AN EXPERIMENTAL STUDY OF FE-MG AND OXYGEN ISOTOPE EXCHANGE BETWEEN RELICT OLIVINE AND CHONDRULE MELT.

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Introduction: Relict grains are mineral fragments that were produced in a prior generation of chondrules [1] and escaped complete dissolution when they were incorporated into the present chondrule generation. [2] has estimated that relict grains are found in approximately 15% of all chondrules. The most common relict grains are refractory (FeO-poor) olivines found within high-FeO, porphyritic chondrules in Type 3 ordinary and carbonaceous chondrites. Typically, they have sharp transitional boundaries between the core and normally-zoned rim. These olivines include the so-called blue olivines [3,4,5,6,7], which have a spectacular blue cathodoluminescence. Most relicts are ^{16}O-rich and FeO-poor, while the chondrule phenocrysts are ^{16}O-poor and FeO-rich. There are several cases of the reverse, and reversals tend to be more common in ordinary chondrites than carbonaceous chondrites.

Among the largest problems remaining in meteorite research is the thermal history of chondrules. How long were they melted? How long did they crystallize? What were the conditions in the nebula during their formation? Determining the thermal history of the relict grains in chondrules is a major step in answering these questions.

We have done both isothermal and dynamic crystallization experiments in vacuum to determine 1) what is the expected Fe-Mg and oxygen isotopic profile in relict olivine? 2) what is necessary to erase or conceal the Fe-Mg and oxygen isotopic signatures of relict olivine 2) does diffusion or dissolution play a larger role in obscuring or erasing the relict signature? 4) How common should relict olivine grains be?

Experimental Procedure: Both the isothermal and dynamic crystallization experiments consisted of Eagle Station olivine chips (Fo_{80}, $\delta^{18}O$= -2.78, 125 to 425 μm in diameter) mixed with a terrestrial IIAB chondrule melt composition (liquidus ~1504ºC, $\delta^{18}O$ = 11.98). The isothermal experiments were run at 1300ºC, 1400ºC, 1500ºC and 1515ºC for durations up to 64 minutes. The dynamic crystallization experiments were held at 1515ºC for 15 minutes, cooled at a rates between 5ºC and 3000ºC per hour to 1000ºC and then "air" quenched. All experiments were run at Rutgers Univ. in our vertical muffle tube vacuum furnace at $3x10^{-3}$ torr ($4x10^{-6}$ atmospheres). The pressure was maintained by a constant flow of argon. The $f(O_2)$ was calculated to be ~ IW-0.5, however it is known that the initial fugacity starts out more oxidized and becomes more reducing over time. Water quenching is not possible in the vacuum furnace due to turbopump limitations. The experiments are quenched by moving them to a cold portion of the furnace. The high temperature (1500ºC and 1515ºC) isothermal runs produce melt-grown quench olivines and pyroxenes as a result. The other experiments show no discernable effects.

Results: The experiments were analyzed by electron microprobe (AMNH) for compositional data and ion microprobe (CNRS-isothermal runs, UCLA-dynamic crystallization runs) for their oxygen isotopic compositions.

The isothermal experiments show that at low temperature little occurs with respect to the Eagle Station olivine other than at the rim where very minor exchange with the melt occurs. There is no detectable change in the $\delta^{18}O$ of the olivine. At high temperature and increasing duration, there is progressive dissolution of the Eagle Station olivine into the melt. There is minor diffusion of Fe-Mg, but no change in $\delta^{18}O$. Based on the composition of the melt, ~20% of the Eagle Station olivine has been dissolved into the melt after only 32 minutes at 1515ºC. This agrees with the lighter isotopic composition of the melt. All melt-grown olivines and pyroxenes have the $\delta^{18}O$ composition of the melt.

The dynamic crystallization runs show definite (and in the slow cooling runs, significant) exchange of Fe-Mg towards the cores of the Eagle Station olivines with decreasing cooling rate, but again show no change in $\delta^{18}O$ composition. The melt-grown olivine overgrowths produced during crystallization have the $\delta^{18}O$ of the melt. The melt gets progressively heavier in $\delta^{18}O$ with duration as a result of FeO evaporation. The very slow cooling runs (5ºC and 10ºC) contain crystallized silica (tridymite) and pyroxene along the walls of the charge. The silica and pyroxene act as a protective cover to the charge and slow the rate of FeO loss by evaporation. The silica occurs as a result of evaporation, melt fractionation (bulk composition moves from being olivine normative to pyroxene normative) and slow cooling.

Discussion: Because of the relatively FeO-rich relict Eagle Station olivines, reversely zoned core to rim sequences were produced in the dynamic crystallization experiments when equilibrium magnesian, melt-grown, olivine overgrowths formed around the relict cores. The zoning produced however was rapidly obscured by Fe-Mg diffusion between core and rim, when cooling rates of less than 100ºC per hour were employed. Thus, the relict cores became camouflaged. However, ion probe oxygen analyses still easily revealed the location of the core-overgrowth boundary (Figure 1 and 2). These results imply that relict grains found in chondrules which have melt compositions that produce equilibrium olivines (and overgrowths) similar to the relict composition can easily be obscured in Fe-Mg within the crystallization time of the chondrule (i.e. FeO–poor relicts in Type I chondrules or FeO-rich relicts in Type II chondrules). However, their relict oxygen isotopic composition will remain intact (assuming they are in a low metamorphic grade chondrite).

