CHONDRULE TIESCHITZ IIIM: CLUES TO THE ORIGIN OF EARLY LIQUIDS?

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Introduction: Porphyritic chondrules containing variable volumes (55 - 85 vol %) of microcrystalline mesostasis are one of the two types of "glass-rich" chondrules present in unequilibrated ordinary chondrites [1]. The texture of these objects indicates that they are quenched liquid droplets. While there is still no agreement on the source of the liquid that formed the droplets, there is, however, a complete consensus on the time of their formation: early in the history of the solar system. Consequently, these chondrules might help us to decipher the early steps of chondrule formation. Here we report the results of an ASEM and SIMS study of a porphyritic olivine chondrule that is very rich in microcrystalline mesostasis, from the Tieschitz (H3.6) unequilibrated ordinary chondrite.

Results: Tieschitz IIIM, a perfectly round chondrule from the Tieschitz PTS L3443 (NHM, Vienna), is about 575 µm in diameter (Fig. 1) and has a Ca-Mg-Al-Si-rich bulk chemical composition (Table).

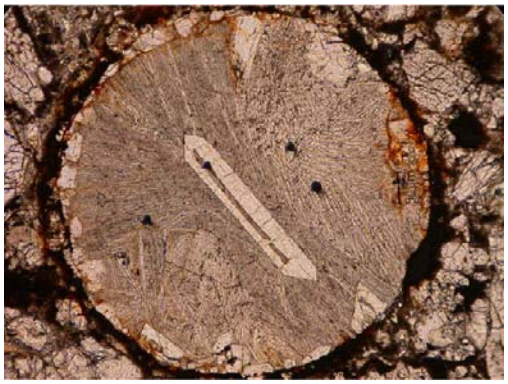

Figure 1: Transmitted light image of chondrule Tieschitz IIIM.

The cryptocrystalline mesostasis (~70 vol% of the object), is Ca-Mg-Al-Si-rich (CMAS, Table) with low contents of Na, Ti, and Fe. The euhedral olivine at the center of the chondrule, 300 µm in length, is CaO-rich (0.51 wt% core, 0.28 wt% surface) and FeO-poor (0.22 wt% core to 1.03 wt% surface). The olivine contains an elongate inclusion with mineralogical and chemical compositions similar to those of the microcrystalline mesostasis. Euhedral olivines, 25 to 100 µm in size, which are decorating the surface of the chondrule, also have high CaO (varying from 0.31 to 0.52 wt%) and low FeO (varying from 0.2 to 4.7 wt%) contents.

The trace element (TE) content of olivine and mesostasis was determined following a modified procedure of [2]. The recrystallized mesostasis (Mesostasis) is rich in TEs with abundances of refractory elements at 10 - 20 x CI and those of moderately volatile and volatile elements around CI abundances (Fig. 2). The elongated inclusion inside the central olivine (Ol Incl) has a TE content very similar to that of the mesostasis. The euhedral central olivine also has high TE contents with Sc at 3.6 x CI and the REEs at about 0.7 x CI abundances. The latter display an almost flat abundance pattern with a slight La/Lu fractionation (0.42; Fig. 2).

Table: Chemical composition of bulk and mesostasis in chondrules Tieschitz IIIM and Semarkona CH5 [13].

	Tieschitz IIIM	Meso IIIM	CH5 -[13]	Glass CH5
SiO2	46.0	46.9	48.6	51.2
TiO2	0.75	1.04	0.78	1.03
Al2O3	15.9	22.4	16.3	21.0
Cr2O3	0.22	0.27	0.33	
FeO	1.18	0.99	0.53	0.45
MnO	0.06	0.07	0.09	0.06
MgO	23.5	9.6	20.1	8.78
CaO	11.0	15.3	13.1	17.1
Na2O	1.24	1.75	0.02	0.23
	99.8	98.4	99.9	99.85

