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Evidence for the presence of planetesimal material among the precursors of magnesian chondrules of nebular origin

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Abstract

Chondrules are the major high-temperature components of chondritic meteorites, which are conventionally viewed as the samples from the very first generation of undifferentiated planetesimals. Growing evidences from long- and short-lived radionuclide chronologies indicate however that chondrite parent asteroids accreted after or contemporaneously with igneous activities on differentiated asteroids, questioning the pristine nature of chondrites. Here we report a discovery of metal-bearing olivine aggregates with granoblastic textures inside magnesian porphyritic (Type I) chondrules from the CV carbonaceous chondrite Vigarano. Formation of the granoblastic textures requires sintering and prolonged, high-temperature (>1000 °C) annealing — conditions which are not expected in the solar nebula during chondrule formation, but could have been achieved on parent bodies of olivine-rich differentiated or thermally metamorphosed meteorites. The mineralogy and petrography of the metal-olivine aggregates thus indicate that they are relict, dunite-like lithic fragments which resulted from fragmentation of such bodies. The very old Pb–Pb absolute ages and Al–Mg relative model ages of bulk CV chondrules suggest that such planetesimals may have formed as early as the currently accepted age of the Solar System (4567.2±0.6 Ma).

Keywords: chondrites; magnesian chondrules; relict olivines; differentiated planetesimals; chondrule formation; early Solar System

1. Introduction

Chondrules constitute up to 80% by volume of chondrites, and are believed to have formed by incomplete melting of solid precursors composed of fine-grained dust and rare fragments of refractory inclusions [Ca–Al-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs)] and chondrules of earlier generations during localized, brief, repetitive heating events, possibly by shock waves, in the protoplanetary disk (solar nebula) [1–4]. It has been generally accepted that evolution of solids in the inner protoplanetary disk, within 5 AU (astronomical units) from the proto-Sun, started from the origin of refractory inclusions and continued for several million years during chondrule

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formation [5]. Subsequently, chondrules, refractory inclusions and fine-grained matrices accreted into planetesimals which experienced various degrees of thermal processing (aqueous alteration, metamorphism, and igneous differentiation), probably by radioactive decay of short-lived radionuclides such as ^{26}Al and ^{60}Fe [6,7]. This evolutionary sequence has been generally confirmed by the precise ^{207}Pb–^{206}Pb absolute ages of CAIs in CV chondrites and chondrules in several primitive ordinary and carbonaceous chondrites [8,9], and of metamorphic plagioclase and phosphates in ordinary chondrites [7,10]. These measurements indicate that CAIs in CV chondrites formed 4567.2 ± 0.6 Ma; the absolute ages of chondrules range from 4566.6 ± 1.0 to 4566.3 ± 1.7 to 4564.7 ± 0.6 Ma in CV, ordinary and CR chondrites, respectively [8,11]. The parent body of the H4 ordinary chondrites St. Marguerite and Forest Vale experienced thermal metamorphism ~5–6 Ma after formation of the CV CAIs [7,10]. However, recently reported Pb isotopic ages of 4566.2–4566.5 Ma of basaltic meteorites (angrites) [12,13] indicate that their parent asteroid accreted and differentiated prior to the formation of chondrules in CR chondrites. That planetesimals and chondrules were at least contemporary is now gaining acceptance as more works on other isotopic systems [14,15] have confirmed this conclusion.

The early accretion of planetesimals is generally consistent with theoretical models of growth and dynamic evolution of the main asteroid belt [16–19]. In addition, these models predict early formation of planetary embryos, which produce a strong dynamical excitation of planetesimals resulting in their high-velocity collisions [16–19]. Small percentage of such collisions may occur at pre-encounter velocities of >8–$10\ \mathrm{km\ s^{-1}}$ [19], sufficient to provide the energy required to melt and even vaporize some of the chondritic materials. A catastrophic collision between planetary embryos resulting in formation of a vapor-melt plume has been recently invoked to explain the origin of chondrules in CB carbonaceous chondrites [20]. Most of the collision energy, however, goes into fragmentation of asteroids [21]; some of these collisions could have resulted in the complete shattering and disruption of the colliding bodies [17].

