# COARSENING OF CRYSTALS DURING TEMPERATURE CYCLING IN MAGMAS AND ICY MATERIALS.

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**Introduction:** Development of large crystals is typically attributed to slow cooling and limited nucleation sites. Coarsening can also occur during aging under isothermal conditions owing to the inverse relationship between crystal size and surface energy (i.e. Ostwald ripening). Another process that can greatly enhance development of large crystals is thermal cycling, a process that is well known to anyone who has eaten old, crunchy ice cream or skied on spring snow. We have performed melting and crystallization experiments on a magma analog at 40°-50°C [1] and have performed similar experiments on a basalt in a 1-atm gas mixing furnace in order to better understand and quantify the effects of T cycling on coarsening.

**Magma analog results:** Results from heating-stage experiments on the ammonium thiocyanate-cobalt chloride system at Ts around 50ºC indicate that crystal coarsening increases dramatically during T cycling by dissolution-crystallization (Fig. 1). Small crystals disappear as their mass is transferred to growing large crystals, dramatically skewing the crystal size distribution [2]. Crystals grown by dissolution-crystallization during thermal oscillation have much greater aspect ratios (Fig. 1) and often show a shape-preferred orientation parallel to the thermal gradient.

**Alkali basalt results:** Melting and crystallization experiments at 1150ºC near the Ni-NiO buffer indicate that coarsening of plagioclase crystals is accentuated greatly by T cycling (Fig. 2). We investigated the role of both amplitude and period on coarsening and found that the magnitude of the amplitude positively correlates with crystal size and negatively correlates with crystal number density (Fig. 2). However, there is no observed correlation between period and crystal size or number density.

**Coarsening of ice:** Donhowe and Hartel [3] performed T cycling experiments on ice cream in order to understand the recrystallization process that leads to unsavory crunchy texture. Their results indicate that the rate of recrystallization positively correlates with T cycle amplitude and mean T. Colbeck [4] found that T cycling caused ice in snow to coarsen by inducing multiple crystals to coalesce into single larger crystals. This process of metamorphism and coarsening, along with dissolution-crystallization, can create layers in the snow with reduced porosity and permeability.

**Temperature cycling in nature:** Coarsening during T cycling is likely an important aspect of crystal growth because monotonically decreasing Ts, although commonly assumed in discussions of magmatic systems, are rare in nature. Incremental magma emplacement and convection are two processes that can induce T cycling in magmatic systems, and thermochronology [5] and crystal size distribution studies [2] indicate that such cycling occurs. The large crystals of K-feldspar that characterize many granites probably arise via late-stage dissolution-crystallization [6]. On Earth, diurnal variations in T and solar radiation contribute to ice recrystallization in snow [4].

**Application to extraterrestrial bodies:** Primary and secondary crust formation on the moon occurred under different T conditions. Primary crust formed from a magma ocean, and secondary crust formed from incompatible-rich minimum melts. It is possible that both types of magmatism involved continuous T cycling. Temperature in the magma ocean probably cycled owing to convection and/or tidal heating [7]. During secondary crust formation magma genesis was a protracted process [8] which, if comparable to long-lived felsic magmatism on Earth [5], is best explained by episodic input of heat.

It is intriguing to speculate that T cycling may induce significant crystal aging and growth of ices on planetary bodies. On Mars, diurnal variations in T could promote crystal aging in near-surface ices, although sublimation could wipe out any crystal size gains. In comets, rotation of the nucleus [9] will cause significant short-term T cycling in those with perihelia sufficiently close to the sun. Although ablation will again destroy surface ice crystals, nuclei with rotation periods on the order of days will see significant T variations to depths of several tens of cm.

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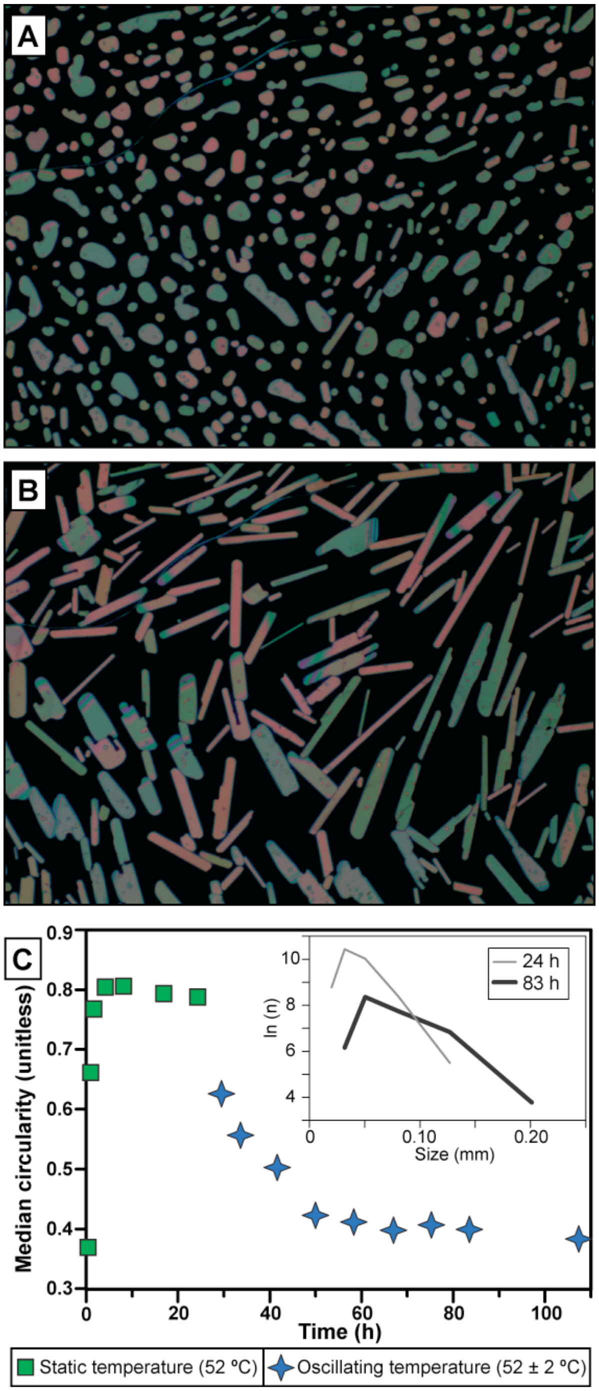


