

EVIDENCE FOR HIGH TEMPERATURE CONDENSATION OF MODERATELY-VOLATILE ELEMENTS DURING CHONDRULE FORMATION. G. Libourel^{1*}, A. N. Krot² and L. Tissandier¹, ¹CRPG-CNRS 15, Rue Notre-Dame des Pauvres, BP20, 54501 Vandoeuvre les Nancy, France, ²ENSG-INPL, BP40, 54501 Vandoeuvre les Nancy, France (libou@crpg.cnrs-nancy.fr), ²Hawai'i Institute of Geophysics and Planetology, School of Ocean and Earth Science and Technology, University of Hawai'i at Manoa, Honolulu, HI 96822, USA.

Introduction: In our quest to comprehend chondrule formation processes, significant efforts have been placed until recently to unravel the behavior of moderately-volatile elements in chondrules, and notably the factors that control their concentrations in chondrule melts. Amongst these elements, alkalis received much of the attention because of their dual behavior, i.e., lithophile at low temperature, they become volatile at high temperature and/or under reducing conditions, and hence may help to put some valuable constraints on chondrule formation processes. Although recent petrologic studies [1-4] have suggested that chondrules may have formed in open systems, as shown by zoning of moderately-volatile elements, no consensus exists yet on the extent to which chondrules exchanged and reacted with the surrounding medium, nor on the nature of the reactions involved, i.e., evaporation vs. condensation, and neither on the effects of such interactions on chondrule characteristics. In order to tackle these questions, we report here a systematic study of the petrology of Type I chondrules from unequilibrated ordinary and carbonaceous chondrites. We particularly striven to document glass and high-Ca pyroxene compositions.

Results: Our survey focused on Type I FeO-poor porphyric olivine (PO), porphyric olivine-pyroxene (POP) and porphyric pyroxene (PP) chondrules from the CR carbonaceous (El Djouf 001, GRA 95229 and PCA 91082), and the Semarkona (LL3.0) ordinary chondrites. The studied chondrules are characterized by several of the following textural, mineralogical and chemical characteristics (Fig. 1): (i) glass inclusions are present only in olivines, (ii) olivine/pyroxene ratio increases inward in chondrules suggesting that low-Ca pyroxenes crystallize preferentially at the edge of PO/POP chondrules, (iii) when coexisting with low-Ca pyroxenes, olivines are either resorbed or poikilitically enclosed in pyroxenes, (iv) silica-rich igneous rims are located exclusively at the outer portions of many Type I chondrules in CR chondrites [5], (v) when occurring, zoning of Na, K, Mn and Si are inward in chondrule mesostases, and (vi) high-Ca pyroxenes are quench crystals. PP chondrules are systematically enriched in alkali and silica compared to POP chondrules; PO are depleted in Na and Si (Fig. 2). Zoned mesostases in individual chondrules (Fig. 2) mimic this general trend with a positive correlation between Na₂O and SiO₂. In

contrast, glass inclusions in olivines are very often depleted in alkali and poorer in silica than their corresponding mesostasis (Fig. 2).

Discussion: Since glass inclusions and clinopyroxene form during the earliest- and the latest-stage of crystallization of chondrules, respectively, their compositions may help us to document the high temperature history of individual chondrules. Based on the observed Na enrichment of chondrule mesostases relative to Na-free/poor glass inclusions that cannot be reproduced by any equilibrium or fractional crystallization models, we suggest that Na condenses into chondrule melts at high temperatures. This is further supported by the inward gradient of Na in zoned chondrules. A more definitive argument is also given by the Na contents of high-Ca pyroxene (Fig. 3) which clearly show that, at the time of the quenching of chondrule melts, chondrule mesostases were already sodium-rich. Because Na partitioning in high-Ca pyroxene of chondrules is almost equivalent to experimental equilibrium values and because of fast kinetic of high-Ca pyroxene crystallization, the observed chondrule to chondrule differences and zoning in alkali are thus compelling evidence that Na distribution in chondrules results from high temperature processing. Finally, because Na diffusion in molten silicate is orders of magnitude higher than that of Si, systematic covariations of Na and Si suggest that Na entering in chondrules is controlled by the silica content of the molten mesostases (solubility?).

Both individual chondrule characteristics listed above and general trends from PO to PP chondrules of CR and OC chondrites may thus be explained in the light of either direct gas condensation into chondrule melts and/or accretion of volatile-rich dust at the surface of chondrules followed by subsequent melting. In either case, condensation occurred from a fractionated nebular gas enriched in Si, Na, and very likely in K and Mn [5].