If accretion and differentiation of planetesimals started prior to or contemporaneously with chondrule formation [9,12–15,20], and collisions between planetesimals were common [16–22], it seems likely that some of this planetesimal material (melted or metamorphosed) could have been ejected into the solar nebula and incorporated into chondrule precursors and thermally processed during chondrule formation. However, no attempts to search for material of planetesimal origin inside chondrules of nebular origin have been done so far. Here, we report a discovery of lithic clasts inside magnesian porphyritic (Type I) chondrules in the CV carbonaceous chondrite Vigarano, and discuss their origins and implications for understanding chondrule formation.

2. Experimental

Seven polished thin sections (UH 2, 3, 6, 35, 53, USNM 477-2, and USNM 6295-3) of Vigarano were carefully examined using both optical and scanning electron microscopy. These thin sections were mapped in Ca, Al, Mg, Si, Mn, Cr, Ti, and Na Kα X-rays with resolutions of 5–10 μm per pixel (2 μm per pixel for individual chondrules) with a Cameca SX-50 electron microprobe at University of Hawai‘i. Type I chondrules were studied in backscattered electron (BSE) mode with the JEOL LV5900 scanning electron microscope at University of Hawai‘i. Mineral compositions were determined with a Cameca SX-50 electron microprobe using 15 keV accelerating voltage, with beam current of 10–20 nA for silicates and 30 nA for metal. Counting times on both peak and background were 10 s for Na and K and 30 s for all other elements. Mineral and metal compositions were measured with a focussed (1–2 μm) beam. Glasses (mesostases and melt inclusions) were measured with a defocused beam (3–7 μm); to further reduce volatilization of Na and K during electron microprobe analyses, these elements were analyzed first. Well-characterized silicates, oxides and metals were used as standards. Matrix corrections were applied using a PAP software routine. Detection limits in silicates were (in wt.%) SiO_2, Al_2O_3, MgO−0.03; TiO_2, CaO, K_2O−0.04; Na_2O, Cr_2O_3−0.06; MnO−0.07; FeO−0.08. Detection limits in metal were (in wt.%) Si, P, S−0.03; Co−0.04; Fe−0.05; Ni−0.06.

3. Results

Our petrographic survey of Type I chondrules in Vigarano revealed the presence of olivine-rich aggregates showing granoblastic textures and composed of coarse-grained forsteritic olivines (Fo ≥ 99) and Fe,Ni-metal nodules (Figs. 1 and 2). Such textures are easily recognizable in optical microscope using transmitted cross-polarized light, but can be missed if studied only in BSE images using scanning electron microscope. In two dimensions, the aggregates consist of polygonal, randomly oriented, four-to five-sided olivine grains (Fig. 1). At olivine triple junctions, the interfacial angles are ~120° (120 ± 20°, $n = 45$; Fig. 1b,e). In some of these

