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Interpreting plagioclase-melt (dis)equilibrium due to cooling dynamics: implications for thermometry, barometry and hygrometry

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Plagioclase is particularly useful for deciphering magma chamber dynamics due to the sluggish diffusion of its major and minor constituents. However, the interpretation of plagioclase crystallization conditions and plagioclase-liquid exchange reactions is often ambiguous because cooling rate can change the primary plagioclase composition. Cooling dikes and lava flows may affect the crystal growth and the chemistry of plagioclase during post magmatic activity. Moreover, cooling kinetics may also have an impact on plagioclases which crystallized before magma ascent from deeper magmatic chambers. In consequence the study of plagioclase compositions that grow under dynamic crystallization conditions are crucial to decipher the cooling history of magmas. In this study the compositional variation of plagioclase and the partitioning of major elements between plagioclase and melt have been experimentally measured as a function of cooling rate. Crystals were grown from a basaltic melt at a pressure of 500 MPa under (i) variable cooling rates of 0.5, 2.1, 3, 9.4, and 15 °C/min from 1250 °C down to 1000 °C, (ii) quenching temperatures of 1025, 1050, 1075, 1090, and 1100 °C at the fixed cooling rate of 0.5 °C/min, and (iii) isothermal temperatures of 1000, 1025, 1050, 1075, 1090, and 1100 °C. Our results show that euhedral, faceted plagioclases form during isothermal and slower cooling experiments exhibiting idiomorphic tabular shapes. In contrast, dendritic shapes are observed from faster cooled charges due to a diffusion-controlled growth mechanism. As the cooling rate is increased, concentrations of Al+Ca+Fe+Mg increase and Si+Na+K decrease in plagioclase favouring higher An and lower Ab+Or contents. These exchange reactions occur because the diffusion rate of components rejected by the crystal away from the growing interface is much slower than the crystal growth rate; in other words, the incompatible elements are rejected less efficiently during rapid crystal growth, thus they are essentially trapped into the plagioclase crystal lattice ("diffusion-controlled" growth mechanism). Significant variations of major element distribution coefficients ($^{pl-liq}$Kd) are also observed by the comparison between isothermal and cooled charges; notably,$^{pl-liq}\mathrm{Kd}_{Ab-An}$, $^{pl-liq}\mathrm{Kd}_{Ca-Na}$ and $^{pl-liq}\mathrm{Kd}_{Fe-Mg}$ monotonically change with increasing cooling rate. Therefore, crystal-melt exchange reaction has the potential to reveal the departure from equilibrium for plagioclase-bearing cooling magmas. Finally, thermometers, barometers, and hygrometers derived through the plagioclase-liquid equilibria have been tested at these non-equilibrium experimental conditions. Since such models are based on assumption of equilibrium, any form of disequilibrium will yield errors. Results show that errors on estimates of temperature, pressure, and melt-water content increase systematically with increasing cooling rate (i.e. disequilibrium condition) depicting monotonic trends towards drastic overestimates. These trends are perfectly correlated with those of $^{pl-liq}\mathrm{Kd}_{Ca-Na}$, $^{pl-liq}\mathrm{Kd}_{Ab-An}$, and $^{pl-liq}\mathrm{Kd}_{Fe-Mg}$, thus demonstrating the ability of models to test (dis)equilibrium conditions.