A GLASS INCLUSION HOSTED BY SPINEL INSIDE A GLASS-RICH CHONDRULE FROM CATALINA 278 (LL 3.4): A SAMPLE OF THE INITIAL LIQUID?
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Introduction: The genesis of Ca-Al-rich glass inclusions in olivine grains of carbonaceous chondrites is a matter of ongoing debate since the seventies. Those found in the Murchison type CM2 chondrite were considered to be the result of a condensation process that formed the olivine [1]. Subsequently, [2] and [3] considered them to be trapped remnants of a parent liquid and thus be the product of fractional crystallization of chondrule melts. The first trace elements ever done in glass inclusions in olivine from the Renazzo CR2 chondrite [4] supported a condensation origin of the glass inclusions. Hence, variations in the chemical composition of the glasses could reflect processes in the early solar nebula. Up to date glass inclusions in chondrules have been found in olivine almost exclusively. Here, we report of the first glass inclusion hosted in spinel within a glass-rich chondrule from the unequilibrated ordinary chondrite Catalina 278 (LL3.4), found 2017 in the Atacama desert in Chile.

Analytical techniques and samples: The glass-rich chondrule was studied with an optical microscope for the petrographic characteristics of their constituent phases (e.g., glass, olivine, pyroxene and spinel) and the occurrence of glass inclusions. Major-element chemical compositions of these phases were obtained with a JEOL JSM-6610 scanning electron microprobe and a JEOL JXA-8530F FE electron microprobe at NHM Vienna. The bulk compositions of all selected objects were determined by electron microprobe point profiles across the entire diameter of the object. The studied chondrule is located in the polished thick section (PTS) Catalina 278 from Icate.

Results: Cata 278-1 is a perfectly round chondrule about 500 µm in apparent diameter mainly composed of glass (~64 vol % of the object) which is rich in Al, Na and K (Fig. 1). CIPW-norms show the glass to be rich in plagioclase (51.7 vol%), orthoclase (19.9 vol%) and nepheline (19.9 vol%). Several of the euhedral Mg-rich olivine grains ($Fa_{0.47}$) are hopper crystals of variable sizes from 20 to 200 µm. They are compositionally homogeneous, rich in Ca (varying from 0.30 to 0.41 wt%) and low in FeO (varying from 0.35 to 1.07 wt%). The Ca-rich pyroxene as well as the spinel are minor phases with ~4 vol% and ~2 vol%, respectively. The latter is Al-rich (69.3 wt%), Cr-poor (0.55 wt%) and inhomogeneous with respect to FeO (varying from 0.7 wt% in the core to ~7 wt% in the spinel rim).

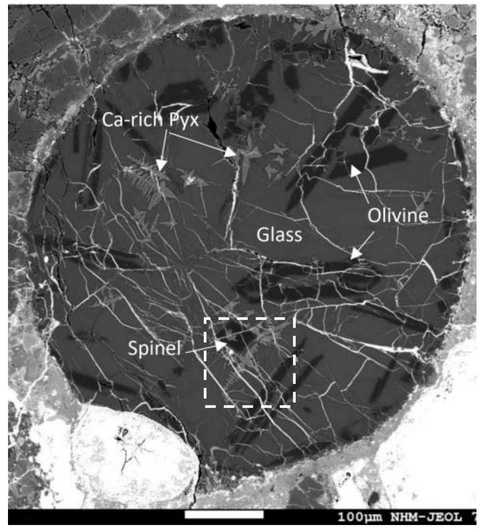

Figure1: Backscatter electron image of chondrule Cata 278-1.

The glass inclusion in spinel has a rounded irregular shape (~20 µm in size) characterized by a Si-Al-Ca-Mg-rich composition free of Na and K (Fig. 2, Table 1).

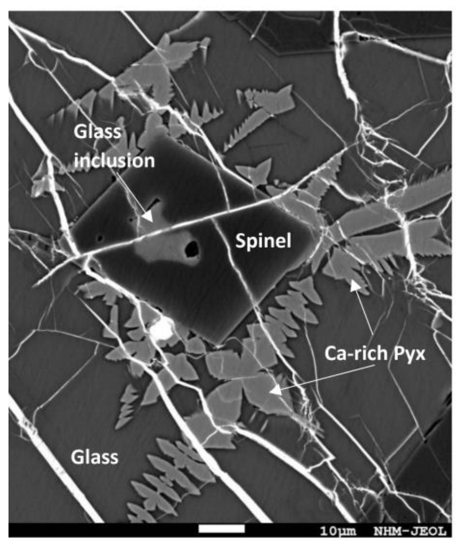

Figure 2: Backscatter electron image of the inset of Fig.1 showing the euhedral spinel crystal with a glass inclusion.

The estimated bulk chemical composition of the glass-rich chondrule Cat 278-1 (Table 1) is Si-Al-Mg-rich with plagioclase-olivine-orthoclase-nepheline normative composition.