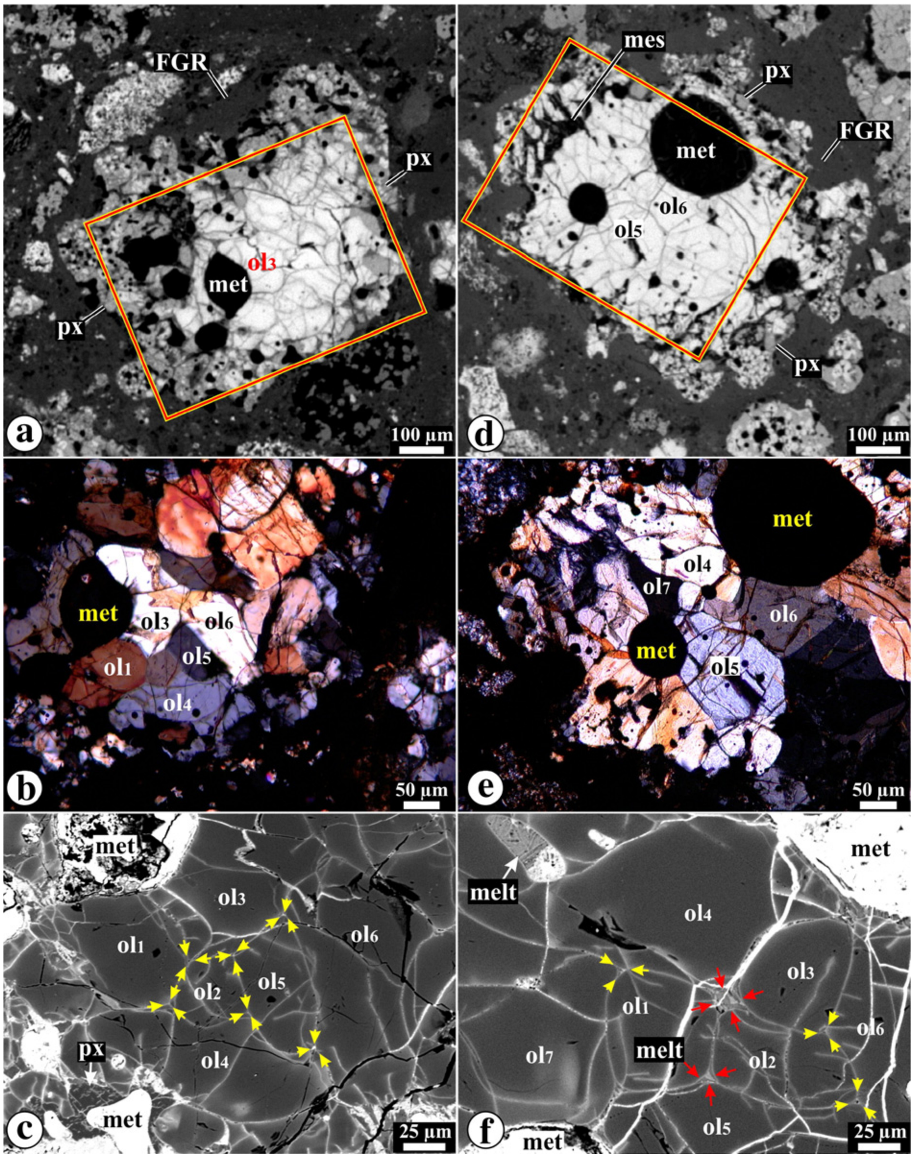

Fig. 1. a,d) X-ray elemental maps in Mg Kα, b,e) optical micrographs in crossed-polarized light, and c,f) backscattered electron images of the Type I chondrules #1 (left column) and #2 (right column) in the CV carbonaceous chondrite Vigarano. Regions outlined in a) and d) are shown in details in b,c) and e,f), respectively. The chondrules contain coarse-grained, aggregates composed of Fe,Ni-metal (met) and magnesian olivines (ol) surrounded by the igneous shells composed of low-Ca pyroxene (px) and glassy mesostasis (mes) and by the fine-grained, matrix-like rims (FGR). Olivine grains in the aggregates show triple junctions with interfacial angles of ~ 120° (yellow and red arrows in c,f), indicative of granoblastic equilibrium textures; such textures can not be produced by crystallization from chondrule melts. Olivine–olivine grain boundaries in aggregate #1 lack any layer of glassy mesostasis, i.e., dry (indicated by yellow arrows, see for instance grain labelled ol2 in c). Some of the olivine–olivine grain boundaries in aggregate #2 (indicated by red arrows in f) are separated by thin layers of glass, whereas others (indicated by yellow arrows in f) are dry. Olivine grains separated by glass have rounded outlines and embayments, indicating dissolution. Notice that the significant difference in the wetting angles between olivine grains and glassy mesostasis, and between olivine and metal grains. We infer that these olivine dominated (dunite-like) aggregates are relict grains resulting from fragmentation of differentiated planetesimals.

aggregates, the olivine–olivine and olivine–metal grain boundaries are “dry”, i.e., lack any layer of glassy mesostasis (Fig. 1c,f). In lithic clast-bearing, Type I chondrules with high abundance of glassy mesostasis, some of the olivine–olivine grain boundaries are “wet”, i.e., separated by a thin layer of glass, whereas others remain “dry” (Fig. 2). Olivine grains with “wet” contacts have rounded outlines, indicating dissolution in chondrule glass. The aggregates are surrounded by shells of low-Ca pyroxene and glassy mesostasis, commonly observed in

