Jour. Petrol. Soc. Korea Vol. 13, No. 1, p. 34~45, 2004

Fluid Inclusions Trapped in Xenoliths from the Lower Crust/upper Mantle Beneath Jeju Island (I): A Preliminary Study

Kyounghee Yang

Geological Environmental Science Major, College of Natural Sciences, Pusan National University

제주도의 하부지각/상부맨틀 기원의 포획암에 포획된 유체포유물: 예비연구

양 경 희

부산광역시 금정구 장전동, 609-735, 부산대학교 지질환경과학전공

Abstract: This paper describes the textural relations of mantle xenoliths and fluid inclusions in mantle-derived rocks found in alkaline basalts from Jeju Island which contain abundant ultramafic, felsic, and cumulate xenoliths. Most of the ultramafic xenoliths are spinel-lherzolites, composed of olivine, orthopyroxene, clinopyroxene and spinel. The felsic xenoliths considered as partially molten buchites consist of quartz and plagioclase with black veinlets, which are the product of ultrahigh-temperature metamorphism of lower crustal materials. The cumulate xenoliths, clinopyroxene-rich or clinopyroxene megacrysts, are also present. Textural examination of these xenoliths reveals that the xenoliths are typically coarse grained with metamorphic characteristics, testifying to a complex history of evolution of the lower crust/upper mantle source region. The ultramafic xenoliths contain protogranular, porphyroclastic and equigranular textures with annealing features, indicating the presence of shear regime in upper mantle of the Island. The preferential associations of spinel and olivine with large orthopyroxenes suggest a previous high temperature equilibrium in the high-Al field and the original rock-type was a Al-rich orthopyroxene-bearing peridotite without garnet. Three types of fluid inclusions trapped in mantle-derived xenoliths include CO_2-rich fluid (Type I), multiphase silicate melt (glass ± devitrified crystals ± one or more daughter crystals + one or more vapor bubbles) (Type II), and sulfide (melt) inclusions (Type III). CO_2-rich inclusions are the most abundant volatile species in mantle xenoliths, supporting the presence of a separate CO_2-rich phase. These CO_2-rich inclusions are spatially associated with silicate and sulfide melts, suggesting immiscibility between them. Most multiphase silicate melt inclusions contain considerable amount of silicic glass, reflecting the formation of silicic melts in the lower crust/upper mantle. Combining fluid and melt inclusion data with conventional petrological and geochemical information will help to constrain the fluid regime, fluid-melt-mineral interaction processes in the mantle of the Korean Peninsula and pressure-temperature history of the host xenoliths in future studies.

Key words: ultramafic xenolith, buchite, cumulate, fluid inclusions, melt inclusions

요 약: 본 연구는 제주도에 분포하는 현무암에 포획된 맨틀포획암과 맨틀포획암에 포획된 유체포유물에 대한 암석 및 조직에 대한 기재와 하부지각물질이 초고온의 변성작용을 받아 형성된 부카이트라는 산성질포획암에 관한 예비연구이다. 제주도에 분포하는 알칼리현무암에는 초염기성포획암, 산성질포획암, 큐물레이트포획암이 풍부하게 포획되어 있다. 초염기성포획암은 첨정석(스피넬)-레졸라이트가 대부분이며, 첨정석-레졸라이트는 감람석, 사방휘석, 단사휘석과 첨정석로 이루어져 있다. 부카이트는 석영, 사장석과 검은 세맥으로 이루어져 있으며, 큐물레이트포획암은 단사휘석 혹은 단사휘석과 사장석으로 이루어진 거정의 결정들로 구성되어 있다. 이들 포획암들의 구성입자들은 조립질이며, 하부지각/상부맨틀에서의 복잡한 진화사를 보여주는 변성암의 특징을 나타낸다. 초염기성포획암에는 프로토그라뉼라, 반상쇄성, 등립질의 조직이 관찰되며, 이러한 조직의 존재는 제주도의 상부맨틀에 전단체계가 형성되어 있음을 나타낸다. 프로토그라뉼라 조직에서는 거정의 사방휘석 결정들 중간에 첨정석, 세립의 감람석이 시공간적인 연관성을 지니고 항상 같이 산출되어지는데 이는 첨

---

*Corresponding author: Tel: +82-51-510-2247, E-mail: yangkyhe@pusan.ac.kr

정석과 감람석이 사방휘석에서 용리되어진 것으로 여겨진다. 이러한 첨정석과 감람석이 사방휘석에서 용리되어진 조직은 프로토그라뉼라조직이 형성되기 이전에 고온에서 알루미나 함량을 많이 지닌 암석이 평형상태를 유지했음을 의미하며, 원래의 암석은 알루미나가 풍부한 사방휘석을 지닌 페리도타이트인 것을 암시한다. 이러한 하부지각/상부맨틀에서 유래하는 포획암에는 세 종류의 유체포유물이 포획되어 있다. I형은 이산화탄소를 풍부하게 가지고 있는 포유물이고, II형은 다상의 규산염용융포유물로서 유리±탈유리화된 결정들±딸결정들 + 수축기포로 구성되어 있다. III형은 황화용융포유물이다. 제주도의 맨틀포획암에는 I형이 가장 풍부하게 포획되어 있으며, 이산화탄소가 맨틀에 존재하는 가장 풍부한 휘발성성분이며, 맨틀과 같은 고온고압에서 하나의 독립된 상으로 존재한다는 것을 반영하고 있다. 또한 맨틀과 같은 환경에서 규산염멜트(melt), 황화멜트, 이산화탄소가스 사이에 서로 불용융(immscibility) 상태도 형성되고 있음을 나타내고 있다. 대부분의 다상의 규산염용융포유물 (II형)은 상당한 양의 규산질 유리를 지니고 있으며, 이는 하부지각/상부맨틀에서 SiO_2 함량이 높은 규산질마그마가 형성되고 있음을 지시한다. 암석학적, 지화학적 정보와 함께 맨틀 혹은 하부지각 암석에 포획된 유체포유물과 용융포유물 데이터는 한반도의 맨틀에 대한 유체체계, 유체-마그마-광물 사이의 상호작용, 모암인 포획암에 대한 압력-온도 진화사를 파악하는데 크게 이용될 것이다.

