Structural Change in Hydrous Magma in the Earth's Asthenosphere

High-pressure X-ray diffraction for hydrous magma has been conducted to reveal how the structures of hydrous magma (MgO-SiO_2 join) change with pressure corresponding to the Earth's asthenosphere. Intermediate range ordering in hydrous magma, which consists of the linkage of SiO_4 tetrahedral molecules (silicate network), was found to be lengthened at 3–5 GPa, suggesting that the silicate network can be polymerized by the effect of water. This polymerization may influence the increase in viscosity of hydrous magma in this pressure range. The present result suggests that hydrous magma may be able to stay in the Earth's asthenosphere, and may be a factor in the decrease in seismic wave velocities.

The decrease in seismic wave velocities in the Earth's asthenosphere (depth 100–180 km), which is the so-called Low Velocity Zone (LVZ), has long been a controversial issue. One of the most likely candidates is the existence of a small amount of magma (e.g. [1]). However, considering the temperature at the depth of the asthenosphere (mantle geotherm, e.g. [2]), it would be difficult for the mantle minerals to melt in the anhydrous condition. In a recent study, a mantle mineral, aluminum-bearing pyroxene, suddenly dehydrated at around 100–150 km [3], which means that water could be locally available at that depth. Because water in the Earth dramatically decreases the melting temperature of minerals (e.g. [4]), a small amount of hydrous magma could be generated. However, to explain the LVZ with the effect of hydrous magma, a key issue is whether the magma can be trapped at that depth. Magma that contains water has significantly different properties from anhydrous ones (i.e., density, compressibility, viscosity and so on). The properties of magma should be dominated by microscopic properties such as the structures.

In this study, high-pressure and high-temperature X-ray diffraction (XRD) for hydrous magma was performed to investigate how the structures of hydrous magma change with pressure at around the depth of the Earth's asthenosphere.

Samples were prepared by mixing $Mg(OH)_2$ and SiO_2 as a simple approximation of the composition of the mantle (MgO-SiO_2). Water was added via structural water of $Mg(OH)_2$. The compositions of the starting materials were $MgSiO_3$, Mg_2SiO_4 and the intermediate composition. Water contents of the three samples were 15.2, 20.4 and 18.3 wt%, respectively. High-pressure XRD was conducted with the MAX80 cubic-type multi-anvil apparatus installed at AR-NE5C. The structure of the sample melted at high pressure was examined by polychromatic X-ray of 30–80 keV by the energy-dispersive method. Hydrous magma was completely encapsulated in single-crystal diamond tubing and platinum lids under pressurized conditions (e.g. [5]). The structure factor for the hydrous magma was determined by using the analysis developed by [6].

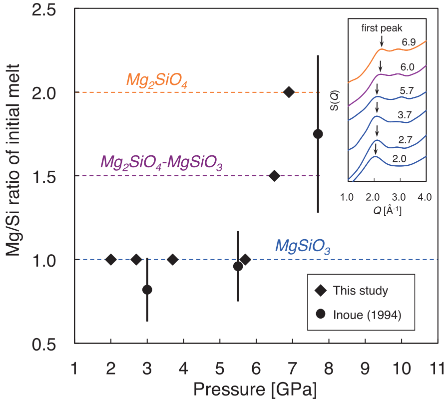

Figure 1
Pressure dependence on Mg/Si of initial melt generated in the MgO-SiO_2-H_2O system reported in [4]. The diamonds show the data where the structural data have been taken in the present study. The structure factors, S(*Q*), are shown in the inset. The colors, arrows and numbers indicate the composition, the approximate positions of the first peak in the structure factor and the pressure [GPa] where the S(*Q*)s were taken, respectively.

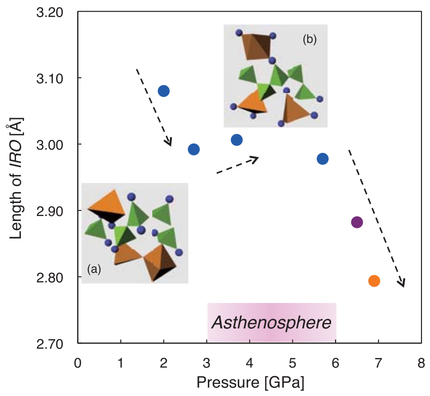

Figure 2
Pressure dependence on the length of the intermediate range ordering (*IRO*) according to the composition of initial melt reported by [4]. The color of the plot indicates the compositions as shown in Fig. 1. The insets represent the schematic illustrations of the depolymerized (a) and the polymerized (b) silicate networks by the effect of water (see text). Green tetrahedra, orange polyhedra and blue spheres show the SiO_4 tetrahedra, MgO_n polyhedra and hydrogen atoms, respectively. The hatched area indicates the pressure range of the Earth's asthenosphere.