Fig 1. *A* and *B* are images from a magma analog experiment observed through circularly cross-polarized light at 4x (width of view is ~2.5 mm). *A* was obtained 20 hours into experiment and *B* was obtained 70 hours into experiment. Temperature of experiment is 52 ± 0.3 ºC when static and 52 ± 2 ºC when oscillating (period of 10 minutes). *C* is from [1] and illustrates the change in crystal morphology and crystal size distribution when the temperature is cycled.

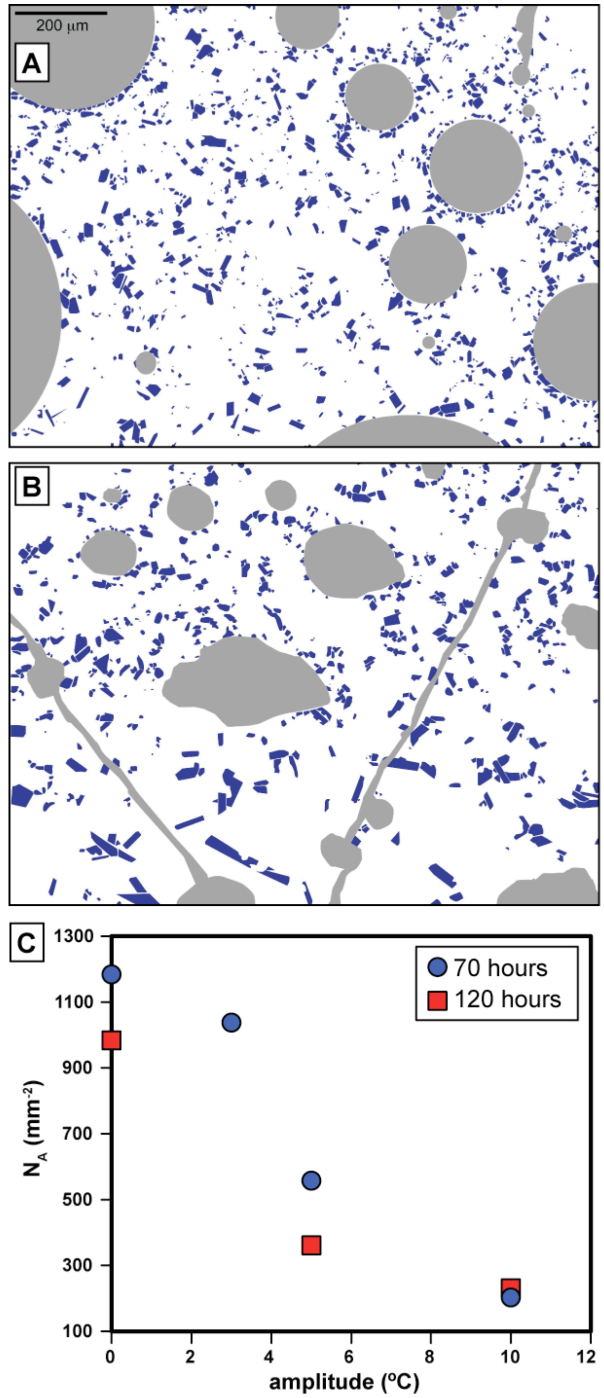


Fig. 2. *A* and *B* are images of digitized plagioclase crystals (dark blue) and bubbles and cracks (gray) in basalt experiments (scale on *A* applies to *B*). Mean T for all experiments in this figure is 1150ºC. *A* is from a static temperature experiment with duration of 70 hours. *B* is from a 70 hour T cycled experiment with amplitude of ± 5ºC and period of 40 minutes. *C* is a plot of crystal number density ($N_A$) vs amplitude and illustrates the negative correlation between number density and cycle amplitude.