

EXPERIMENTAL EVIDENCE FOR SLOW COOLING OF TYPE B CAIS FROM A PARTIALLY MOLTEN STATE.
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Introduction. Despite the diversity of models for the origin of coarse-grained Ca-Al-rich inclusions from Allende, most authors agree that at least some inclusions were molten or partially molten at some stage in their history. In order to provide criteria for choosing between available models, which are distinguishable by the time-temperature histories that they imply for inclusions, we have conducted experiments designed to determine the effects of cooling history on the textures, crystallization sequences, and phase chemistries of CAIs. Crystallization experiments were conducted on an average Type B CAI composition (1) at 1 atm in air with approximately linear cooling rates varying from 2 to 1000°C/hr. Samples were quenched at different temperatures during the cooling sequence in order to determine the crystallization sequence and to observe the development of textures. Samples were held at maximum temperature (T_{\max}) for 3 hrs before beginning the cooling sequence. T_{\max} was varied from 1275°C (melilite field) to 1580°C (above liquidus).

Crystallization sequences. Petrographic observations of CAI textures have suggested that anorthite crystallized before or nearly simultaneously with pyroxene in most inclusions (but see ref. 2). Under equilibrium conditions, anorthite crystallizes before pyroxene for the composition we have studied (1). Figure 1 shows that when cooling starts from the melilite field of crystallization ($T_{\max} = 1375^\circ\text{C}$) pyroxene crystallizes well before anorthite at fast cooling rates (>200°C/hr) and nearly simultaneously with it at slow rates (<20°C/hr). Similar results were obtained when cooling was started from a lower temperature in the melilite field ($T_{\max} = 1275^\circ\text{C}$). For T_{\max} above the liquidus, melilite entry was depressed more than 200°C from the temperature of its appearance in the equilibrium crystallization sequence and pyroxene always crystallized before anorthite (3). Charges cooled from the spinel field ($T_{\max} = 1420^\circ, 1450^\circ, \text{ and } 1500^\circ\text{C}$) also crystallized pyroxene before anorthite.

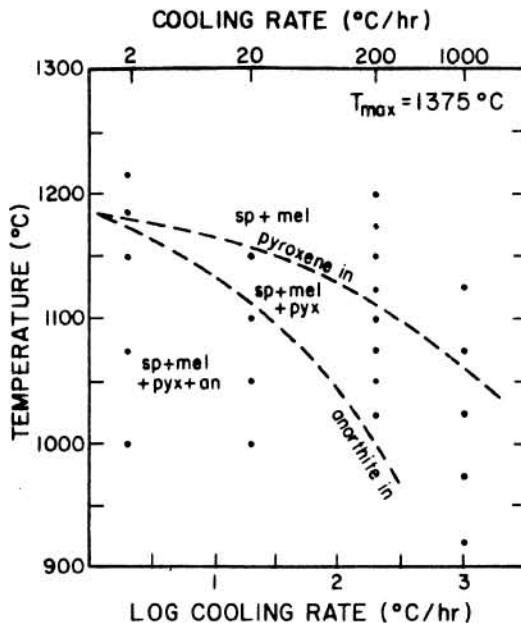


Figure 1

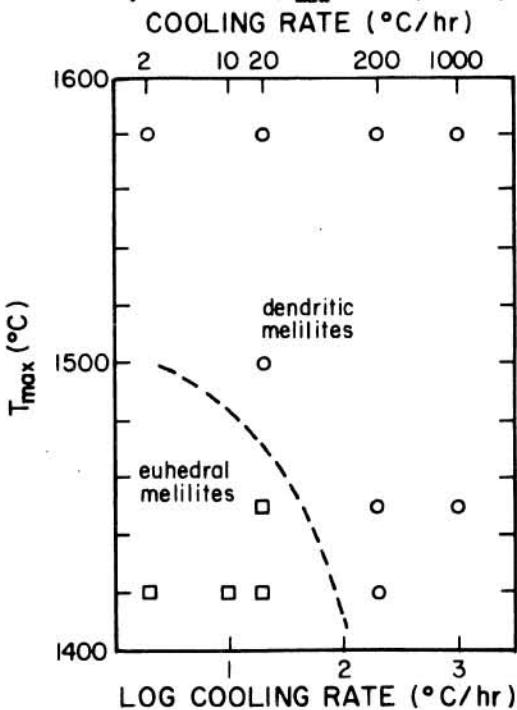


Figure 2

Textures. T_{\max} has more of an effect on the textures of our run products than does the cooling rate. Samples cooled from above the liquidus are dominated by dendritic melilites in a herringbone pattern, with pyroxene between the limbs of the melilites (3, 4). Euhedral spinels nucleated on the surface of the charge or on the platinum loop, are characteristic of samples cooled from above the liquidus. The sizes of the spinels (up to 1mm) produced by cooling from above the liquidus at the slowest cooling rates are much larger than those found in Type B CAIs.

Experiments with T_{\max} in the melilite field produced prismatic melilites (max. length $\approx 120\mu\text{m}$), anhedral to subhedral pyroxenes, interstitial anorthite, and small euhedral spinels (up to $60\mu\text{m}$) dispersed throughout the sample. Although crystal shapes and intergrowths in these run products are similar to those in natural inclusions, the grain sizes in these experiments are much smaller than those in most Type B CAIs.