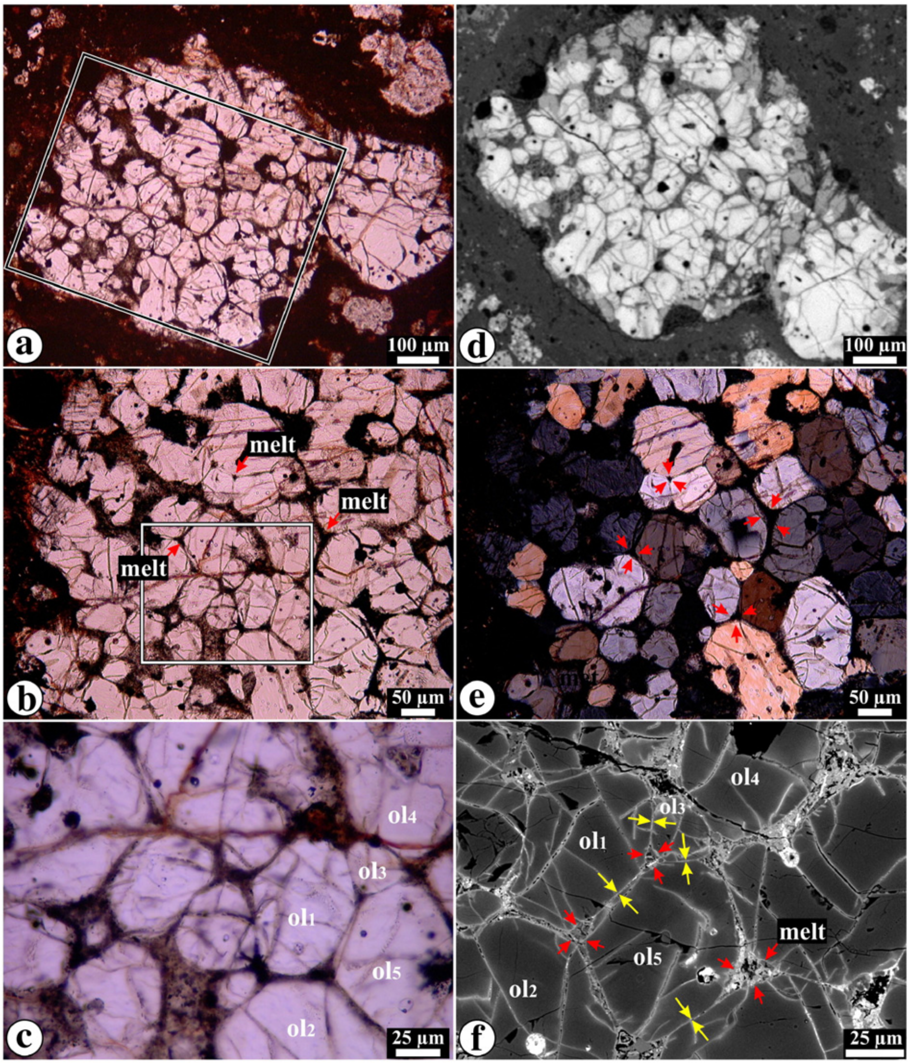

Fig. 2. a,b,c) Optical micrographs in transmitted and e) cross-polarized light, d) X-ray elemental map in Mg Kα, and f) backscattered electron image of Type I chondrule #3 in the CV carbonaceous chondrite Vigarano. Regions outlined in a) and b) are shown in details in b,e) and c,f), respectively. The chondrule consists of coarse-grained magnesian olivine (ol), mesostasis (mes), and low-Ca pyroxene (px). Olivine grains in the aggregate show triple junctions with interfacial angles of ~120° (see red arrows in e,f). Despite of the widespread occurrence of the glassy mesostasis, some of the olivine–olivine grain boundaries are dry (indicated by yellow arrows), others are separated by a thin layer of glassy mesostasis (indicated by red arrows). The olivine grains separated by mesostasis have rounded outlines and/or embayments, indicating dissolution. The presence of dry triple junctions and the low dihedral angles (<60°) between the olivine grains and the glassy mesostasis indicate that olivine grains were initially part of an olivine aggregate with a granoblastic texture; the aggregate was later infiltrated by a silicate melt that progressively dissolved the olivine grains.

Type I chondrules in ordinary and carbonaceous chondrites [23,24], and by fine-grained, matrix-like rims (Fig. 1a,e).