In addition, basic diffusion [8] and dissolution calculations, based on the experimental results and assuming a 100µm FeO-rich relict olivine grain surrounded by a Type IIAB chondrule melt, indicates that in 32 minutes at 1515ºC roughly 4 µm of the exterior sphere is dissolved into the melt. However, Fe-Mg under the same conditions diffuses 5 µm, while oxygen diffuses only 0.1 µm. Therefore, the oxygen signature in relict grains are essentially permanent under any reasonable chondrule forming conditions (hours to days), while dissolution and Fe-Mg diffusion compete as to which is dominant, depending on duration and temperature conditions.

Conclusion: These results suggest a vastly greater population of relicts in chondrules than has previously been estimated [2]. If only one relict grain is missed for every one found (this is probably conservative given the limited number and diversity of oxygen studies to date), relicts are probably present in greater than 30% of all chondrules. This is further supported by the distinct lack of pyroxene relicts yet found [1,2,3,9]. An oxygen survey of the chondrules in the major Type 3 chondrite groups would prove extremely useful.

In order to erase ALL traces of the relict signature from a relict olivine, the grain must be either dissolved in the chondrule mesostasis or outright melted. However, to simply obscure a relict from simple electron microprobe analysis (Fe-Mg) standard estimated chondrule cooling rates (<100ºC/hr) easily suffice.

References: [1] Rambaldi E. R. (1981) *Nature 293*, 558-561. [2] Jones R. H. (1996) In *Chondrules and the Protoplanetary Disk* (R. H. Hewins et al, eds.) pp. 163-172, Cambridge Univ. Press, NY. [3] Kracher A., Scott E. R. D. and Keil K. (1984) *Proc.14th LPSC (Part 2) JGR (Suppl) 89*, B559-B566. [4] Steele I. M. (1986) *GCA 50*, 1379-1395. [5] Steele I. M. (1988) In *Meteorites and the Early Solar System* (J. F. Kerridge and M. S. Matthews, eds.) pp. 808-818. Univ. of Arizona Press, Tucson. [6] Steele I. M. (1989) *GCA 53*, 2069-2079. [7] Palme H., Spettel B. and Steele I. (1986) *LPS XVII*, 640-641. [8] Freer R. (1981) *Contrib. Mineral. Petrol.* 76, 440-454.[9] Leitch C. A. and Smith J. V. (1982) *GCA 46*, 2083-2097.

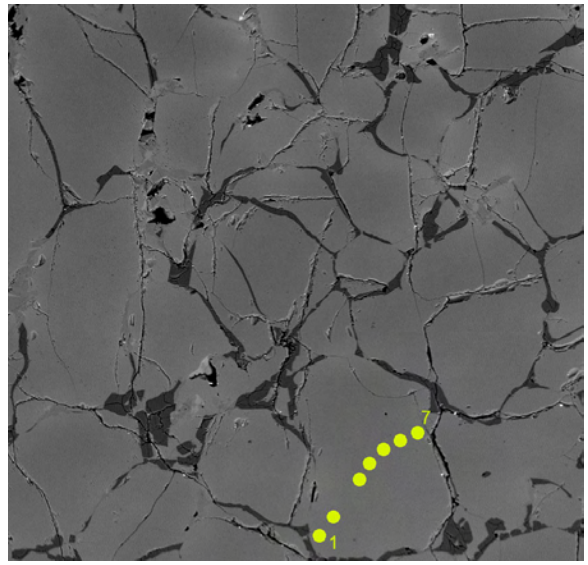

Figure 1: Backscattered electron image of the 100ºC per hour dynamic crystallization run showing multiple overgrown Eagle Station relicts which are obscured in Fe-Mg. Yellow dots are the ion probe analysis spots shown in Figure 2. Field of view is 1 mm wide.

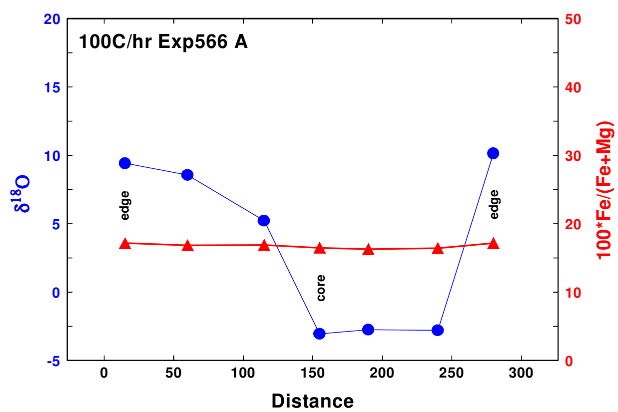

Figure 2: Distance versus $\delta^{18}O$ and Fe/(Fe+Mg) diagram showing the ~100 um relict core ($\delta^{18}O$ ~ -3) surrounded by a melt-grown olivine overgrowth. In Fe/(Fe+Mg), the relict would be completely undetectable.