Improving grain size analysis using computer vision techniques and implications for grain growth kinetics

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ABSTRACT

Earth’s physical properties and mantle dynamics are strongly dependent on mantle grain size, shape, and orientation, but these characteristics are poorly constrained. Experimental studies provide an opportunity to simulate the grain growth kinetics of mantle aggregates. The experimentally determined grain sizes can be fit to the normal grain growth law \( G^n - G_0^n = k_0 t \exp(-\Delta H/R T) \) and then be used to determine grain size throughout the mantle and geological time. The grain growth dynamics of spinel-orthopyroxene mixtures in the upper mantle are modeled here by experimentally producing small grain sizes in the range of 0.5 to 2 µm radius at pressures and temperatures equivalent to the spinel lherzolite stability field. To accurately measure the sizes of these small grains, we have developed a computer vision workflow; using a watershed transformation, which rapidly measures 68% more grains and produces a 20% improvement in the average grain size accuracy and repeatability when compared with manual methods. Using this automated approach, we have been able to identify a significant proportion of small grains, which have been overlooked when using manual methods. This additional population of grains, when fit to the normal grain growth law, highlights the influence of improved accuracy and sample size on the estimation of grain growth kinetic parameters. Our results demonstrate that automatic computer vision enables a systematic, fast, repeatable method of grain size analysis, across large data sets, improving the accuracy of experimentally determined grain growth kinetics.

Keywords: Grain growth kinetics, advanced image processing, watershed algorithm, grain size analyses

INTRODUCTION

Rocks are composed of large numbers of grains or crystallites. A grain is formed of a coherent, continuous lattice, the boundary of which has a discontinuous change in crystal lattice or other properties. The properties of these grains: their size, shape, orientation, and how they interact influence the bulk properties of rocks. These aggregate properties influence many of Earth’s physical properties, including strength or viscosity and seismic anisotropy; these in turn impact the large-scale motion of plates and mantle overturns (Bercovici and Ricard 2013; Chu and Korenaga 2012; Dannberg et al. 2017; Evans et al. 2001; Hirth and Kohlstedt 1995; Karato 1984; Yamazaki et al. 2010). On a smaller length scale, grain size is often used as the basis for the classification of some igneous and clastic rocks, as well as interpretations of the geological environment and the processes, which formed it. Grain growth and recrystallization are active processes, continuously changing the grain size of mantle aggregates. This has far-reaching consequences; for example, the decoupling of the upper and lower mantle may be due to a sudden grain size reduction associated with the spinel to perovskite transformation at the 660 km discontinuity (Dobson and Mariani 2014).

Interpreting indirect geophysical observations in terms of grain size is extremely difficult, and therefore the aggregate grain size of the mantle is poorly constrained. It is widely thought to vary from millimeters to centimeters at ~400 km depth, close to the transition zone (Faul and Jackson 2005). Estimates of the lower mantle (depths >660 km) grain size may vary from 1 to 1000 µm (Solomatov et al. 2002; Solomatov and Reese 2008). Constraining the evolution of grain size of the mantle by experiments is difficult because they are limited by both extent and sample volume and result in small grain sizes tens of micrometers at most (Karato 1989; Kim et al. 2004; Faul and Jackson 2005; Yamazaki et al. 2005, 2010; Faul and Scott 2006; Nishihara et al. 2006; Hiraga et al. 2010b). The experimental pressure-temperature-time series results are extrapolated over many orders of magnitude to mantle scales using kinetic models (Hillert 1965; Chu and Korenaga 2012). These models assume the normal grain growth law:

\[ G^n - G_0^n = k t \]  

where \( G \) is grain size, \( G_0 \) the initial grain size, \( k \) rate constant, \( t \) time, and \( n \) the grain growth exponent. The rate constant, \( k \), has an Arrhenius temperature dependence and a global fit can be applied of the form:

\[ (G^n - G_0^n) = k_0 t \exp(-\Delta H/R T) \]  

where \( k_0 \) is the pre-exponential exponent, \( H \) the activation enthalpy for grain growth, and \( R \) the gas constant.

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