From pioneering work of Watson [25] on theories of interfacial energies and melt behavior, it is well-established that the ratio of solid–liquid interfacial energy to solid–solid grain boundary energy (γ_{sl}/γ_{ss}) controls the equilibrium morphology, distribution and connectivity of a small liquid fraction in a polycrystalline aggregate (Fig. 3a). The wetting (dihedral) angle, θ, at a solid–liquid–solid triple junction is a measurable indicator of the interfacial energy ratio and is commonly used to discuss the morphology and connectivity of the liquid. The wetting angle can be expressed as $\cos(\theta/2)=\gamma_{ss}/2\gamma_{sl}$. At textural equilibrium, a small volume fraction of liquid will take one of two fundamental grain-scale distributions depending on θ : (1) if $0\leq\theta<60°$, the melt will form a network of channels along grain edges, and melt interconnection will be established for an infinitely small melt percentage, and

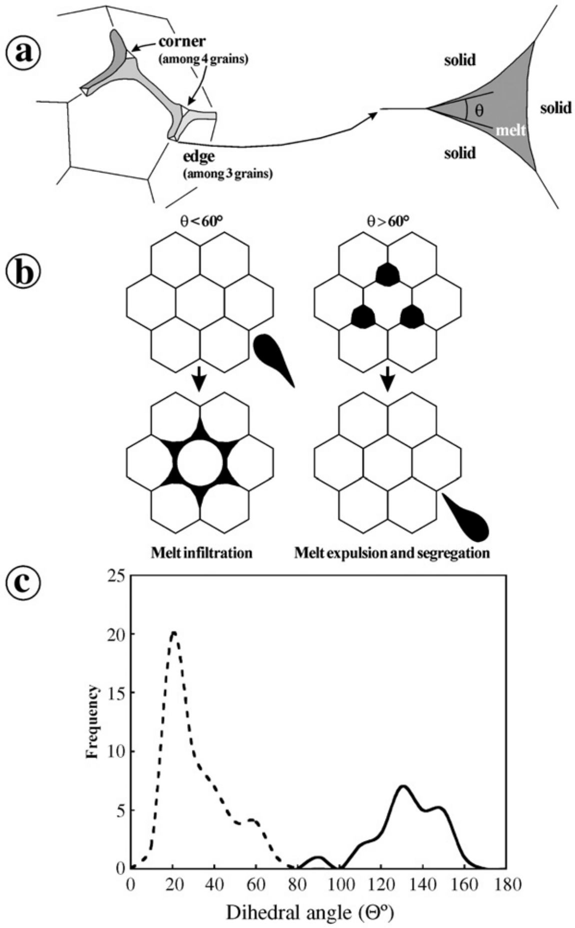

Fig. 3. a) Schematic representation of dihedral angle, θ, at a solid–liquid–solid triple junction. The true dihedral angle is defined by the tangents to the grain surfaces at their point of intersection. Liquid may occur at corners or along grain edges. b) Theoretical considerations of interfacial energies indicate that if $0 \leq \theta < 60°$, the liquid will form an 3D-interconnected network of channels along grain edges, while if $\theta \geq 60°$, the liquid will occur in isolated pockets at grain corners. Liquid infiltrates a crystalline aggregate, when $\theta < 60°$; it is expelled from the aggregate, when $\theta > 60°$. c) Frequency distributions of apparent dihedral angles in chondrules depicted in Figs. 1 and 2. The dashed line corresponds to olivine–silicate melt–olivine dihedral angles and the solid line to olivine−metal−olivine dihedral angles. See text for further discussions.

(2) if $\theta \geq 60°$, the melt will occur as isolated pockets at grain corners [26]. The interfacial energies control not only liquid connectivity but also melt infiltration and expulsion [25,27,28]. Melt infiltrates a crystalline aggregate, when $\theta < 60°$; it is expelled from the aggregate, when $\theta > 60°$ (Fig. 3b).

The olivine−silicate liquid−olivine wetting angle measurements in the granoblastic aggregates in the Vigarano chondrules (Figs. 1 and 2) indicate that θ values are systematically below the critical value of 60° ($\theta_{\text{average}} = 27 \pm 14°$, $n = 48$; Fig. 3c). From the interfacial energy considerations discussed above, we infer that chondrule silicate melt infiltrates the initially glass-free (dry) olivine aggregates. The path of melt penetration is restricted to grain-edge intersections which connect at grain corners (Figs. 1c,f, 2f, 3a). In contrast, olivine−metal−olivine dihedral angles significantly exceed 60° ($\theta_{\text{average}} = 129 \pm 16°$, $n = 24$; Fig. 3c), suggesting that liquid Fe,Ni-alloy, from which metal nodules formed, occur as isolated pockets at the corners of olivine grains. Based on these observations, we infer that the coarse-grained olivine–metal aggregates with granoblastic textures inside CV chondrules are relict, i.e., predate crystallization of the host chondrule melts; in a similar manner, terrestrial mantle xenoliths predate basaltic lavas.