Table 1: Chemical composition of the glassy mesostasis, the glass inclusion in spinel and the bulk composition of Cata 278-1

	Mesostasis	Glass in spinel	Bulk composition
SiO_2	54.3	46.7	49.0
TiO_2	1.44	1.17	1.05
Al_2O_3	28.4	13.8	20.4
Cr_2O_3	0.18	0.15	0.16
FeO	1.89	0.52	1.45
MgO	0.35	19.0	18.5
CaO	0.07	18.4	0.98
Na_2O	9.9	n.d	6.3
K_2O	3.16	n.d	2.03
Total	99.7	99.7	99.8

Discussion: Glass inclusions and mesostasis can behave as either closed or open systems, respectively. Glasses in chondrules are able to record different stages of the liquid/solid–gas exchange processes: from the early, primitive event (e.g., condensation: kept in unaltered and sealed primary glass inclusions) to late ones (recorded in the mesostasis glass). The latter, behaving as open systems can give evidence of a vapor-solid reaction. The presence of alkali elements (Na+K) coupled with a very low Ca content in Cata 278-1 mesostasis is in agreement with previous finding in barred olivine (BO) and glass-rich chondrules and glass inclusions in olivine from CR and CV3 chondrites and indicates that Ca was replaced by the volatile elements Na and K (e.g., Na–Ca exchange). This took place presumably through a vapor–solid reaction between glasses in the chondrule and the cooling nebula, as temperatures in the nebula will drop allowing condensation of alkali elements [4-7]. In addition to Na enrichments, the mesostasis glass in Cata 278-1 is also enriched in Si as compared to the glass inclusion in spinel, similar to what has been observed in chondrules from the Kaba CV3 chondrite [6].

The spinel in Cata 278-1 has a chemical composition that resemble the mean composition of spinel from Ca,Al-rich inclusions (CAIs) in CM and CV carbonaceous chondrites (Table 2) and differ from the Al-spinel calculated by [7] at 1800 K during condensation from a vapor having a dust/gas enrichment of 100× at $p_{tot} = 10^{-3}$ bars. The latter, resemble that found in a primary glass inclusion in olivine from the Allende dark inclusion (Table 2) [8]. Thus, spinel in Cata 278-1 could be the earliest phase of the assembly and may document crystallization from an Al-Ca-Mg-rich silicate liquid.

Spinel grew from that liquid, which was continuously replenished in spinel component from the vapor in a process known as vapor-liquid-solid condensation [9].

Table 2: Chemical composition of spinel from CAIs, Cata 278-1, Allende DI [8] and [7].

	CAIs CM	CAIs Type A	CAIs Type B	Mean CAIs	Spinel Cata 278-1	Spinel Allende DI [8]	Spinel [7]
TiO_2	0.24	0.25	0.31	0.26	0.39	0.25	0.115
Al_2O_3	70.7	68.8	69.2	69.6	69.3	67.0	67.9
Cr_2O_3	0.40	0.18	0.26	0.28	0.55	4.63	4.22
FeO	0.30	3.05	4.83	2.73	2.11	3.02	0.03
MgO	27.6	26.0	25.1	26.2	25.6	25.5	27.7
CaO	0.16	0.44	0.22	0.27	0.05	0.15	0.03
Total	*99.4*	*98.8*	*99.9*	*99.3*	*97.9*	100.5	*100.0*

A sample of that “initial liquid” was trapped during spinel growth and formed the glass inclusion. The ”initial liquid” is similar in TiO_2, MgO and CaO contents as compared to the Al-Ca-Mg-rich silicate liquid calculated by [7] but higher in Al_2O_3 and lower in SiO_2 contents. The liquid condensate involved in chondrule formation is expected to be always refractory in composition [e.g., 10-11]. Chondrule Cata 278-1 appears to be a relative of the class of chondrules that formed from all-liquid droplets: radial pyroxene (RP), barred olivine (BO) and glass-rich chondrules [e.g., 7, 9, 12-13]. Chondrules with such bulk chemical composition (SiO_2: 49.0 wt%, Al_2O_3: 20.4 wt%, MgO: 18.5 wt%, CaO: 0.98 wt%, Table 1) represent the most refractory members of the all-liquid chondrule class. Therefore, such liquid could be the product of direct condensation from the solar nebula gas. Cooling of Cata 278-1 must have been very fast, which prevented the liquid from becoming continuously richer in Mg. Low abundance of skeletal olivine plates further documents this relatively low Mg content of the liquid. The spinel with the “initial liquid” preserved as a glass inclusion must have served as a foreign nucleus, which caused crystallization of the surrounding liquid into the glassy matrix. The remaining liquid formed Ca-rich pyroxene and the hopper olivine plates. Subsolidus thermal processes of the chondrule in the cooling gas changed its bulk chemical composition by partial replacement of Ca by Na + K.

References: [1] Fuchs et al. (1973) Smithson. Contrib. Earth Sci. 10, 38 pp.; [2] McSween (1977) GCA 41, 411–418; [3] Roedder (1981) Bull. Mineral. 104, 339–353; [4] Varela et al. (2002) GCA 66, 1663–1679; [5] Kurat et al., (2004) MAPS 39. Abstract 57: [6] Varela et al., (2005) Icarus 178, 553–569; [7] Varela et al., (2006) Icarus, 344–364; [7] Boesenberg and Ebel (2009) LPSC XXXX, Houston. #2125. (abstr.); [8] Varela et al., (2012) MAPS 47, 832–852.; [9] Varela and Zinner (2018) GCA 221 (2018) 358–378; [10] Ebel and Grossman (2000) GCA 64, 339–366; [11] Alexander C. M. O’D. (2004) GCA 68, 3943–3969; [12] Engler et al., (2007) Icarus 192, 248–286.; [13] Nagahara et al., (2005) GCA 72, 1442–1465.