핵심어: 초염기성포획암, 부카이트, 큐뮬레이트, 유체포유물, 용융포유물

Introduction

Various types of fluid inclusions are trapped in minerals of the lower crust/upper mantle-derived xenoliths in alkali basalts from Jeju Island. Such inclusions represent accidentally trapped samples of fluid- and melt phases present in the lower crust/upper mantle. They provide important information for the understanding of mineral-fluid-melt interaction processes in the lower crust/upper mantle (Andersen and Neumann, 2001). Such fluid inclusions together with xenoliths in mafic volcanic rocks from the lower crust/upper mantle can constrain geological nature and evolution of the lower crust/upper mantle. In South Korea, mantle xenoliths within Cenozoic alkali basalts occur in several locations (Lee, 1995). A few studies have been reported mainly focusing on the geochemistry of mantle xenoliths from the South Korea (Yun *et al.*, 1998; Choi *et al.*, 2001). No work has been yet reported about fluid inclusions trapped in mantle-derived rocks from the lower crust/upper mantle of the South Korea.

This preliminary paper is a part of the project which has been designed in order to constrain the pressure-temperature history of the host xenoliths and mineral-melt-fluid interaction process in the mantle beneath the Korean Peninsula using fluid and melt inclusions in the lower crust/upper mantle-derived xenoliths. This paper investigates the textural characteristics of the peridotites in the upper mantle together with those of fluid inclusions in the mantle-derived xenoliths. It focuses on the significance of fluid inclusions and its application to petrology, and on the information that can be obtained by petrographic analysis. Although the term "fluid inclusion" is employed in some geologic literature to refer to the inclusions trapped in the aqueous state, it is generally used to refer to the state of the trapped material at the time of trapping and not to its condition as we observe it now. Thus, the concept of "melt inclusion" is employed as a sub-type of fluid inclusions which has been trapped in fluid state at a high, magmatic temperature in this paper.

Geological Setting

Jeju Island (Fig. 1) is located at the southernmost part of the main Korean Peninsula. It is elliptical in shape and is about 35 km wide by 75 km long. The island was formed by hot spot activity from 1.2 Ma to recent and is composed of mainly lava flow of alkali basalt-trachyte series with a minor amount of pyroclastic rocks and tholeiitic basalt (Yun *et al.*, 1986; Won *et al.*, 1993, 1995; Park *et al.*, 1996). Basement of the island consists of Jurassic-Cretaceous granites and Cretaceous-Tertiary rhyolitic tuff, which can be observed only as xenoliths in lapilli tuff, basaltic lava or in drill cores (Lee *et al.*, 1994). Several stages of volcanism are recognized, including basal lava flow, lava plateau, volcanic edifice and parasitic scoria cone.

Alkali basalts from Jeju Island contain various

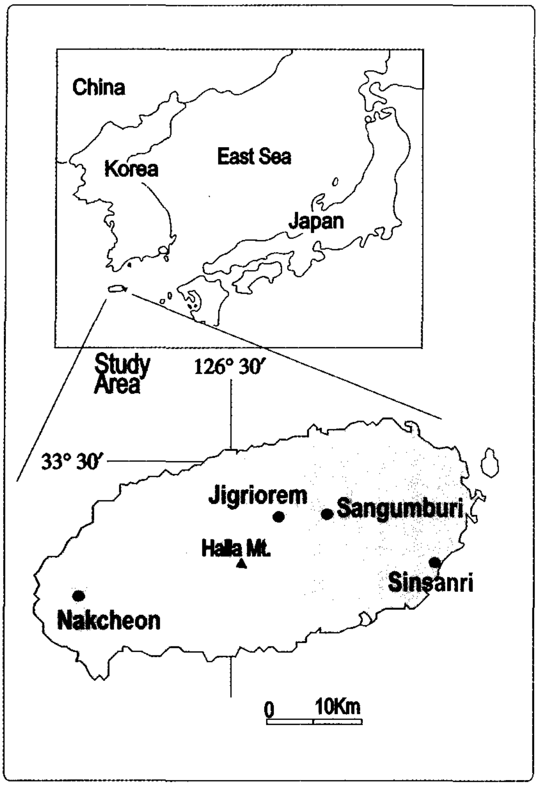

Fig. 1. Simplified map of Jeju Island showing samples locations.

mantle-derived ultramafic, felsic and cumulate xenoliths, mostly showing sharp contacts (Fig. 2). The host basalts belong to the alkaline series, having normative hypersthene and rarely normative nepheline (Yun *et al.*, 1998) and show fine-grained and holocrystalline~cryptocrystalline textures. They consist of olivine ($Fo_{75\text{-}86}$) phenocrysts in the matrix of plagioclase ($An_{52\text{-}62}$) lath, intersertal augite, granular olivine ($Fo_{73\text{-}81}$) and dark brown glass (Choi, *et al.*, 2001). A smaller amount of plagioclase and augite phenocrysts also occur.

Mantle Xenoliths

Ultramafic xenoliths

Most of the ultramafic xenoliths are spinel lherzolites with lesser amount of spinel harzbergite and dunite. Spinel lherzolites mainly contain 50-60vol% of light green olivine (Fo_{90}), 30-40vol% of black or dark brown orthopyroxene (Wo_2-En_{88}-Fs_{10}), 5-10 vol% of grass green clinopyroxene (WO_{48}-En_{46}-Fs_6), and 1-2vol% of black spinel (mg#75.9, cr#10.2) (Yun *et al.*, 1998). All samples show metamorphic textures with annealing features. They consist of mainly protogranular texture with small amounts of porphyroclastic and equigranular textures (Fig. 3). At contact between xenoliths and host basalts, orthopyroxenes affected by reaction with the enclosing magma show fine-grained symplectic rims that are composed of olivine plus silica-rich glass (Fig. 3a), probably formed by incongruent reaction melting. Spinels at the contact between mantle xenolith and host basalt display a reaction zoning showing gradual darkening color toward the host basalts (Fig. 3b). These optical characteristics are interpreted as a reflection of chemical zoning implying increase of Fe^{3+} and Ti contents as magmatic fractionation occurred (Tracy, 1980). Three textural groups have been defined in the spinel lherzolite.