4. Discussion

Most Type I chondrules in primitive ordinary and carbonaceous chondrites are mineralogically- and chemically-zoned objects with an Fe,Ni-metal-bearing, olivine-rich core surrounded by a low-Ca pyroxene mantle [23,24,29]. Type I chondrule glasses (mesostasis + melt inclusions) show enrichment in silicon, sodium, and potassium towards chondrule peripheries and are not in chemical equilibrium with chondrule olivines, as indicated by olivine-melt partition coefficients for both trace (e.g., Ca, Al, rare earth elements) and major (Fe, Mg) elements [30]. When plotted on a CaO–MgO–Al_2O_3–SiO_2 (CMAS) phase diagram, chondrule glasses form a well-defined linear trend that is outside the olivine–CMAS saturation field, inconsistent with liquid lines of descent controlled by olivine crystallization [29]. Libourel et al. [29] have recently concluded that crystallization of low-Ca pyroxene mantles and melt compositions of Type I chondrules had been controlled by the surrounding nebular gas and that evolution of chondrule melt compositions resulted mainly from high-temperature gas-melt interaction. Our discovery of relict, olivine-dominant, lithic clasts inside Type I chondrules may indicate that olivine-rich cores of at least some of Type I chondrules are remnants of olivine-dominated lithic fragments that experienced melt infiltration accompanied by dissolution and recrystallization of olivine grains. This interpretation could explain why chondrule melts are not in chemical equilibrium with olivine grains. Due to low-Ca pyroxene saturation and enrichment of the late chondrule melts in silica, olivines from the aggregates are no longer stable and dissolve, as indicated by rounded corrosion embayments at olivine grain edges (Fig. 2). Although some of the olivine grains in Type I chondrules have faceted outlines (Fig. 1a,b in [24]), the presence of such olivines is not incompatible with dissolution process [25,26]; e.g., they could have resulted from olivine overgrowths acquired upon cooling during boundary layer crystallization of otherwise dissolving olivine grains. Driven by both interfacial energy minimization and olivine dissolution, melt infiltration will proceed into the olivine aggregates insulating olivine grains (and metal nodules) into a glassy mesostasis in which low-Ca pyroxenes may eventually crystallized (Fig. 4), leading ultimately to classical porphyritic olivine and porphyritic olivine-pyroxene chondrule textures [1–3,23,30].

Only few relict grains, including fragments of ferrous olivine chondrules (Type II), fragments of amoeboid olivine aggregates (AOAs) and Ca, Al-rich inclusions (CAIs), have been hitherto recognized in Type I chondrules [31–33]. These relict grains have chemical and isotopic compositions which are inconsistent with crystallization from the host chondrule melts. We suggest that relict olivine grains or their aggregates may be ubiquitous in Type I chondrules. This hypothesis can be tested by measurements of oxygen isotopic compositions of olivines, pyroxene and glasses in magnesium-rich porphyritic olivine and porphyritic olivine–pyroxene chondrules: in an individual chondrule, pyroxenes and glasses are expected to be in isotopic disequilibrium with olivines, consistent with [34].

Granoblastic polygonal texture is a typical recrystallization texture resulting from mutual adjustment of grain boundaries in a solid state by reducing grain boundary area and the number of defects to achieve textural equilibrium. Because this process occurs through transport of elements to promote grain growth, granoblastic texture of magnesian olivine aggregates can only be produced by sintering and prolonged annealing of pre-existing material at high temperature. While these conditions are readily achieved in the Earth's mantle rocks (e.g., dunites, harzburgites, lherzolites), they are not expected in the chondrule-forming regions of the protoplanetary disk characterized by low total pressure ($<10^{-3}$ bar) and low ambient temperature (<1000 K). Even high-temperature nebular condensates, such as AOAs, which appear to have experienced prolonged annealing at temperatures ≥ 1300 K, are characterized by very fine-grained, porous textures [35]. Based on these observations, we infer that olivine-dominant (dunite-like) lithic fragments with granoblastic textures in CV chondrules originated from a differentiated or extensively metamorphosed parent body(ies), mimicking to a certain extent textures observed in some olivine-rich achondrites, such as ureilites and brachinites, and in some regions of primitive achondrites, such as lodranites [36,37]. This interpretation is consistent with the presence

