COMPOSITIONAL EFFECTS OF LOW-PRESSURE IMPACTS IN CHONDRITIC METEORITES: OXYGEN ISOTOPE HOMOGENIZATION AND MG-FE DIFFUSION IN MATRIX OLIVINE AND PRESOLAR GRAINS.

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Introduction: Chondrites are believed to have accreted as porous dust aggregates [1]. The transit of chondrules through nebular dust formed fine-grained rims (FGR), which may be related to planetesimal accretion [2]. Further compaction and lithification of such precursors may have occurred via low velocity impacts, preserving accretionary fabrics observed in Allende [3,4].

Recent work has explored the effects of low-intensity impacts into primordial parent bodies, specifically the temperatures and pressures produced at lengthscales commensurate with matrix grains [5]. In this study, we explore whether the metamorphism experienced in these events is sufficient to homogenize the oxygen isotope composition of matrix olivines and presolar grains. We take Allende as an example, as pre-impact porosity and the magnitude of a compressive low-intensity impact are constrained [4]. We show that the local temperature excursions, coupled with other effects from low-pressure impacts, could homogenize 100-500 nm grains within seconds. This has important consequences for the origin and evolution of matrix grains in chondritic meteorites. In particular, this process may also explain fayalitic matrix olivine via Mg-Fe diffusion occurring in the aftermath of the event.

Calculating Rate of Oxygen Diffusion: To explore oxygen isotope diffusion during low-pressure shock events, we assume that diffusion obeys Fick's 2nd law:

$$\frac{C - C_o}{C_1 - C_o} = erf\left(\frac{x}{2\sqrt{Dt}}\right)$$

This corresponds to the following boundary conditions for an infinite source of diffusing atoms: $C(x,0) = C_o$; $C(0,t) = C_1$; $C(\infty,t) = C_o$. We define grains as equilibrated when the grain radius a equals the characteristic lengthscale of diffusion ($2\sqrt{Dt}$). There are several factors, however, that augment the rate of diffusion.

Role of $f(H_2O)$ and $f(O_2)$: Work on Allende has shown that aqueous alteration occurred in its parent body. We also see evidence for oxidation in this meteorite. Fayalitic olivine, sulfide and magnetite are the primary iron-bearing phases. Fluid volatilization would therefore accompany a low-pressure shock.

Even in nominally anhydrous minerals ([OH]≈10 ppm), the effect of H_2O on diffusion is observed [6]. Under hydrous conditions, oxygen lattice diffusion in olivine (D_l) is defined by $D_o = 1.43*10^4$ m^2/s and activation energy E_a= 437 kJ/mol. These experiments were performed at P=2 GPa and $f(H_2O)$=0.93 GPa. For a grain size applicable to presolar grains (a =100 nm), this corresponds to timescales of ~2.5 hours at 1200°C.

These conditions, however, likely underestimate both the $f(O_2)$ and $f(H_2O)$ that would result from an impact on Allende. The experimental $f(H_2O)$ was achieved under nominally dry conditions. When a source of H_2O was added (brucite), $f(H_2O)$ > 9.2 GPa and diffusion was too close to equilibration to obtain data. Phyllosilicates are observed in this meteorite and are a plausible source of water. In addition, the $f(O_2)$ of this experiment is approximately that of the iron-wustite buffer. The brucite-present experiment, whose $f(O_2)$ approaches the fayalite-magnetite-quartz buffer, is more consistent with Allende mineralogy.

The dependence of the diffusion rate on these variables can be approximated by incorporation into the pre-exponential factor:

$$D_o = A \times fO_2^n \times fH_2O^r \times aSiO_2^m$$

Oxygen fugacity, water fugacity, and aqueous silica activity will all effect the rate of diffusion according to the exponential factors n,r,and m (A is constant). Experimental work suggests that $f(O_2)$ is described best by n=1/3-1/5, while r is unconstrained (0.2-2). Using this relationship and the experimental data [6], diffusion could be augmented by 1-2 orders of magnitude.

Dislocations: Abundant screw dislocations along the Burgers vector [001] have been observed in matrix olivine from multitudinous chondrites: Allende [7], Leoville [8], and low-shock ordinary chondrites [9]. Dislocation densities have been estimated at $3*10^9$ to $1*10^{10}$ cm^{-2} for Leoville matrix grains, though some smaller grains (10-1000Å) have lower densities due to thermal annealing [7]. Densities in excess of 10^{11} cm^{-2} are also common in matrix grains of chondrites [10].