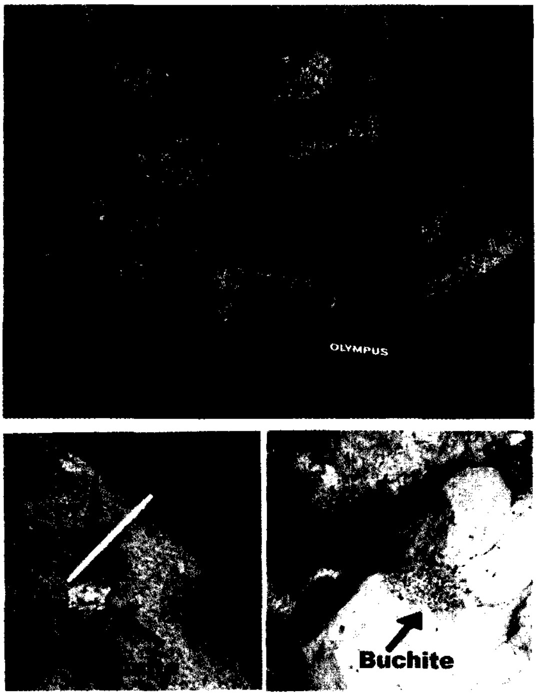

Fig. 2. Photographs of various mantle-derived xenoliths from the Sinsanri area in Fig. 1.

The protogranular texture presents typically coarse orthopyroxene and olivine crystals (Fig. 3c). Olivine

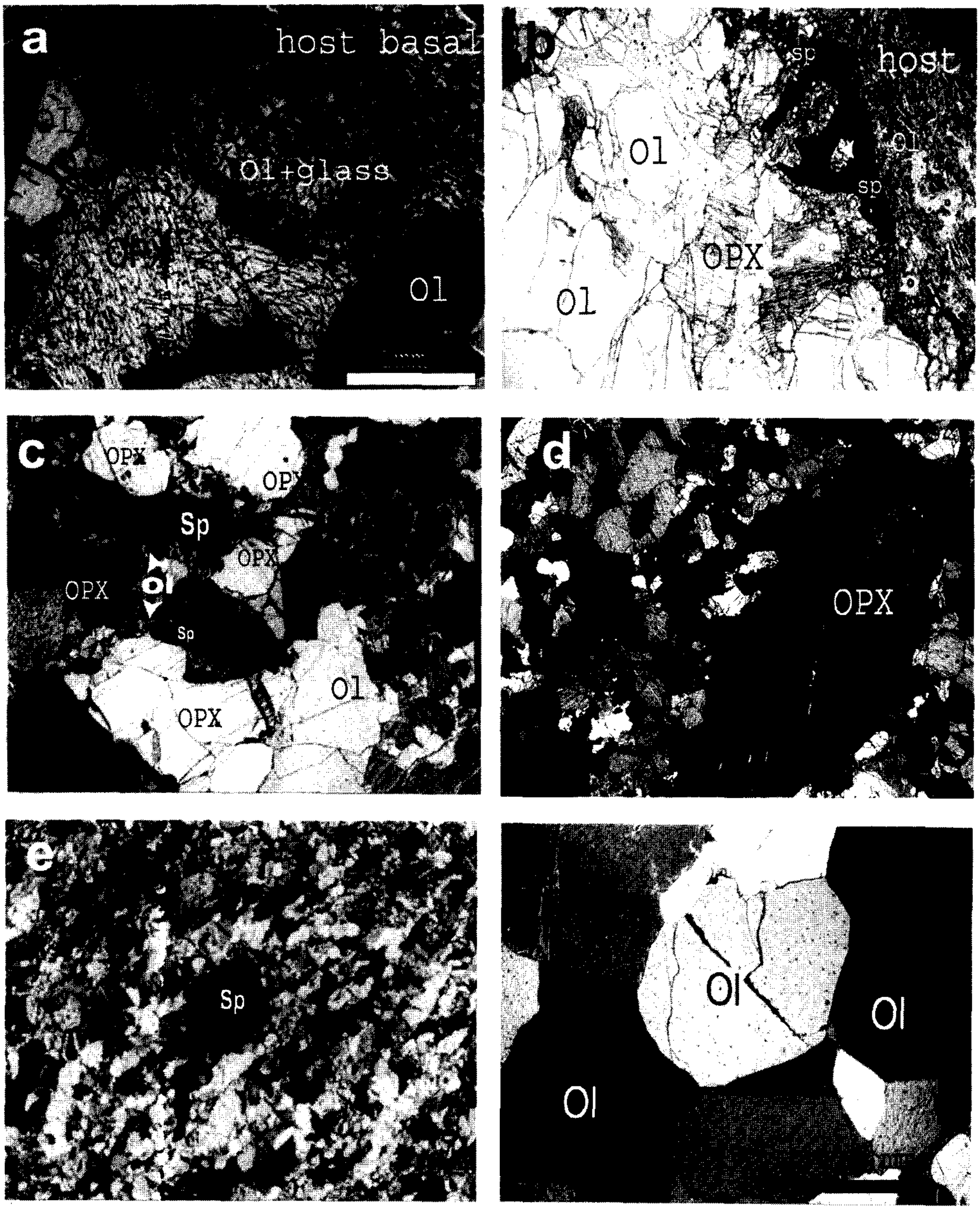

Fig. 3. Photomicrographs of ultramafic xenoliths showing textural relations in spinel lherzolites. (a, b, c) Protogranular texture. (d) Porphyroclastic texture. (e, f) Equigranular texture. The same scale bar is applied for all pictures except for Fig. 3f. OPX = orthopyroxene, Ol = olivine, Sp = spinel.

and orthopyroxene have kink band textures and undulatory extinction, reflecting either thermal shock due to incorporation of xenoliths into hotter basaltic magma, or solid state deformation in the mantle (Tracy, 1980). The clinopyroxene and spinel are smaller in size than olivine and orthopyroxene. Symplectite melting sometimes occurs inside of large olivine crystals which are highly embayed by basaltic magma. Spinels and small olivine blebs in peripheral parts of spinel are almost always in contact with the large orthopyroxene grains (Fig. 3c). This texture may have developed first in Al-rich orthopyroxene-bearing peridotite, probably due to a recrystallization process which is regarded as occurring during partial melting. In addition, the spinels sometimes occur in elongated or vermicular forms inside the orthopyroxenes, reflecting decomposition of Cr- and Al-rich phases either during metamorphism in the mantle or during decomposition as xenoliths ascended to the surface (Tracy, 1980).

The porphyroclastic texture (Fig. 3d) presents two kinds of olivine and orthopyroxene crystals: large and strained grains (porphyroclasts) and small generally polygonal strain-free ones (neoblasts). Large orthopyroxene porphyroclasts are often deformed probably by plastic flow, revealing a shear regime in the upper mantle (Mercier and Nicolas, 1975). Orthopyroxene often contains exsolution lamellae of clinopyroxene, indicating the xenoliths cooled down before they were trapped in host basaltic magma. Compared to the protogranular texture, more advanced polygonization and recrystallization are present in the porphyroclastic texture. However, there is no strong foliation or any strong flow direction.

