평양판의 섭입에 연관된 마그마작용에 성인적으로 연관된다. 그들은 섭입에 관련된 마그마에서 보이는 바와 같이 고장력원소가 결핍되며 LIL원소가 부화되는 특성을 지닌다. K-h 관계에 기초하여 마그마의 생성 깊이를 180~230 km라고 한 이전의 연구들은 재고되어질 필요가 있다. 물을 0.4% 함유한 감람암의 부분 용융의 깊이는 80~120 km로 알려져 있으며, 성숙되기 전의 호에서 섭입 슬랩은 70 km보다 얕은 깊이에서도 용융이 될 수 있다. 더욱 더 K_2O 함량은 지각 물질에 의한 혼염과 섭입 슬랩의 유체에 의해서, 그리고 적은 정도의 부분 용융에 의해서도 증가될 수 있다. 섭입의 각도를 30° 로 가정하였을 때 수직 깊이 180~23 km는 수평거리가 해구로부터 310~400 km로 계산된다. 이 깊이는 도호 및 대륙호에 속한 다른 지역의 근원마그마 생성심도에 비해 매우 큰 값이며 섭입에 의해 야기되는 화산암의 생성지의 분포화는 조화적이지 못하다. 경상분지 화산암의 K_{55}는 0.3~2.3 wt.%이며, 그 평균값을 Marsh and Carmichael (1974)의 도표에 적용하면 섭입대의 깊이는 80~170 km가 된다. 깊이 180~230 km의 맨틀 암석은 석류석 러졸라이트로 가정되며 이것의 분별로부터 나타나는 희토류 양상은 경상분지의 것과 일치하지 않는다. 더욱 더 섭입에 관련된 마그마작용을 연구한 여러 연구자들은 이보다 더 얕은 깊이를 제안하였다. CaO와 Na_2O 함량을 이용하여 구한 후기 백악기~고 제 3기의 경상분지의 고지각 두께는 각각 30 km, 35 km이며, La/Sm대 La/Yb 에 의한 값은 약 30 km로 추정되며, 이들은 이전의 연구들을 지지한다.