These observations are consistent with laboratory experiments [11]. Fine-grained olivine aggregates exhibit screw dislocations analogous to those in meteor-

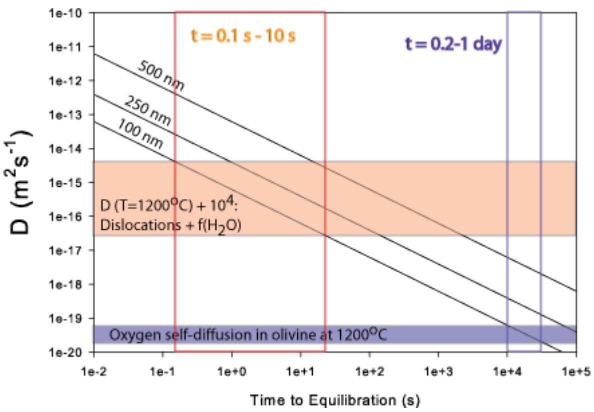

Figure 1: Diffusion coefficient for oxygen versus the time required equilibrate a given grain size. Grain sizes of 100 nm, 250 nm, and 500 nm are plotted. Using standard diffusion coefficents for oxgen, 0.2-1 day is required to homogenize a given grain size. However, when modifying D for volatilization and dislocations, grains are equlbrated in 0.1-10s.

ites at pressures of 11 GPa after heating at 1400°C for1min-1hr. At higher temperature, edge dislocations begin to disappear in favour of screw dislocations along [001]. After 1 minute, dislocation densities of $2.5*10^{10}cm^{-2}$ are observed, with EBSD showing no texture (CPO). After 1 hour of heating, EBSD reveals weak CPO and only screw dislocations remain.

Yurimoto et al. (1992) [12] showed that diffusion of oxygen along dislocations in its structure is $\sim10^4$ times higher than that of lattice diffusion. Thus, at high enough dislocation densities, the effective diffusion coefficient D_e becomes the following:

$$D^e = fD^d + (1-f)D^l$$
$$D^e = \left[\left(f \times 10^4\right) + 1\right]D^l$$

Assuming a dislocation dimension of 75nm x 0.5 nm, at dislocation densities of $10^{10}cm^{-2}$ we would expect a ~40-fold increase in D^e.

Results: Figure 1 illustrates how low-pressure shocks are a plausible mechanism for isotopic homogenization of presolar grains. Assuming the presence of trace H_2O, homogenization at 1200°C would occur at timescales of 0.2-1 day(s). The high temperatures locally produced by a shock are unlikely to persist on these timescales. However, when taking into account increased $f(O_2)$ and $f(H_2O)$ produced by a shock and the observed dislocations in fine-grained matrix grains, the timescales required to homogenize an isotopic anomaly are on the order of 0.1-10 s.

Implications for Mg-Fe Exchage: These low-pressure impact events also have important implications for the chemical composition of chondries, specifically fine-grained olivine in the matrix and rims. Matrix olivine has a restricted compositional range: $Fa_{42.3\pm2.4}$ [13] while FGR olivine spans a large compositional range: averaging $Fa_{30\pm14}$, with the coarsest-grained rim olivines averaging Fa_{11} [14].

Recent EBSD data is consistent with a nebula setting for formation of FGR fabric, indicating that grain size and shape, as well as textural relationships in the matrix and FGR, are primary [4]. However, the same processes that augments oxygen diffusion described above (volatilization and dislocations) would also serve to increase the Mg-Fe diffusion of these grains.

Diffusion parameters for Mg-Fe exchange in forsterite are also a function of oxygen fugacity, temperature, and pressure, the effects of which have been explored [15]. Increased Fe content and higher oxygen fugacity augments exchange, for the oxidation of Fe^{2+} leads to point defects in the olivine structure, as well as cation vacancies. Interdiffusion via these cation vacancies was the primary mechanism of cation exchange. As described, higher oxygen fugacity will result from the low-velocity impact due to volatilization.

Furthermore, the volatilization of H_2O would also increase fayalite content of the olivine. Mg-Fe exchange in an aqueous medium is up to 50x faster than under anhydrous conditions [16,17]. The increased rate of exchange was shown to be entirely due to a significant increase in the number of cation vacancies. This results from the incorporation of H^+ into the olivine structure, the same mechanism which contributes to the increased diffusion of oxygen in the mineral. Therefore, we would expect diffusion of both species to be an important metamorphic under the temperature and pressure conditions experienced during impact.

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