The equigranular texture presents fine-grained tabular to mosaic equigranular grains plus some rare porphyroclastic relics indicating a transition from porphyroclastic texture in some samples (Fig. 3e). Samples showing the equigranular texture can be simply recognized even at hand samples because of strong foliations and the elongated spinel crystals. The grain boundaries show well-developed 120° angles in triple points, especially in this equigranular texture (Fig. 3f). The spinel displays a holly-leaf shape defining a lineation. The spinel crystals do not in contact with orthopyroxene any more in the equigranular texture (Fig. 3e). It seems like that the equigranular texture was developed after more intensive recrystallization of rocks in protogranular and porphyroclastic textures.

Cumulate xenoliths and felsic xenoliths

We briefly describe these cumulate and felsic xenoliths here, which will be studied in the other paper. Although these xenoliths are significant for providing information about the evolution of the lithosphere beneath Jeju Island (Torok, 2002; Zajacz and Szabo, 2003), less attention has been paid to them (Yun *et al.*, 1998; Choi *et al.*, 2001).

The cumulate xenoliths, which are clinopyroxene-rich or clinopyroxene megacrysts with more than 3-4 cm long, are composed of only clinopyroxene (Fig. 4a) or clinopyroxene and plagioclase (Fig. 4b). Xenoliths in the host basalt displays sharp boundaries (Fig. 4a). Although these xenoliths are considered as cumulates of underplated basaltic magmas which intruded into the lower part of the crust, there will be other possibilities, such as products of magmatic veining, metamorphic segregations owing to anatexis of the host mantle portion, or fragments of subducted oceanic crust streaked out into layers by mantle convection (Kovacs, *et al.*, 2003).

The felsic xenoliths considered as a partially molten buchite are white in color and composed of quartz and plagioclase with black veinlets (Fig. 4c, d, e, and f). Their sizes are usually less than 5 cm in the longest dimension. They are round or ovoid in shape. The boundary with the enclosing basalt is sometimes brecciated (Fig. 4c, d, and e), showing recrystallized small quartz crystals (Fig. 4d). Quartz grains also show partial melting, and contain many glass inclusions with several bubbles. The black veinlets contain brownish glass with hair-like crystals (Fig. 4f). These hair-like minerals are very small in size and can only be studied by electron microprobe. The hair-like minerals in the veinlets are presumably formed by the ultrahigh temperature transformations (Torok, 2002).

Fluid Inclusions

Based on the phase behavior and chemical compositions of fluid inclusions at the room temperature, three types of fluid inclusions have been recognized in olivine, orthopyroxene, and clinopyroxene from the mantle xenoliths, quartz and plagioclase from the felsic xenoliths, and clinopyroxene from the cumulate xenoliths.

Type I is CO_2-rich fluid inclusions ranging in size from 5-60 μm and distributed in clusters or along microfractures (Fig. 5). They present two sub-types; Type 1a inclusions do not show any association

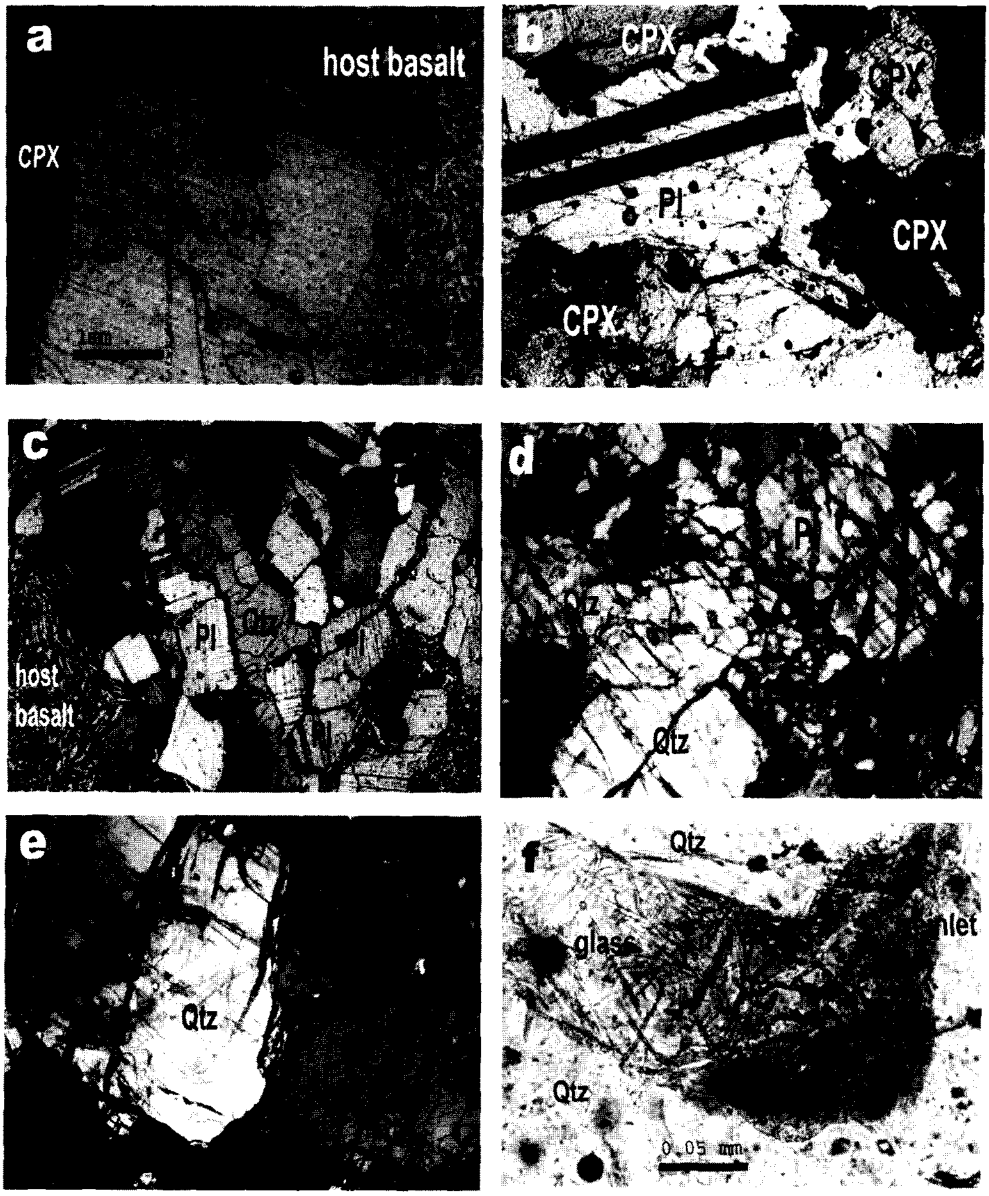

Fig. 4. Photomicrographs of cumulate xenoliths (a, b) and felsic xenoliths (c, d, e, f). The same scale bar is applied for all pictures except for 4f. CPX = clinopyroxene, Pl = plagioclase, Qtz = quartz.

