

COMPARISON OF EXPERIMENTAL STUDIES ON CHONDRULES AND Ca-Al-RICH INCLUSIONS; Julie M. Paque, Center for Materials Research and Geology Dept., Stanford University, Stanford, CA 94305-4045; and Gary Lofgren, SN-2 NASA Johnson Space Center, Houston, TX 77058

Many experimental runs have been performed on compositions representing chondrules (summarized in 1) and Ca-Al-rich inclusions (CAIs; e.g., 2-4) in an effort to gain a better understanding of the conditions under which these objects formed. In addition, experiments on basaltic compositions yield basic information relating to the formational history of chondrules and CAIs (5,6). This large body of results affords us an opportunity to make generalizations about the processes of crystallization with respect to chondrules and CAIs.

Many variables, such as the maximum temperature attained by the object and the cooling rate, affect the texture and chemistry of the chondrule or CAI. Other more subtle factors, such as the nature of starting material (glass, sintered, etc.), the presence of dust or foreign material to act as nuclei, are less well studied but may play an important role.

We will compare the crystallization properties that have been found from experiments on chondrule and CAI compositions. An important outcome is that the experimental results cross compositional boundaries. Whether we are discussing chondrules from enstatite chondrites, or CAIs from Type C inclusions, we find the same crystallization processes producing similar results.

Effect of maximum temperature. The maximum temperature attained by a sample in the experimental runs has a prominent effect on the resulting texture. The maximum temperature controls the number of nuclei available when the sample begins to cool, which in turn influences the number of crystals that form and the maximum size the crystals attain. The maximum temperature and presence or absence of nuclei also affect the degree of supersaturation (supercooling) present when the phases begin to grow upon cooling. With nuclei present in the sample, there is a smaller degree of supercooling prior to the initiation of crystallization. When embryos (sub-critical nuclei) are present the degree of supercooling is increased. In the absence of embryos the largest supercooling effect is observed.

Dendritic or radial textures form if there are only embryos or no pre-existing nuclei in the samples for both chondrules (7, 8) and CAIs (9). Because samples brought to temperatures at or below their liquidus generally contain nuclei, they produce porphyritic textures, regardless of the cooling rate. The phase that dominates the texture in chondrules is either pyroxene or olivine, and in CAIs it is generally melilite. For many CAIs bulk compositions samples brought to subliquidus temperatures, but above the temperature at which melilite melts, generally produce dendritic melilite. Even though the liquidus phase is spinel, the melilite does not nucleate on spinel.

The time a sample is held at the maximum temperature will also affect the number of nuclei. However, no systematic studies have been performed to ascertain the extent of this effect, which is dependent on the dissolution rate of pre-existing crystalline phases.

Another factor affecting the nucleation characteristics of a sample is the presence of foreign matter that act as nucleation sites for the phases in the melt. Most experiments are done using Pt wire to hold the experimental charge. This wire is known to act as a nucleation site for crystals (10). The effect is to lower the degree of supercooling or supersaturation from what would occur if such heterogeneous sites were not present. For CAIs it is possible that Fremdlinge act as nuclei.

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Effect of cooling rate. Conventional wisdom suggests that the barred and radial textures found in chondrules are a result of rapid cooling and that porphyritic chondrules and CAIs formed when cooling is slower. Most experimentalists now agree that cooling rate is secondary to maximum temperature in determining the textures of samples. Barred and radial textures have been produced in samples cooled at 5 °C/hr (7). The shape of phenocrysts depends on the growth rate, which in turn is dependent on the cooling rate (8). As cooling rate increases the crystals become increasingly skeletal. The dominant effect of cooling rate is on the phase chemistry, zoning patterns, incorporation of trace elements, and order of crystallization of phases.

Extensive comparisons of phase chemistry between experimental and natural samples of chondrules are sparse. Miyamoto et al. (11) concluded that moderate cooling from temperatures slightly below the liquidus accounts for the Mg-Fe zoning and CaO contents of olivines. Fe/Mg diffusion coefficients between olivine and glass were found to be lower than the equilibrium value and rapid cooling was suggested as the cause (12). On the other hand, several studies have suggested that slow cooling rates are responsible for the features found in Ca-Al-rich inclusions (2,3). The Ti and Al concentrations in pyroxenes and the zoning patterns of melilite both imply slow cooling rates for CAIs.

Experiments to date have been done for the most part with linear cooling histories. Complications that may be responsible for features found in meteorite samples in non linear cooling rates, plateaus in the cooling history, or multiple heating and cooling cycles. In addition, the nucleation of crystals in a melt is a stochastic process and several samples run under the same conditions will not produce identical results.

Effect of bulk composition. The bulk composition affects the absolute value of maximum temperature and cooling rate that produces specific textures in a given sample. With an average composition of a particular chondrule type, it is possible to produce nearly all possible chondrule textures (7). This is also true for CAIs (3). The presence of Ca-Al-rich chondrules in ordinary chondrites (13) also suggests that a continuum of sorts exists from CAIs to chondrules. However, no experimental data is available on the Ca-Al-rich chondrules.

Summary and conclusions. The development of textures for both chondrules and CAIs is controlled primarily by the maximum temperature attained by the object. Cooling rate is secondary in the formation of textures. When interpreting the conditions required to produce an individual chondrule or CAI it is important to consider both the texture and the chemistry of the object, and realize that there may be a range of conditions (maximum temperature, cooling rate, etc.) which may be capable of reproducing the object.

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