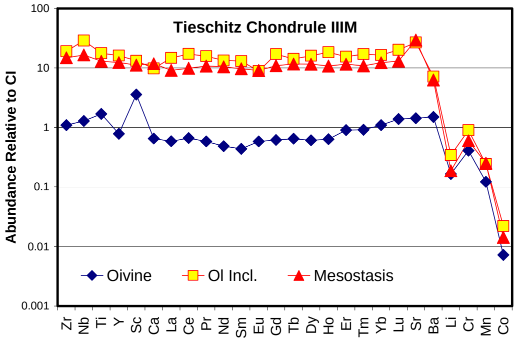

Figure 2: CI-normalized trace element abundances of the crypto-crystalline mesostasis (Mesostasis), of the elongated inclusion in olivine (Ol Incl.) and the euhedral central olivine.

Discussion: Chondrule Tieschitz IIIM was created as an all-liquid droplet and the few olivines present very likely crystallized from this liquid. This textural evidence is supported by the equilibrium partitioning of Ca between olivine and the chondrule matrix. Our previous studies of glass inclusions in olivines from the Kaba, Allende and Tieschitz chondrites have shown that if the olivine is a primitive high-Ca olivine and the glass kept its pristine composition (e.g., Ca-Al-rich with chondritic Ca/Al ratio), both phases are always in equilibrium with respect to their CaO contents [e.g., 3]. Distribution coefficients ($D_{ol\text{-}gl}$) ranging from 0.022 to 0.026 that match the experimental equilibrium value, $D_{equ} = 0.025$ [4], suggest that these olivines grew from a liquid with the chemical composition of this particular inclusion glass [5 - 7]. Similarly, the Ca distribution coefficient of $D_{ol\text{-}gl} = 0.027$ for the central euhedral olivine in chondrule Tieschitz IIIM suggests growth from a liquid with the chemical composition of the microcrystalline mesostasis.

The liquid from which the olivine grew was not only rich in CaO but was rich in all refractory lithophile TEs (10 – 20 x CI) and poor in moderately volatile and volatile elements. The elemental abundance pattern of this liquid (the precursor of the recrystallized mesostasis) is governed by volatility only and consequently documents vapor fractionation.

The olivine, which clearly crystallized from that liquid, is also rich in trace elements. Their abundances are, however, not governed by crystal-liquid distribution coefficients as experimentally determined. Instead, an approximately constant crystal-liquid distribution coefficient $D_{ol\text{-}l}$ ~ 0.06 for all moderately incompatible to strongly incompatible elements is indicated (Fig. 3). Apparently, the abundances of these elements were not governed by igneous partitioning but rather by other factors such as high degree of undercooling of the liquid and, consequently, very fast crystallization of the olivine. Nevertheless, the compatible elements Sc, Mn and Cr are in (or close to) equilibrium – as is Ca – possibly because of their fast diffusion ability.

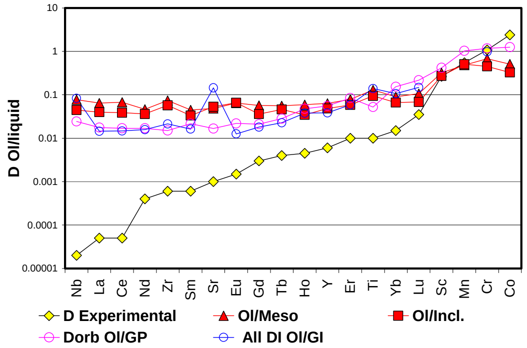

Figure 3: Apparent trace element distribution coefficient (D) between olivine and the recrystallized mesostasis (Ol/Meso) and the inclusion (Ol/Incl.) in chondrule Tieschitz IIIM. For comparison are shown the apparent Ds between olivine and Si-Al-Ca-rich glass inclusions of an Allende dark inclusion (All DI Ol/GI) and a glass pocket in the angrite D´Orbigny (Dorb Ol/GP) [8]. Experimental Ds from [9, 10 and 4].