with other types of inclusions (Fig. 5a and b), while Type 1b inclusions are spatially associated with silicate melt inclusions (Fig. 5c) and/or sulfides (Fig. 5d), reflecting CO_2-phase has been trapped simultaneously with silicate melt (now glass). Most of Type Ia inclusions have leaked during transport to the surface because of the high internal pressures in the inclusions. Minor, but unidentified, volatile species are present, which are recognized during microthermometry. Preliminary microthermometry of the Type Ia inclusions indicates the high densities of CO_2-rich inclusions homogenized by disappearance of vapor bubble between −5 ~31°C, indicating mantle characteristics. However,

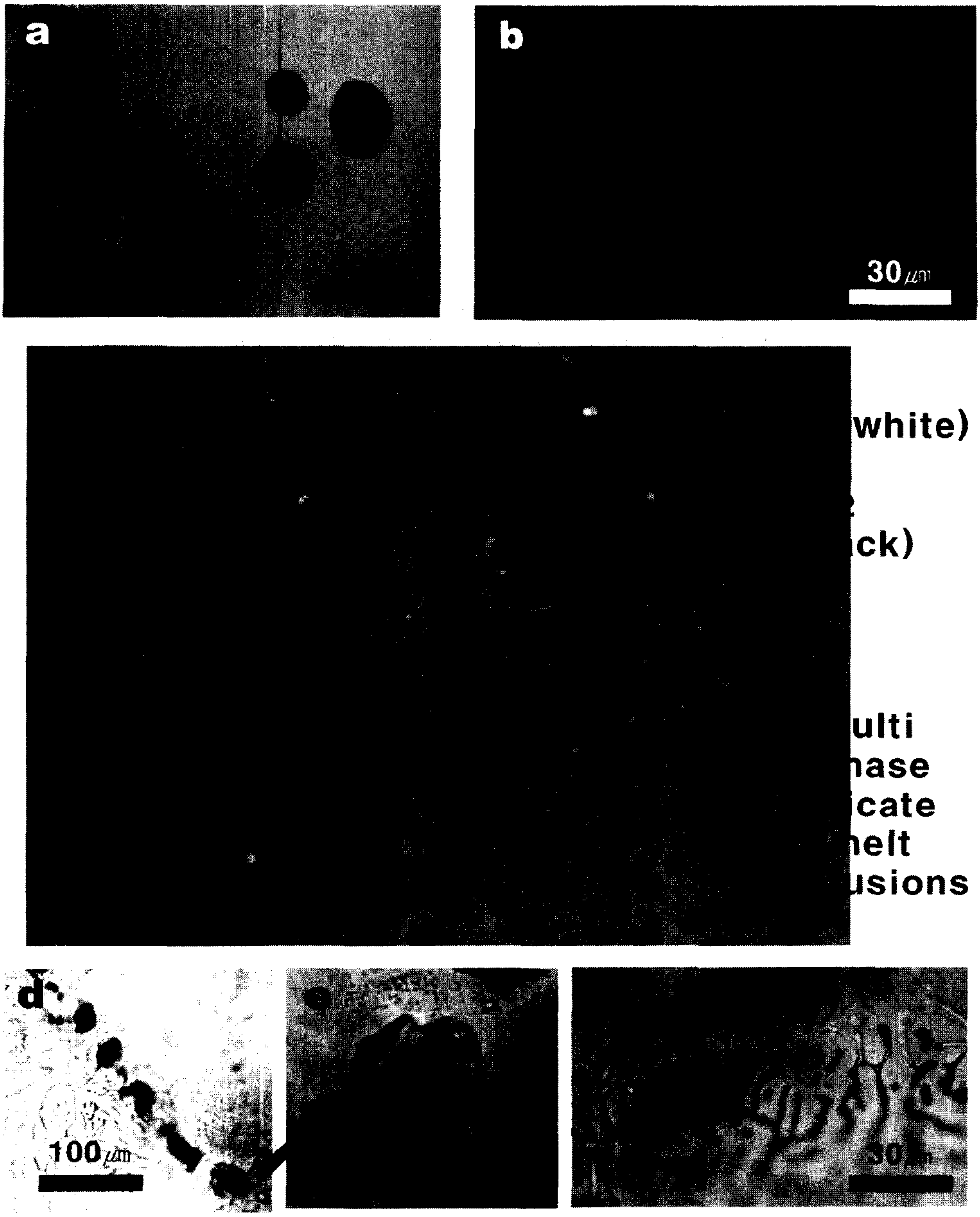

Fig. 5. Photomicrographs of fluid inclusions (Type I) trapped within the constituent minerals of ultramafic rocks in Jeju Island. (a) Primary(?) CO_2-rich inclusions (Type Ia). (b) Secondary CO_2-rich inclusions (Type Ia). (c) CO_2-phase trapped simultaneously with silicate melt (now glass) in elongated shape in the center of the figure (Type Ib). (d) Two generations of fluid inclusions. (e) One of those inclusions in Fig. 5d, showing devitrified glass with a CO_2-bearing vapor bubble. (f) One of those inclusions in Fig. 5d.

they show the wide density variation, probably due to reequilibration and different generations of inclusions.

Type 1b inclusions always show secondary textures in origin (Fig. 5c and d). The spatial coexistence between CO2-rich inclusions and silicate melt inclusions (Fig. 5c) and/or sulfides (Fig. 5d) presumably indicates the presence of immiscibility between CO_2

and melt (silicates or sulfides). It is thought that ascending mantle xenoliths captured simultaneously melt and CO_2-rich fluid were in the lower depth than the immiscibility phases. They are probably trapped together with silicate melt forming glass and a sulfide mineral grain. Some of the glass is devitrified forming hair-like crystals (Fig. 5e) especially around the contracting bubble. Inclusions containing glass and sulfide grain are irregular in shape and often observed at borders of major mantle mineral silicates (Fig. 5f).