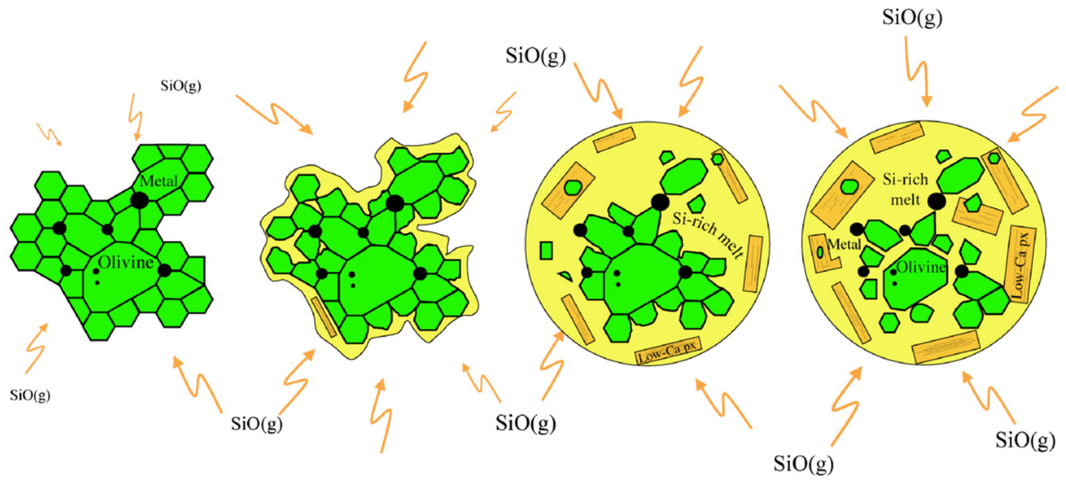

Fig. 4. Cartoon illustrating formation of a magnesian, porphyritic olivine (Type I) chondrule containing a relict component — Fe,Ni-bearing forsteritic olivine aggregate with granoblastic texture (green), and an igneous component — glass (yellow) + low-Ca pyroxene (light brown). The relict component could have originated from olivine-dominated (dunite-like) mantle material of earlier generations of differentiated planetesimals. The igneous component crystallized from the host chondrule melt that was in equilibrium with nebular gas. Depending on the temperature at which the interaction with the nebular gas (mainly SiO) takes place and its duration [29], changes in the melt composition may lead to crystallization of new phases, when saturation is reached, i.e., preferentially low-Ca pyroxene ±silica polymorphs, and/or to the dissolution of pre-existing phases, which are no longer in equilibrium, mainly olivine. At the infiltration front, olivine dissolution proceeds along grain edges and creates melt-filled porosity. This model accounts for several features observed in Type I chondrules: mineralogical and chemical zoning, preferential orientation of elongated low-Ca pyroxene crystals parallel to the chondrule edge, common occurrences of olivines resorbed or poikilitically enclosed in pyroxenes, and possibly oxygen isotopic heterogeneity in chondrules [34].

of metal nodules with high dihedral angles at olivine triple junctions of the granoblastic aggregates which match experimental textures aimed to simulate metal-silicate differentiation and planetary core formation [38].

5. Conclusions

In agreement with a companion study of Type I chondrule glass compositions [29], we conclude that Type I chondrules are complex objects composed of an inherited component, mainly forsteritic olivine and ±Fe, Ni-metal, originating from olivine-dominated material of earlier generations of differentiated planetesimals, and an igneous component equilibrated with nebular gas−glass, low-Ca pyroxene, high-Ca pyroxene, and ±silica phase (Fig. 4). This implies that Type I chondrules are not as pristine as conventionally viewed [5]; instead, they consist of nebular and asteroidal materials and must have postdated accretion, thermal metamorphism and differentiation of some early generation planetesimals. The very old Pb–Pb absolute [11] and Al–Mg relative model ages [9] of the CV chondrules suggest that accretion and differentiation of such primordial planetesimals could have occurred as early as 4567.2±0.6 Ma, the currently accepted age of the Solar System [8]. However, more work is needed to evaluate how the present finding would affect the interpretation of model ages for whole CV chondrules.

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