

Optimization of geothermobarometry for zoned minerals in spinel peridotite xenoliths: thermodynamic and kinetic considerations

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Mantle xenoliths are fragments of mantle materials brought up to the surface by alkali basalt or kimberlite and provide useful sources of information not only about lithosphere but also sources of their host magmas. Because appropriate geobarometers are available for garnet-bearing lithologies mostly brought by kimberlite magmas, structures of the thick lithospheric mantle beneath cratons (e.g., Kaapvaal, Siberia, and Slave) have been well examined. The situation drastically changes for a thin and younger lithosphere, where alkali basalts sample mostly spinel peridotite xenoliths (e.g., arc, intraplate basin and plateau, and continental margin; Nixon, 1987; O' Reilly and Griffin, 2006). Garnet-absent peridotites are stable at depths shallower than ~60 km, and reliable geobarometers are not available for them (e.g., O' Reilly et al., 1997). Because of this, structures of shallow upper mantle are poorly constrained. We attack this problem by estimation of derivation pressures of spinel peridotite xenoliths from Ichinomegata maar in the back-arc side of Northeast Japan Arc and Tafroute maar in the northwestern part of the African continent through optimization of geothermobarometry for zoned minerals on the basis of thermodynamic and kinetic considerations.

Extensive mineral chemical study on nine xenolith samples from Ichinomegata maar revealed various patterns of chemical zoning in pyroxenes and olivine, suggesting diverse thermal histories of the xenoliths. They are responsible for (1) simple cooling, (2) cooling followed by weak heating, (3) cooling followed by strong heating, and (4) cooling followed by long heating. Examination of mineral chemical compositions of the eight samples from Tafroute maar also revealed various chemical zonings in olivine, orthopyroxene, and clinopyroxene indicating diverse thermal histories similar to Ichinomegata maar. We examined the timescales of development of each zoning pattern and identified minerals, grain portions, and components closely approached equilibrium just before the xenolith extraction. We found that the mineral parts for equilibrium change by minerals and their thermal history. They are outermost rims of orthopyroxene and clinopyroxene and rims and cores of olivine. The best geothermobarometer pair was chosen from the four pairs and was applied to the Ca-Mg-Fe components of the mineral parts for equilibrium. They are (1) $T_{\text{Ca-in-Ol}}$ (Aoki et al., submitted to Lithos) and $T_{\text{Opx-L}}$ (Lindsley, 1983), (2) $T_{\text{Ca-in-Ol}}$ and $T_{\text{Ca-in-Opx}}$ (Brey and Köhler, 1990), (3) T_{BKN} (Brey and Köhler, 1990) and $T_{\text{Ca-in-Opx'}}$, (4) $T_{\text{Ca-in-Ol}}$ and T_{BKN} . Application of the pair of (3) to Ichinomegata xenoliths gave plausible pressure ranging 0.72-1.6 $\pm$ 0.4 GPa and temperature 830-1080 $\pm$ 21 °C, whereas application of the pair of (1) for Tafroute xenoliths gave plausible pressure ranging 1.0-2.1 $\pm$ 0.3 GPa and temperature 761-931 $\pm$ 9 °C. The pressure estimates for Tafroute xenoliths using the geothermobarometer pair of (3), which provides the best pressure and temperature estimates for Ichinomegata xenoliths, are extremely high and implausible (1.8-4.9 $\pm$ 1.2 GPa). This is attributable to thermodynamic problem of the geothermobarometry. Clinopyroxene in the Tafroute xenoliths contains significantly high Na contents than those of the experiments used for calibration of T_{BKN} . Contrary to this, the pressure estimates for Ichinomegata xenoliths using the geothermobarometer pair of (1), which provides the best pressure and temperature estimates for Tafroute xenoliths, are high and highly scattered for low-temperature plagioclase peridotite xenoliths (0.96-1.3 $\pm$ 0.2 GPa). This is attributable to kinetic problems in application of the geothermobarometry. Significant deviation from equilibrium between olivine and orthopyroxene was caused by slow subsolidus reactions at low temperatures involving decomposition of plagioclase and olivine into two-pyroxene and

spinel symplectite.

On the basis of the optimization of the geothermobarometry to the two localities, we successfully detected thermal, chemical, petrological, rheological, and seismic structures of the mantle on the scale of ~20 km beneath Ichinomegata and Taфраoute. This study demonstrates the importance of careful examination both of thermodynamic and kinetic aspects of reactions relevant to geothermobarometries for their application to chemically heterogeneous minerals.

Keywords: Spinel peridotite xenolith, Geobarometry, Chemical zoning, Thermal history, Structures of mantle