Type II inclusions are multiphase silicate melt inclusions consisting of glass ± devitrified crystals ± one or more daughter crystals+one or more vapor bubbles ± opaque minerals (Fig. 6). They range 5-150 μm in size. Type II inclusions are partially to mostly crystallized (10-60% crystallization) (Fig. 6b, d, e, and h). The crystallized daughter minerals may be carbontes, micas, amphiboles, pyroxenes, or sulfides based on the crystal shape and birefrigence, although they should be identified by electron microprobe. Most inclusions of the type are distributed along microfractures in porphyroclast (Fig. 6a), indicating secondary in origin, while those in neoblast are randomly distributed or isolated (Fig. 6c), indicating primary. Many primary silicate melt inclusions have decrepitated to produce a halo or trail of CO_2-bearing inclusions, especially in porphyroblast. Most silicate melt inclusions decrepitated before they had reached the temperature of homogenization during microthermometry using the vertical furnace. One inclusion in the secondary fracture has shown bubble disappearance at around 1230°C but opaque minerals still existed.

Silicate melt inclusions in quartz from buchites are distinctively different from those in olivine and pyroxenes of the ultramafic xenoliths. They commonly contain several contracting bubbles (Fig. 6f and g), which may be due to viscosity of silica-rich silicic melt (now glass). They also contain considerable amount of silicic glass showing an initial stage of devitrification near the inclusion walls or next to the bubbles (Fig. 6g). Silicate melt inclusions in plagioclase also contain peculiar, but interesting phases as shown in Fig. 6h and 6i. Daughter crystals or solid inclusions in Fig. 6h may be apatite and sulfide or oxide crystals. Melt has been attached to horsetail-like minerals (quenched plagioclase texture) showing two segregated glass phases (Fig. 6i). This texture may indicate an example of liquid immscibility between high and low silica-containing melts.

Type III inclusions are sulfide inclusions, which are monosulfide bleb- or tube-shaped solid inclusions showing no association with other types of inclusions (Fig. 7), This type of sulfide inclusions is found as primary (Fig. 7a and b) or secondary (Fig. 7c and d) in origin. Primary sulfide inclusions tend to be more abundant in clinopyroxene. Sulfide inclusions all show bright silver reflectance. The bleb- or tube-shaped sulfide inclusions are likely formed from a sulfide melt coexisting with a silicate melt, which was the source of host clinopyroxene-rich cumulates. The sulfide inclusions will be able to provide a better understanding of upper mantle processes such as mantle depletion and enrichment, as well as the origin of Fe-Ni-Cu sulfide ore deposits when the detailed investigations on the texture and chemistry are provided (Zajacz and Szabo, 2003).

Discussion and Summary

Fluid inclusions in mantle xenoliths may preserve important information on the nature and evolution of the lower crust/upper mantle not easily available from their host xenoliths. Fluid and melt inclusions are integral parts of the phase assemblages of their host xenoliths which are the components of the upper mantle. Therefore, the geological processes in the mantle can be more tightly constrained by study of fluid and melt inclusions together with the lower crust/upper mantle xenoliths hosted in mafic volcanic rocks.

As expected in any field of studies, fluid inclusion studies in mantle xenoliths have many possibilities and limitations. Fluid inclusions in mantle xenoliths can provide significant information such as the oxidation state of the upper mantle, mantle degassing processes, immiscibility relationships, the mantle metasomatism and so on (Anderson and Neumann, 2001; Frezzotti, 2001), which are not easily