The composition of the magma generated over the entire upper-mantle condition in the hydrous condition was investigated by [4] Fig. 1). The MgO composition of hydrous magma becomes markedly enriched at 5.5 GPa (~170 km). Similarly, the MgO component in aqueous fluid abruptly increases at 3 GPa [7]. These phenomena imply that the characteristics of water for the interaction with MgO change dramatically at around this pressure range. Considering the compositional change with pressure, the lengths of intermediate range ordering (*IRO*) consists of the linkage of the SiO_4 tetrahedral molecule (silicate network), which can be obtained from the position of the first peak in the structure factor as shown in Fig. 1 (see [8]), and the obtained lengths are plotted in Fig. 2 as a function of d spacing ($d = 2\pi/Q$ [Å]). It is widely known that the silicate network (…Si-O-Si…) in magma is dissociated by the effect of water. Specifically, water dissolves in magma by forming Si-OH structural units (Fig. 2 (a)). In fact, the length of *IRO* decreases markedly up to ~3 GPa, and yet despite compression, lengthening of *IRO* has been observed at 3–5 GPa, which corresponds to the depth of the Earth's asthenosphere. This lengthening can be attributed to the polymerization of the silicate network due to the effect of water because it has not been observed in anhydrous Mg-silicate melt [9]. The polymerization of hydrous silicate magma was proposed in a previous study on hydrous silicate glass using nuclear magnetic resonance (e.g. [10]). This polymerization is thought to occur due to the appearance of the Mg-OH unit (Fig. 2 (b)), whose H is taken from the Si-OH structural unit. Such polymerization significantly influences the physical properties of the magma, such as viscosity, electrical conductivity. In general, magma including water is thought to be low viscosity compared to anhydrous magma. However, hydrous magma generated at the depth of the Earth's asthenosphere may have relatively high viscosity, which would be kept in the Earth's asthenosphere due to the low mobility.

REFERENCES

[1] I.B. Lambert and P.J. Wyllie,0. *Science* **169** (1970) 766.
[2] T. Katsura, A. Shatskiy, M.A.G.M. Manthilake, S. Zhai, H. Fukui, D. Yamazaki, T. Matsuzaki, A. Yoneda, E. Ito, A. Kuwata, A. Ueda, A. Nozawa and K. Funakoshi, *Phys. Earth Planet. Inter.* **174** (2009) 86.
[3] K. Mierdel, H. Keppler, J.R. Smyth and F. Langenhorst, *Science* **315** (2007) 368.
[4] T. Inoue, Phys. *Earth Planet. Int*. **85** (1994) 233.
[5] A. Yamada, T. Inoue, S. Urakawa, K. Funakoshi, N. Funamori, T. Kikegawa, H. Ohfuji and T. Irifune, *Geophys. Res. Lett.* **3** (2007) L10303.
[6] K. Funakoshi, Ph D Thesis (1997) Tokyo Inst. Technol.
[7] T. Kawamoto, K.N. Matsukage, K. Mibe, M. Issiki, K. Nishimura, N. Ishimats and S. Ono, *Am. Mineral*. **89** (2004) 1437.
[8] A. Yamada, T. Inoue, S. Urakawa, K. Funakoshi, N. Funamori, T. Kikegaw and T. Irifune, *Earth Planet. Sci. Lett*. **30** (2011) 113.
[9] N. Funamori, S. Yamamoto, T. Yagi and T. Kikegawa. *J. Geophys. Res.* **109** (2004) B03203.
[10] X. Xue and M. Kanzaki, *Geochim. Cosmochim. Acta* **6** (2004) 5027.

BEAMLINE

AR-NE5C

A. Yamada and T. Inoue (Ehime Univ.)