Very similar results have previously been obtained on the trace element distribution between olivines and their Si-Al-Ca-rich primary glass inclusions in chondrites and achondrites. The constant olivine-matrix distribution coefficient ($D_{o\text{-}l}$ ~ 0.06) in chondrule Tieschitz IIIM, therefore, is not unusual and has also been observed in other objects that experienced fast cooling (e.g., glasses and olivines of chondrules, of the angrite D'Orbigny and of an Allende dark inclusion). Interestingly, the liquid involved in chondrule formation – and also formation of achondritic objects – always is refractory in composition and must have been a common initial phase in the early solar nebula [e.g., 11].

Glass- and microcrystalline mesostasis-rich chondrules are unusual types of objects that can help to decipher the origin of the initial liquid droplets that turn into chondrules. Although there are several possible ways to produce these liquids, the most widespread model invokes melting of solid precursors in a nebular setting [e.g., 1]. In the case of Na,Al-rich, glass-bearing chondrules in H, L and LL chondrites, [12] see melting of a mixture of albitic or nephelinitic and ferromagnesian precursors as the most suitable process for their formation.

Recently, an object similar to chondrule Tieschitz IIIM (but composed of 78 % clear glass instead of crystalline mesostasis) from the Semarkona (LL3.0) unequilibrated ordinary chondrite has been studied [13]. Its forsterite is CaO-rich (average 0.38 wt%) and the chemical composition of the clear glass is also Si-Al-Ca-Mg-rich and has a chondritic CaO/Al_2O_3 ratio (0.8). (Table, Glass CH5: mean of 10 analyses from [13]). The authors of this study speculate that the chemical composition of the "initial melt" of that droplet was close to that of type C CAIs and was formed by melting of such CAI precursors in a shock heating event. Unfortunately, no trace element data are available for this chondrule but predictably it should be very similar to that of Tieschitz IIIM mesostasis.

Chondrule Tieschitz IIIM appears to be a relative of the class of chondrules that formed from all-liquid droplets: RP and BO chondrules [e.g., 14, 3]. Chondrules with the bulk chemical composition of Tieschitz IIIM represent the most refractory members of the all-liquid chondrule class. Such a liquid could be the product of direct condensation from the solar nebula gas. Indeed, the re-calculated (volatile-free) CMAS liquid composition of Tieschitz IIIM (weight % MgO: 24.4, Al_2O_3: 16.5, SiO_2: 47.8, CaO: 11.4) does approximately fit that calculated by [15] for liquid condensates from a ~100x dust-enriched solar nebular gas at 10^{-3} bar and ~1700 K. Compositions of condensed liquids calculated by [16] for solar nebula gas at 1.5 atm. and ~1700 K fit in part and there is no fit with the condensate liquids calculated by [17]. Similar results are obtained with the data of chondrule CH5 from Semarkona [13] (Table).

In general, chondrule bulk compositions are determined by mixing different proportions of the initial constituents: the refractory liquid (glass or matrix) and olivine [e.g., 18]. In this scenario, the liquid is the first condensate from the solar nebula gas, nucleates an olivine (or several) and helps to grow these olivines from the nebula gas via the vapor-liquid-solid process. In this way well crystallized olivines are created as well as objects with a variety of olivine/liquid ratios and, consequently highly varying bulk refractory element contents. All-liquid chondrules are the exception as they are all-liquid nebula condensates. Their bulk composition is determined by the primary liquid composition (always refractory at 10 – 20x CI) and the amount of olivine dissolved. Metasomatic addition of varying amounts of moderately volatile and volatile elements (e.g., Mn, Cr and Na) - that takes place after crystallization of olivine and mesostasis - will determine the final composition of these objects.

In conclusion, chondrule Tieschitz IIIM appears to be a fine example of a refractory chondrule, which – in contrast to common PO chondrules – originated from an all-liquid droplet possibly formed by direct condensation from the solar nebula gas, a sample of the "universal liquid" [11]. However, the fit between the bulk chemical compositions of natural objects with those calculated for liquid condensates from modified solar nebula gas [e.g., 15, 16] is not perfect. Therefore, improved theoretically and experimental work on early liquid condensates is needed.

Acknowledgements: Financially supported by CONICET and Agencia PICT 212 (Argentina), NASA (USA), and FWF (Austria)

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