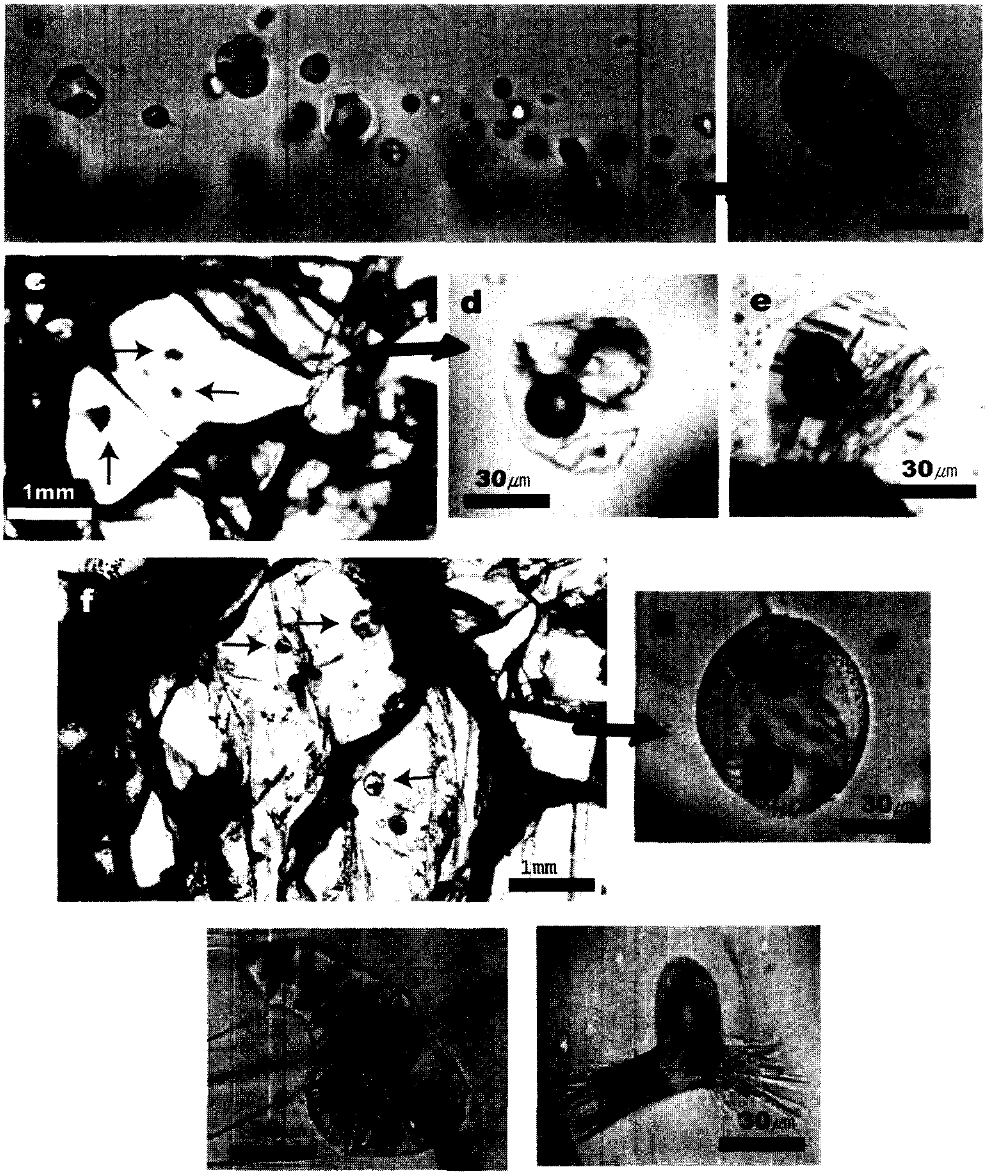

Fig. 6. Photomicrographs of fluid inclusions (Type II) trapped in the ultramafic rocks (a, b, c, d, e) and buchites (f, g, h, I) in Jeju Island. (a) Secondary silicate melt inclusions trapped in olivine porphyroclast. (b) One of inclusions in 5a. (c) Primary silicate melt inclusions in olivine neoblast. (d, e) Two of inclusions in 5a have been magnified, containing crystallized daughter minerals with a vapor bubble, glass, and epitaxial daughter crystals. (f) Primary silicate melt (now glass) inclusions (small arrows) in quartz from buchite. (g) One of inclusions in 5f. (h) A peculiar fluid inclusion trapped in plagioclase from buchite. (i) Another percular inclusion attached to horsetail-like minerals (quenched plagioclase texture) with two segregated glass phases.

available from their host xenoliths. On the other hand, more sophisticated and sensitive analytical techniques, coupled with a better understanding of the phase properties of fluids and silicate melts are required for successful results. Nevertheless, a large amount of important information can be obtained from observation with a petrographic microscope, which is believed to be the most important and

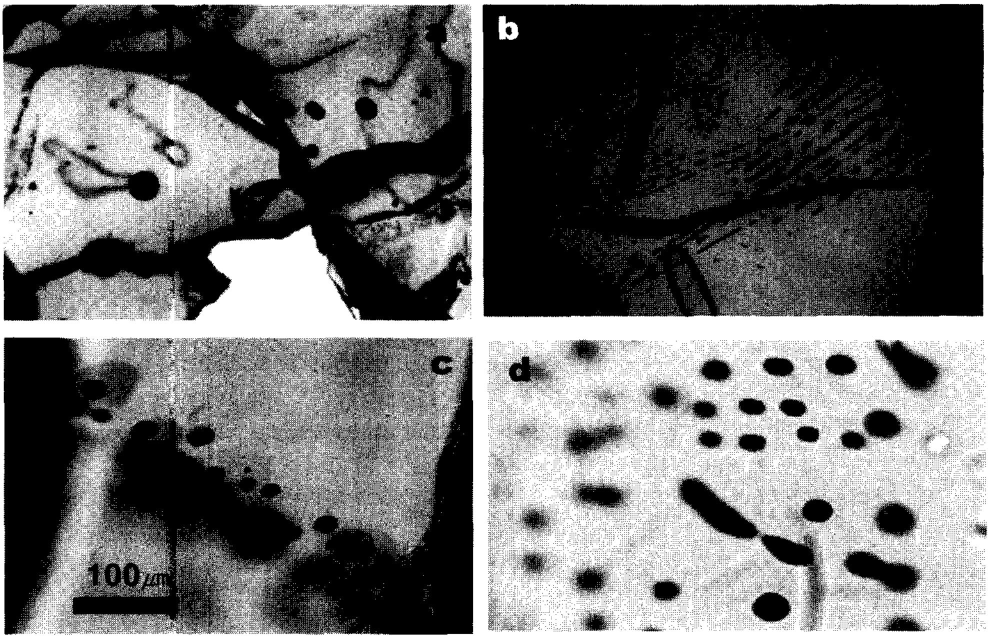

Fig. 7. Photomicrographs of sulfide melt inclusions (Type III) trapped in clinopyroxene megacryst. (a, b) Primary sulfide blebs or tube-shaped sulfide melt inclusions in the clinopyroxene megacryst. (c, d) Secondary sulfide inclusions along the microfractures or in the fracture plane.

basic features. Thus, this preliminary study focuses on the textural characteristics of fluid and melt inclusions in mantle xenoliths and their host xenoliths.

Three textures described in the previous chapter are related to each other showing gradually smaller grain sizes and higher degree of polygonization from protogranular through porphyroclastic to equigranular textures. This relation implies that the degree of deformation has been increased in the mantle or during ascending to the surface after trapped in the host basaltic magma or solid state deformation in the mantle (Tracy, 1980). The occurrence mode of spinel crystals showing three textures also indicates the increased degree of deformations toward the equigranular texture (Mercier and Nicolas, 1975). Spinels are always in contact with orthopyroxene in protogranular textures, while they are scattered and no longer in contact with the orthopyroxene in the equigranular textures. The presence of these various textures reveals the presence of shear regime in the upper mantle of the island. It suggests that the mantle xenoliths were recrystallized probably accompanying plastic flow (Mercier and Nicolas, 1975).

The preferential associations of spinel and olivine immediately adjacent to large orthopyroxene can be interpreted as an exsolution from a previous Al-rich orthopyroxene. This association was observed for almost all of the ultramafic xenoliths in the protogranular and porphyroclastic textures. It is probably due to a recrystallization process which is regarded as occurring during partial melting. This texture leads to assumption that the original rock-type was a Al-rich peridotite (harzbergite?) without garnet.

Considerable amount of silicic glass in most silicate melt inclusions suggests formation of silicic melts in the mantle. There are considerable evidences that silicic melts form at mantle depth and the origin of silicic glass in mantle xenoliths has been the subject of debate (Andersen and Neumann, 2001). It suggests that the most likely model for the formation of silicic melts in the mantle results from very low degrees of in situ partial melting, and reactions between infiltrating basaltic melts and mantle peridotite.

The fluid contained in inclusions in its minerals represents a fluid phase which was present at some stage of its history from its initial residence in the upper mantle to its ejection at the surface of the earth. The worldwide occurrences of CO_2-rich inclusions in upper mantle minerals have reported (e.g., Roedder, 1965, 1984; Pasteris, 1987; Hansteen *et al.*, 1991; Frezzotti *et al.*, 1994; Schiano and Clocchiatti, 1994). CO_2-rich inclusions are also the most abundant inclusions in the mantle xenolith from Jeju Isalnd, supporting the presence of a separate CO_2-rich phase. However, most CO_2-rich inclusions do not preserve a density representing their initial trapping conditions in the upper mantle since they have leaked during transport to the surface because of the high internal pressures in the inclusions. Thus, many complicated problems coupled with temporal sequences of the inclusions have to be answered. The most basic question is what fluid in the inclusions represents? In other words, is this CO_2-rich fluid the complete, original metasomatic fluids that were present in the mantle, or does it represent a fraction of the original fluid remaining following some chemical and/or physical process? These questions will be explored in future works.

