Numerical model of reaction-advection system for serpentinization in permeable flow of silica-rich fluid: Examination of chemical behaviour

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Serpentinite is formed by hydration reaction of mantle peridotite. Its significant distribution in mantle wedge is inferred from geophysical observations. Alignment of serpentine crystals under anisotropic stress changes fluid pathways and, therefore, could have controls on direction and velocity of fluid migration. Understanding of such self-organizing processes of structural formation is very important to gain a dynamic image of fluid processes and hydration in mantle wedge. However, kinetic parameters for these processes in deep subduction zones are almost unknown.

Theoretical and numerical studies of non-equilibrium physics show that patterns of compositional structure can be variable depending on kinetic parameters in reaction-material transfer (e.g., diffusion and advection) systems. In this study, in order to extract direct information of the development processes from the serpentinite structures, we try to construct a non-equilibrium geochemical model of serpentinization including fluid advection. This will be a test whether the idea of non-equilibrium physics can be applicable to rock structures or not. If nature of mineral distributions in rocks is successfully reproduced, this gives constraints on kinetic information.

Our geochemical model is based on structural and petrological analyses of antigorite-olivine layering in the Higashi-akaishi ultramafic body: Infiltration of silica-rich fluid from the surrounding meta-sediments is critical for the heterogeneous hydration. We construct a numerical model adopting following chemical and physical descriptions: Main mineral-fluid reactions are dissolution of olivine and precipitation of serpentine; Aqueous species related to the reactions are Mg^{2+}, SiO_2 and H^+, and concentration of H^+ is buffered by dissociation of water; Extents of disequilibrium between aqueous fluid and minerals are calculated based on Deep Earth Water model (Sverjensky et al., 2013); Reaction rates follow a kinetic model of Lasaga (1995); Infiltration of fluid with a composition of talc-serpentine buffer is mainly driven by buoyant force and the permeable flow is described in Darcy's equation. Numerical calculations are made in a condition of 20 kbar and 550 degree C that are expected in mantle wedge along the Nankai subduction boundary.

We made short calculations for initial stage of serpentinization and checked chemical behaviors of the system upon reactions using a wide range of sets of reaction rate constants and permeability. There are three types of chemical shift in compositions of aqueous fluid under a constant flow rate. One is a smooth shift along or between equilibrium curves in advection-dominant conditions (lower reaction rate constants). In contrast, high reaction rate constants result in consumption of fluid species. Most interesting is that oscillating compositional shifts in fluid chemistry appear in intermediate conditions of reaction rate. Layered structures due to spatial variation of serpentine formation were observed in the oscillating conditions near the limit to the high reaction rate regime. Oscillations in concentrations of chemical species are known as one of the characteristic phenomena for non-equilibrium systems that result in formation of pattern structures. The results of this study implies that the conditions for layering in serpentinite are very limited in a simple reaction-advection system with a minor textural feedback for rate parameters.