References: [1] Huang et al. (1996) *Icarus*, 122, 316-346. [2] Matsunami et al. (1993) *GCA*, 57, 2101-2110. [3] Nagahara et al. (1999) *LPS* 30, #1342. [4] Tissandier et al. (2002) *MAPS* 37, 1377-1389. [5] Krot A.N. et al. (this issue).

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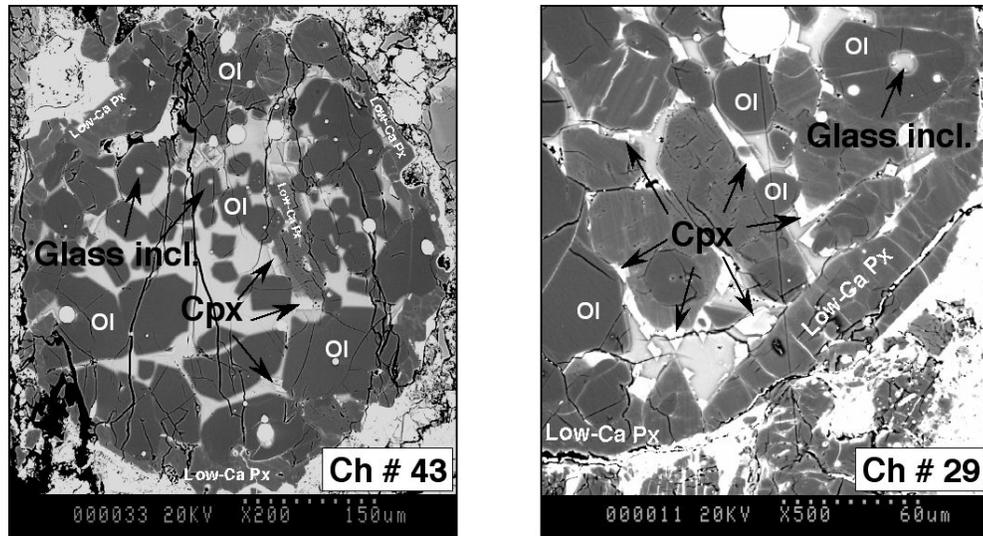


Fig. 1: Representative Type I chondrules from Semarkona with glass inclusions in olivines and quench clinopyroxenes.

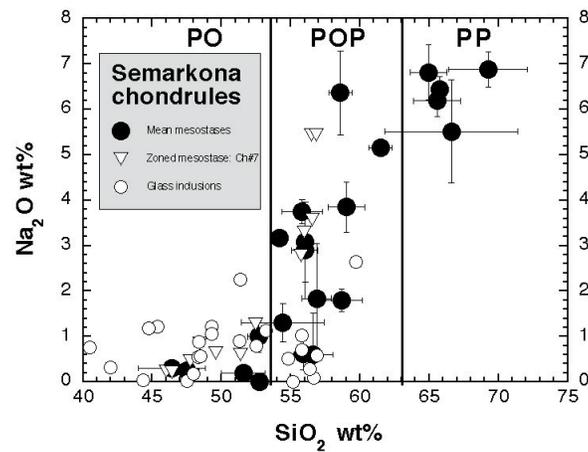


Fig. 2: Compositions of glass in mesostases, zoned mesostases and glass inclusions in Semarkona chondrules

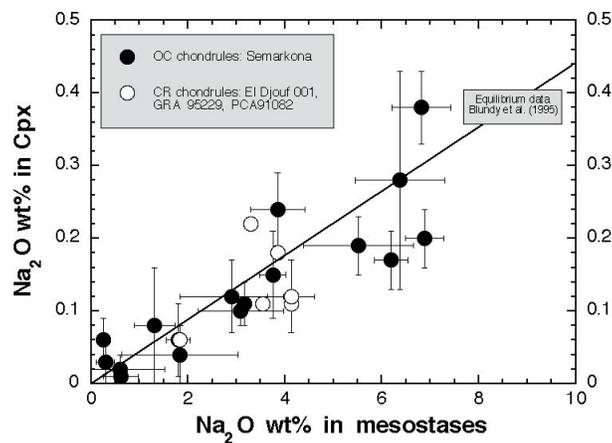


Fig. 3: Sodium partitioning between high-Ca pyroxenes and chondrule mesostases in OC and CR chondrules