This is probably the first paper to report that the felsic xenoliths enclosed in the alkali basalts from Jeju Island are buchites which are the middle crust xenoliths. The buchites composed of quartz and plagioclase, and veinlets may have resulted from very high-temperature metamorphism of the middle crustal materials although minerals in the veinlets have to be analysed. The presence of brownish glass in the veinlets (Fig. 4f) and no daughter crystals in the glass inclusions trapped in buchites suggest that the duration of the heating process was not long enough to extract the melt from the rock and admix it with the a alkaline basaltic melt. Homogenization temperature of primary CO_2 inclusions and mineral equilibrium of hair-like minerals in the veinlets can constrain the pressure and temperature of formation of buchites.

In conclusion, various fluids and melt trapped in mantle xenoliths from Jeju Island represent accidentally trapped samples of fluid- and melt phases present in the lower crust/upper mantle. They are indicators of fluid regime in the lower crust/upper mantle and will provide unique information for the understanding geological processes, such as mantle metasomatism, mantle depletion and enrichment, oxidation state of the upper mantle, and mantle degassing in the mantle (Andersen and Neumann, 2001) in future studies. Thus, combining fluid and melt inclusion data with conventional petrological and geochemical information will help to constrain the fluid regime, fluid-melt-mineral interaction processes in the mantle of the Korean Peninsula and pressure-temperature history of the host xenoliths.

Acknowledgments

This paper has significantly benefited and improved from the corrections and comments by Dr. Kil, Y. and an anonymous reviewer. This work was supported by grant No. R04-2002-000-20045-0 from the Basic Research Program of the Korea Science & Engineering Foundation.

References

Andersen, T. and Neumann, E-R., 2001, Fluid inclusions in mantle xenoliths. Lithos, 55, 301-320.

Choi S.-H., Jwa Y.-J. and Lee H.-Y., 2001, Geothermal gradient of the upper mantle beneath Jeju Island, Korea: Evidence from mantle xenoliths. The Island Arc, 10, 175-193.

Frezzotti, M.-L., 2001, Silicate-melt inclusions in magmatic rocks: application to petrology. Lithos, 55, 273-299.

Frezzotti, M.-L., Touret, J.L.R., Lustenhouwer, W.J. and Neumann, E.-R., 1994, Melt and fluid inclusions in dunite xenoliths from La Gomera, Canary Island: tracking the mantle metasomatic fluids. European Journal of Mineralogy, 6, 805-817.

Hansteen, TH., Andersen, T., Neumann, E-R. and Jelsma, H., 1991, Fluid and silicate glass inclusions in ultramafic and mafic xenoliths from Hierro, Canary Islands: implications for mantle metasomatism. Contributions to Mineralogy and Petrology, 107, 242-254.

Kovacs, I., Zajacz, Z. and Szabo, C., 2003, Type-II xenoliths and metasomatism beneath the Nograd-Gomor volcanic field, Carpathian-Pannonian region. 2003 Korea-Hungary International Joint seminar, 62-68.

Lee, H.Y., 1995, Petrochemical study on the mantle xenoliths in alkali basalts from S. Korea: P-T regime of upper mantle. Journal of the Petrological Society of Korea, 4, 104-123.

Lee, M.W., Won, C.K., Lee, D.Y., Park, G.H. and Kim, M.S., 1994, Stratigraphy and Petrology of Volcanic Rocks in Southern Cheju Island, Korea. Journal of the Geological Society of Korea, 30, 521-541.

Mercier, J.C.C. and Nicolas, A., 1975. Textures and fabrics of upper-mantle peridotites as illustrated by xenoliths form basalts. Journal of Petrology, 16, 454-487.

Park, J.-B., Park, K.-H. and Cheong, C.-S., 1996, Sr-Nd-Pb isotopic compositions of lavas from Cheju Island, Korea. Journal of the Petrological Society of Korea, 5, 89-107.

Pasteris, J.D., 1987, Fluid inclusions in mantle xenoliths, in Mantle Xenoliths, (ed. Nixon, P.H.), John Wiley and Sons, Chichester, 691-707.

Roedder, E., 1965, Liquid CO_2 inclusions in olivine-bearing nodules and phenocrysts from basalts. American Mineralogist, 50, 1746-1782.

Roedder, E., 1984, Fluid inclusions. Reviews in Mineralogy, 12, Mineralogical Society of America, Washington, D.C., 473-532.

Schiano, P. and Clocchiatti, R., 1994, Worldwide occurrence of silicate-rich melts in sub-continental and sub-oceanic mantle minerals. Nature, 368, 621-624.

Torok, K., 2002, Ultrahigh-temperature metamorphism of a buchitized xenolith from the basaltic tuff of Szigliget (Hungary). Acta Geologica Hungarica, 45, 175-192.

Tracy, R.J., 1980, Petrology and genetic significance of an ultramafic xenoliths suite from Tahiti. Earth and Palnetary Science Letters, 48, 80-96.

Won, C.K., Lee, M.W., Lee, D.Y. and Shon, Y.K., 1993, Explanatory text of the geological map of Seongsan. Jeju Province Office. pp. 104.

Won, C.K., Lee, M.W., Lee, D.Y. and Yun, S.H., 1995, Explanatory text of the geological map of Pyoseon. Jeju Province Office. pp. 59.

Yun, S.H., Koh, J.S. and Anh, J.Y., 1998, A study on the Spinel-lherzolite xenolith in the alkali basalt from Eastern Cheju Island, Korea. Economic and Environmental Geology, 31, 447-458.

Yun, S.K., Han, D.S. and Lee, D.Y., 1986, Quaternary geological survey of southern Jeju Island. KIGAM, KR-86-2(B)-2, pp. 64.

Zajacz, Z. and Szabo, C., 2003, Origin of sulfide inclusions in cumulate xenoliths from Nograd-Gomor volcanic field, Pannonian basin (north Hungary/south Slovakia). Chemical Geology, 194, 105-117.

(2004년 1월 5일 접수, 2004년 3월 8일 채택)