

EXPERIMENTAL CONSTRAINTS ON THE ORIGIN OF PLAGIOCLASE-OLIVINE INCLUSIONS AND CA CHONDRULES ^{1,2}Y.J. Sheng, ²J.R. Beckett, ^{1,2}I.D. Hutcheon, and ^{1,2}G.J. Wasserburg. ¹The Lunatic Asylum, ²Division of Geological and Planetary Sciences, Caltech, Pasadena, CA 91125.

Plagioclase-Olivine Inclusions (POIs) are a distinct group of objects in carbonaceous chondrites consisting of plagioclase (Plag; An_{0-90}), olivine (Fo_{0-90}), enstatite (En), clinopyroxene (Cpx), and spinel (Sp) in various proportions [1]. CA chondrules (CACs) in ordinary [2,3] and enstatite [4] chondrites are similar to POIs but Plag is rare to absent while glass or Ca-rich mesostasis (Mes) is common. POIs and CACs cover a wide range of bulk compositions intermediate between those of ferromagnesian chondrules (FMCs) and Ca-, Al-rich inclusions (CAIs). Although there have been experimental efforts to characterize phase relations and dynamic crystallization behavior of CAIs [5,6] and FMCs [7,8], intermediate compositions relevant to POIs and CACs have not been studied systematically. We conducted equilibrium crystallization experiments on representative POI compositions at 1 atm total pressure in order to develop a framework to assist our interpretation of petrographic and isotopic data on POIs and to investigate possible differences in crystallization sequences between POI and CAI melts. For many POIs and CACs, concentrations of Na_2O and FeO are sufficiently low so the system $\text{CaO-MgO-Al}_2\text{O}_3\text{-SiO}_2$ is an excellent approximation to their bulk compositions and we can use projections to describe the crystallization behavior.

Homogeneous glasses corresponding in composition (Table 1) to representative POI were synthesized from oxide mixes. Experiments were conducted at constant temperature in air using techniques of [5] and run products were analyzed using optical microscope, SEM and electron probe techniques. Experimentally determined crystallization sequences are given in Table 1. Figs. 1-3 are multiply saturated liquidus phase diagrams constructed using data from this study and literature sources together with projected compositions of POIs and CACs. In Fig. 1, melt compositions are projected from MgAl_2O_4 Sp onto a plane defined by the compositions of $\text{CaAl}_2\text{Si}_2\text{O}_8$ anorthite (An), Mg_2SiO_4 forsterite (Fo), and tridymite (Tr). Liquid (L) compositions on the Sp-saturated surface are contoured in wt. % Sp above the An-Fo-Tr plane. Sp + cordierite (Cd) is stable as indicated in Fig. 1. However, in short runs ($< \sim 35$ hrs) aluminous En often coexists with Sp. The key feature of this phase diagram is the thermal boundary represented by the Sp-Plag-Fo plane, the exact position of which for CACs and POIs will depend on the Plag composition. During fractional crystallization, liquids on the Tr-poor side of this plane will evolve towards the Cpx + Sp + L field (shown in [5]) and crystallize Cpx. Liquids on the Tr-rich side of the thermal divide will evolve toward the invariant point Sp + An + Fo + Cd + L. However, Sp is in a reaction relationship with the melt at this invariant point, along the Sp + An + Fo + L boundary curve and in the shaded region, so such liquids may leave the Sp saturation surface and crystallize En. This can be seen in Fig. 2, a projection from Fo of olivine saturated melt compositions onto the plane defined by Sp-Tr-diopside (Di). The plane Fo + Plag + Sp is a thermal boundary for compositions in the Sp + L field. Sp-saturated L on the Tr-poor side of this plane will crystallize Cpx, but in many cases won't crystallize Opx. Fig. 3 is the projection of An-saturated melt compositions from An onto the plane Sp + Tr + Di. Fo and Pr are both in reaction with L at the invariant point An + Fo + ortho-enstatite (Oe) + proto-enstatite (Pr) + L.

Figs. 1-3 provide a framework for the interpretation of mineral assemblages observed in many POIs and CACs. Phase assemblages predicted on the basis of phase equilibria are generally consistent with those observed in the meteoritic inclusions. Inconsistencies are either associated with the unexpected presence of Sp or, for CACs, the absence of Plag (+presence of glass or Mes). The latter may reflect faster cooling rates in CACs relative to POIs and the well known difficulty of Plag nucleation [9]. Sp in POIs that appear anomalous based on phase relations also have anomalous Mg isotopes versus other phases and are often strongly resorbed [1]. Hence these grains are relicts that pre-date the melting event. Isotopically anomalous Sp are also found in POIs with Sp on the liquidus. Fig. 4 shows liquidus temperatures (T_{Li}) for these POIs calculated using the model of [10] and ranges in Mg isotopic fractionation (F_{Mg}) in Sp of [1]. Isotopic anomalies in Sp are common in POIs but bulk inclusions are typically normal. Hence Sp that crystallized from or re-equilibrated with the melt will have $F_{\text{Mg}} \sim \text{bulk}$; anomalous Sp are earlier. Sp in POIs with $T_{\text{Li}} < 1500^\circ\text{C}$ have $F_{\text{Mg}} \sim \text{bulk}$ while for $T_{\text{Li}} > 1500^\circ\text{C}$ F_{Mg} is variable. There are no systematic variations in grain size with T_{Li} so the maximum temperature of the melting event (T_{max}) for POIs was probably $\sim 1500^\circ\text{C}$. A $T_{\text{max}} = 1500^\circ\text{C}$ is also consistent with the observation that $|F_{\text{Mg}}|$ tends to increase with T_{Li} . The proportion of Sp in a POI that crystallized from the melt below T_{max} with $F_{\text{Mg}} \sim \text{bulk}$ decreases with increasing T_{Li} . Hence the higher T_{Li} is, the more relict Sp will be present in the final assemblage. From Mg self-diffusion data in spinel [11], POIs were melted at $\geq 1500^\circ\text{C}$ for less than an hour. Otherwise, all of the isotopically anomalous Sp would have completely reequilibrated.

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Table 1 Composition of starting material and experimental results*

	Na ₂ O	MgO	Al ₂ O ₃	SiO ₂	CaO	TrO ₂	SUM	Crystallization sequences
POI-1	0	15.50	34.76	40.18	9.12	0.51	100.07	Sp(1605-13°C)→An(1332-43°C) [†] →Fo(1271-81°C) [†] →Cd(-1260°C)
POI-2	0	12.88	32.53	41.14	12.61	1.01	100.17	Sp(1546-52°C)→An(1381-91°C) →Fo(1271-81°C) [†]
POI-3	0	22.52	21.11	51.41	4.96	1.05	101.05	Sp-Fo(1351-1451°C)→Cd(1285-1301°C)→An(1261-69°C)
POI-2Na2	2.17	12.71	32.06	39.47	12.45	1.14	100.00	Sp(1550-1613°C)→Plag(1300-11°C) →Fo(1281-88°C)
POI-2Na5	5.03	12.43	31.27	38.14	11.92	1.21	100.00	Sp(1550-1613°C)→Fo(1237-50°C)

* WDS analysis on starting glass composition. [†] phase appearance reversed