A TEM study of exsolution in Ca-rich pyroxenes from the Paris meteorite: Determination of type I chondrule cooling rates.

Pricille Cuviller1, Noël Chaumard2, Hugues Leroux1, Brigitte Zanda3, Roger Hewins2, Damien Jacob1, Bertrand Devouard3

1 Unité Matériaux et Transformations, Université Lille 1 & CNRS, 59655 Villeneuve d’Ascq, France
2 Laboratoire de Minéralogie et Cosmochimie, MNHN & CNRS, 61 rue Buffon, 75005 Paris, France
3 CEREGE, Université Aix-Marseille & CNRS, Avenue Louis Philippe, 13545 Aix en Provence, France

Introduction, Methods, Samples

Cooling rates of meteoritic chondrules are mainly estimated from the study of oxidized chondrules (type II), based on the observation of the texture and Fe-Mg zoning in olivine. Indeed, the study of zonations allows diffusion calculations and/or crystallization modeling, providing access to kinetics of chondrule thermal history [34-4]. However, type II chondrules mainly occur in ordinary chondrites, leaving the thermal history of reduced (type I) chondrules, dominant in carbonaceous chondrites, poorly constrained.

To decipher the thermal history of type I chondrules, other thermal markers need to be established since forsterite is essentially un-zoned. Recently, Cu-diffusion profiles in metal grains were proposed to be useful to determine cooling rates [5, 6]. Another method is based on the observation of the disordered/pyroxene exsolution microstructure in Ca-pyroxenes [7]. Indeed, Ca-bearing pyroxenes’ structure and composition depend on thermal history and the study of subsolidus phase transformations may allow the determination of cooling rates within the range of temperature 1200-1400 °C [7-9]. The exsolution process in pyroxene has its origin in the variation with temperature of the miscibility gap between the Ca-rich and Ca-poor pyroxenes. Here we studied grains of Ca-pyroxene by Transmission Electron Microscopy (TEM) from two chondrules in the Paris meteorite classified as a CM2 chondrite [10]. This meteorite combines both moderately and very little altered zones and is hence less altered than other CM chondrites. Chondrules represent about 45% of the chondrite with mostly type I chondrules.

Pigeonite P2₁/c exsolved from Augite C2/c host

The studied Ca-rich pyroxene grains have heterogeneous compositions and microstructures. For compositions outside the miscibility gap (Ca/Mg) ≤ 0.4 and (Mg/Ca+Mg) ≥ 0.9, pyroxene is found un-exsolved. Grains with intermediate compositions plot in the two-phase domain and exhibit exsolution lamellae and twinned microstructure.

Results

For compositions within the miscibility gap, pyroxene grains exhibit a well-developed exsolution microstructure on [001] lamellae, (figure 1 left). Diffraction patterns reveal that h + k odd reflections are present indicating a Ca-rich pyroxene in addition of the pigeonite exsolution lamellae (figure 1 up). Lamella orientation is predominately close to the [001] plane and some secondary exsolution features are close to the [100] plane (figures on the left).

Discussion

Exsolution wavelength is closely related to cooling rates making it a reliable thermal marker. The link between the wavelength, temperature, and time has been explored by [7] who proposed a calibration curve to estimate the cooling rate (figure opposite). The cooling rate of the studied chondrules is deduced from the exsolution wavelengths. According to the phase diagram the crystallization temperature is about 1375°C for pyroxene composition between En₀Dₐ₀ and En₀Dₐ₁. Lamellae wavelength (λ) vary within same a chondrule between 20 ≤ λ ≤ 40 nm which correspond to cooling rates within the range 1-100°C/h.

Pyroxene with composition close to Ca/Ca+Mg = 0.4 frequently exhibit a twinned microstructure revealing that spinodal decomposition occurred without significant coarsening. Complementary studies are in progress to document the influence of the local composition on the exsolution microstructure.

This study shows that type 1 chondrules have experienced cooling rates comparable to those of type 2 chondrules. Despite the oxygen fugacity environment is clearly different (thus the location formation) for type 1 and 2 chondrules, the comparable cooling rates suggest a common trigger for the formation mechanism.

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