Depending on T_{\max} and cooling rate (Figure 2), charges cooled from the spinel field produced either dendritic melilites or relatively large euhedral melilites (to 1.3mm). The temperature dependence may indicate that melilite nucleation sites are destroyed with increasing temperature (and possibly time) at temperatures above that of the equilibrium appearance of melilite (1400°C). Euhedral melilites and pyroxenes poikilitically enclose small euhedral spinel grains. The grain sizes of the melilites produced in these experiments approach those of melilites in coarse-grained CAIs.

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Phase chemistry. Electron microprobe analyses of pyroxenes from run products show wide variations in TiO_2 (2-12 wt.%) and Al_2O_3 (12-32 wt.%). Pyroxenes from fast cooling rate experiments ($>20^\circ\text{C}/\text{hr}$) exhibit the widest scatter and typically differ in composition from most Type B pyroxenes (Figure 3). Pyroxenes from slowly cooled ($<2^\circ\text{C}/\text{hr}$) and equilibrium experiments (1) that contain both pyroxene and anorthite are similar in composition to those in Type B inclusions.

Melilites and pyroxenes from our experiments are concentrically zoned. Pyroxenes large enough to analyze were typically zoned from high Al-low Ti cores to low Al-high Ti rims, although some show the opposite trend. All of the large euhedral melilites from experiments with T_{\max} in the spinel field were zoned from cores of approximately Ak30 to rims varying from Ak40 to Ak83 (depending on quench temperature). For $T_{\max}=1420^\circ\text{C}$ and cooling rates of 2° and $10^\circ\text{C}/\text{hr}$ the melilites exhibit normal zoning with a rim of reverse zoning, attributed to the onset of pyroxene crystallization (2).

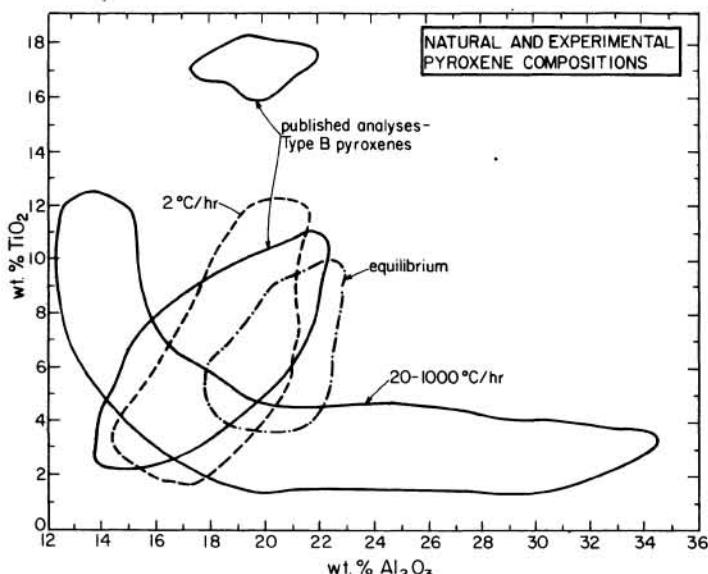


Figure 3

Conclusions. Unless the observed textures in CAIs result from later processing, the absence of distinctive dendritic melilites in inclusions from Allende indicates that coarse-grained CAIs did not form by cooling quickly from above their liquidus. Slow cooling of the inclusions from above their liquidus is also unlikely since the large euhedral spinels produced experimentally under these conditions are also absent in Allende inclusions. These textural comparisons and comparisons between natural and experimental pyroxene compositions and crystallization sequences suggest that Type B CAIs from Allende cooled slowly (< several degrees per hour) from temperatures below the liquidus. Textural comparisons (crystal shapes and grain sizes) also suggest that the cooling of Type B CAIs similar in composition to the bulk composition we have studied could have begun from a temperature above the equilibrium appearance of melilite for this composition (1400°C), but would have had to be low enough to preserve the melilite nuclei.

The cooling rates that we have inferred for CAIs are several orders of magnitude lower than those that have been suggested for chondrules based on similar experiments in which chondrule textures have been duplicated (5).

The results of our experiments can be used to evaluate current models for the origin of coarse-grained Ca-Al-rich inclusions. The metastable vapor to liquid condensation model (6) cannot explain the textural and mineralogical features of Type B CAIs because it would require rapid crystallization from a totally liquid state. This model can only be valid if observed textures reflect a later event. Melting due to release of internal chemical energy (7) or impact melting (8) could be compatible with incomplete melting, but sufficiently slow cooling rates may be difficult to achieve in the context of these models. Direct condensation of partially molten objects or reaction of solid condensates with gas to produce liquid in nebular environments (1,9) appear to be capable of explaining the slow cooling rates and incompletely molten states of CAIs that we have inferred, as well as the variations in bulk compositions of Type B CAIs (1).

References: (1) Stolper E. (1982) *G.C.A.* 46, 2159. (2) MacPherson G., Paque J.M., Stolper E., and Grossman L., this volume. (3) Stolper E. et al. (1982) *Lunar Planet. Sci. XIII*, 772. (4) Beckett J.R. and Grossman L. (1982) *Lunar Planet. Sci. XIII*, 31. (5) Tsuchiyama A. et al. (1980) *E.P.S.L.* 48, 155. (6) Blaebler M. and Fuchs L.H. (1975) *G.C.A.* 39, 1605. (7) Clayton D. (1980) *Astrophys. J.* 239, L37. (8) Reid A.M. et al. (1974) *Meteoritics* 9, 35. (9) Clayton R.N. et al. (1977) *E.P.S.L.* 34, 209.