NIFE-OLIVINE EXCHANGE THERMOMETER AND DIFFUSION COEFFICIENTS IN OLIVINE AS A TOOL FOR DETERMINING THE THERMAL HISTORY OF METEORITE PARENT BODIES.

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Introduction: Element-exchange thermometers in combination with diffusion coefficients provide clues to the thermal history of meteorite parent bodies. Exchange reactions can give limits for peak metamorphic temperatures attained whereas the duration of the heating event [1] or the cooling rate [2] can be calculated by evaluation of zoning profiles using diffusion coefficients. In order to apply data to meteoritic samples a NiFe-olivine exchange thermometer has been experimentally calibrated and Ni diffusion data in olivine have been obtained in the laboratory. Attempts are made to determine the thermal history of oxidized meteorite groups and to check heating models of chondrite parent bodies [3].

Calibration of Exchange Thermometer: For the calibration of a NiFe-olivine exchange thermometer which can be formulated as the reaction

\[ \text{Ni + FeSi}_2\text{O}_4 \rightleftharpoons \text{Fe + NiSi}_2\text{O}_4 \] (1)

mixtures of metal (Ni₀.₅Feₒ.₅, Ni₀.₇Feₒ.₃, Ni₀.₉Feₒ.₁) and olivine (Fo₉ₒ.₂, Fo₇ₒ.₅, Fo₅ₒ.₇) were annealed in an 1-atm furnace between 800 and 1200 °C under controlled oxygen fugacities (f₀₂). Attainment of equilibrium was controlled by reversals at each experimental condition. An equilibrium constant can be defined as

\[ K_0 = (X_{\text{Fe}}/X_{\text{Ni}})^{\text{al}} / (X_{\text{Fe}}/X_{\text{Ni}})^{\text{ol}}. \] (2)

For equilibrium of upper mantle olivine (Fo₉ₒ.₂, 3000 ppm Ni) the temperature dependence of the distribution (Fig. 1) is given by

\[ \ln K_0 = 3776 / T + 1.122. \] (3)

This equation, in combination with activity composition relationships for metal [4] and olivine [5], can be applied to deduce the temperature of metal-olivine equilibration in diverse reduced and oxidized meteorite groups.

Diffusion Experiments: Diffusion couple experiments were carried out with Fo₉ₒ.₂ and NiFe alloys (Ni₀.₁₀Feₒ.₉₀, Ni₀.₇Feₒ.₃₀, Ni₀.₉Feₒ.₁₀) or olivine (Fo₉ₒ.₂, Fo₇ₒ.₅) between 900 and 1445 °C and at an f₀₂ of 10⁻⁸ to 10⁻¹¹ bar in order to find the dependence on temperature, f₀₂, composition and crystallographic orientation of the Ni diffusion coefficient (Dₙi) in olivine. For an f₀₂ of 10⁻¹¹ bar the temperature dependence of Dₙi is given by

\[ \log D_{\text{Ni}} = -11070 / T - 4.48. \] (4)

The dependence of the Ni diffusion coefficient on f₀₂ is given by

\[ \Delta \log f/O_2 = \Delta \log D_{\text{Ni}} \] (5)

and the relationship between diffusion coefficients along different crystallographic axes can be written as

\[ D_{[001]} \equiv 6 \cdot D_{[100]} \equiv 6 \cdot D_{[010]} \] (6)

In addition to Ni diffusion coefficients, Fe, Mn and Ca diffusion data were obtained from some of the same diffusion couples (Fo₉ₒ.₂, Fo₇ₒ.₅). In Fig. 2 it can be seen that Ni, Fe and Mn diffusion coefficients in olivine are very similar to each other whereas diffusion of the larger cation Ca is slower. Ca diffusion has a higher activation energy (slope) and therefore the differences in diffusivity compared to those of the other cations increases with decreasing temperature. The new diffusion data agree well with earlier determinations by [6] → Ni, [7] → Fe-Mg, and [8] → Ca, whereas the commonly used data sets of [9-11] are found to be inconsistent with the results of the current study.

Application: NiFe-olivine exchange thermometry may be applied to all meteorites containing olivine and metal. In ordinary chondrites Ni contents of olivine are low and difficult to analyse with EMP. In the highly oxidized R chondrites NiO can be accurately determined in olivine, but metal is rare or absent. Here we present some data on the R chondrites [12] Rumuruti and Dar al Gani 013. Both meteorites are breccias and contain clasts of different petrologic types (R3-6). Ni profiles in olivine were determined in 1 µm steps. The models of [1] or [2] have been applied to calculate the duration of a heating or the cooling rate based on Ni concentration profiles or Ni contents of equilibrated olivines.

A 100 µm large type 3 olivine shows an Fe (Fa₄₀-Fa₁ₒ.₇₅) and Ni (0.22-0.10-0.22 wt% NiO) profile along rim-core-rim. Assuming these profiles being developed during crystallization the maximum residence time at a given temperature can be calculated (500 °C → 160000 a, 600 °C → 11000 a, 700 → 320 a). In type 6 clasts 200 µm large olivines do not show any concentration profiles. Being equilibrated by a metamorphic event on the parent body (900 °C → ol-opx exchange by [13]) the olivine must have cooled very rapidly (> 4 °C / a) in order to avoid concentration profiles to be developed. This suggests break-up by impacts of the R chondrite parent body.

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Figure 1: Linear fit through all NiFe-olivine distribution experiments. The solid triangles represent the starting-\(\ln K_D\), the open squares the equilibrium-\(\ln K_D\) and the error bars are defined by the most equilibrated couples. A minimum of 10 couples was analysed for each experiment. Individual results are not shown.

Figure 2: Arrhenius diagram with Ni, Fe, Mn and Ca diffusion data in olivine obtained in this study.