論文の内容の要旨

論文題目

Grain-size sensitive creep of forsterite + enstatite aggregates

(粒径依存型クリープにおける
フォルステライト-エンスタタイト系のレオロジー)

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Abstract

We have conducted grain growth and creep experiments on the forsterite (Fo)–enstatite (En) system at 1 atmosphere and temperatures of 1260–1360 °C, and with variable volumetric fractions of the two minerals (Fo_{100} to Fo_3En_{97}).

Firtsly, grain growth of these samples are focused. The grain size ratios of forsterite and enstatite in simply annealed (reference) and deformed samples follow the Zener relationship of $d_I/d_{II} = \beta/f_{II}^z$. For samples where $f_{En} < 0.5$, I (the first phase) is forsterite, II (the second phase) is enstatite, $\beta = 0.67$, and z = 0.52; for samples where $f_{En} > 0.5$, I is enstatite, II is forsterite, β = 0. 73, and z = 0.53; f_{II} is the volume fraction of the second phase, and d is the grain size. Grain growth in the reference samples conforms to the relationship $d_s{}^4 - d_o{}^4 \approx k \cdot t$ (where d_s is the grain size under static conditions, d_0 is the initial grain size, k is the grain growth coefficient, and t is time), and in the deformed samples the relationship is $d_\varepsilon \approx d_s \exp(0.42\ \varepsilon)$ (where d_ε is the grain size under dynamic conditions and ε is the strain). The observed growth coefficient for the first phase (k_I) becomes

smaller with increasing f_{II}, and this is consistent with the theoretical predictions of $k_{\mathrm{I}} = (\beta/f_{\mathrm{II}}^{z})^{4} \cdot \frac{8\gamma c w D_i^{GB} V^2 \nu}{3GRT}$ where f_{II} is the volume fraction of the second phase, γ is the interfacial energy between the first and second phases, c is the concentration of rate-controlling elements, w is the width of the grain boundary, D_i^{GB} is the diffusion coefficient of rate-controlling elements for grain boundary diffusion, V is the molar volume of the solute, ν is a slowly varying quantity with different fractions of the second phase, G is a geometric constant, R is the gas constant, and T is the absolute temperature. Overall, our results are consistent with previously proposed grain growth models for static conditions that use mineral physical parameters such as diffusivity (D_i^{GB}) and interfacial energy (γ). We discuss grain size variations within the mantle, with lithologies from dunite to pyroxenite, and we go on to present a method that predicts the grain sizes of different mantle lithologies, provided the mineral parameters of diffusivity and interfacial energy are known.

Secondary, mechanical characteristics of these samples are focused. At constant temperatures and strain rates, the flow stresses of the samples decrease with increasing f_{En} for samples with $0 < f_{\mathrm{En}} < 0.5$, and increase with increasing f_{En} for samples with $0.5 < f_{\mathrm{En}} < 1$. This behavior is explained primarily by grain size changes as a function of f_{En} under grain size sensitive creep. The pre-exponential term, stress, grain size exponent, and activation energy are flow parameters we have determined for a wide range of enstatite fractions (f_{En}). Samples with a low f_{En} (≤ 0.03) exhibit creep characteristics that correspond to dislocation accommodated grain boundary sliding creep (i.e., a stress exponent of 3), whereas diffusion accommodated grain boundary sliding creep is typical of high f_{En} samples (i.e., the stress and grain size exponents are ~1 and ~2, respectively). The change of creep mechanism is attributed to changes in grain size with respect to f_{En}. Overall, in the Fo–En system, the change of flow strength as a function of f_{En} under grain size sensitive creep can be explained primarily by the change of grain size, and secondarily by changes in the volume fractions of phases that have different flow strengths (enstatite is ca. 10 times stronger than forsterite under our conditions of deformation). Viscosities of all samples can be reproduced in a viscosity model that takes into account, (1) the grain sizes that have been estimated by the grain growth laws, and (2) the flow laws for monomineralic systems of forsterite and enstatite. Furthermore, we demonstrate that our model can be extended to make predictions of viscosity in other mineral assemblages.

Finally geological applications especially on fine-grained mylonite are presented. Microstructures of peridotitic ultramylonite from Oman ophiolite are compared with that of our experimental products. Around 0.5 mm thick layers with different amount of pyroxenes (orthopyroxene and clinopyroxene) in each layer are developed well in the rocks forming their foliation. Average grain sizes and grain size ratio of olivine and pyroxenes from each layer are compared with respect to the fraction of pyroxenes (f_{px}) in the layers. Grain size of the pyroxenes are almost constant among different f_{px} layers, whereas olivine grain size decreases significantly with increasing f_{px}, both of which were the characteristic features found in forsterite + enstatite aggregates after the grain growth experiments. Further, Zener relation (log d_{ol}/d_{px} versus log f_{px}) in the mylonite is remarkably comparable to that found in the experiments. These observations indicate the operation of effective pinning of pyroxene grains on grain growth of olivine grains during the deformation of the rocks. Olivine grains in high f_{px} ($f_{px} > 0.04$) layers do not exhibit lattice preferred orientation (LPO) whereas the grains in low f_{px} ($f_{px} < 0.04$) layers exhibit LPO indicating the deformation proceeded via diffusion and dislocation accommodated creep in the former and the latter layers, respectively. The observation of finer olivine grain size as predicted from the experiments and theory in the low f_{px} layers is explained well by operation of dislocation accommodated creep where the size is determined by stress. Based on our flow laws obtained for diffusion creep of forsterite + enstatite in our series of work, pyroxene-rich layers are 1 to 3 orders of magnitude weaker relative to essentially pyroxene-free layers. We simulated grain growth in forsterite + enstatite aggregates with $f_{px} < 0.5$ under temperature and stress conditions of 700 C and 120 MPa, which are estimated from the chemical compositions of pyroxenes and olivine grain size in the low f_{px} layers, respectively, based on our grain growth and flow laws. The results show that the observed grains grew from ≤ 1 μm grains with spending $\sim 10^4$ years to reach presently observed grain size.