

Hertwig et al. 2017: Formation of chondrules in a moderately high dust enriched disk: evidence from oxygen isotopes of chondrules from the Kaba CV3 chondrite

EA3: Petrographic description of chondrules

Chondrule			Brief petrographic description	Mineral chemistry, remarks
K1	I	AB	K1 is a large (3mm in longest direction), layered and teardrop-shaped porphyritic olivine-pyroxene chondrule. Possibly, K1 is a compound chondrule; the lower appendix might represent an attached smaller chondrule. The inner portions of K1 are composed of subhedral olivine grains (50 - 250µm) that are surrounded by mesostasis phases (high-Ca pyroxenes and plagioclase). Coarse (up to 500µm) low-Ca pyroxene with olivine inclusions constitute a mantle portion, enclosed by an up to 400µm thick rim that comprises finer-grained (<100µm) low-Ca pyroxene with olivine inclusions and abundant opaque phases. Opaque phases are usually fine-grained in the rim and can form coarser grains in the chondrule interior and along the boundary to the rim. Small amounts of mesostasis phases are present in the mantle and chondrule rim.	Low-Ca pyroxene is clinoenstatite (twinning). Opaque phases are magnetite but also troilite and Fe-Ni alloys (identified by SEM-EDS). Mesostasis is composed of mainly high-Ca pyroxene (aluminian augites, Wo ₄₁) and plagioclase (identified by optical microscopy, An ₉₁).
K2	I	A	K2 is an elongated and platy (1mm in longest direction), porphyritic olivine chondrule. Olivine grains are mainly anhedral and of various sizes (<50 - 200µm). Some isolated low-Ca pyroxenes are situated along the edge of the chondrule. Mesostasis (altered) is mainly composed of anorthitic plagioclase and phyllosilicates. Some small (<30µm) blobs of opaque phases.	Opaque phases are magnetite and Fe-Ni sulfide (SEM-EDS).
K3	I	AB	K3 is a large (1.4mm in longest direction) and elongated, porphyritic olivine-pyroxene chondrule. Small (<60µm) anhedral olivine grains are situated in the center of this chondrule and are enclosed by mesostasis. Outer portion of chondrule K3 contains medium- to coarse-grained (up to 300µm) olivine phenocrysts and low-Ca pyroxene. Mesostasis is composed of plagioclase, pigeonite and high-Ca pyroxene (+ silica, identified by SEM-EDS). Mesostasis is altered close to the chondrule margins. Almost no opaque phases within chondrule but small grains are located at chondrule margins.	Olivine grains are relatively Ca-rich (CaO: 0.52 - 0.59wt%). Low-Ca pyroxene is clinoenstatite (twinning). Plagioclase confirmed by optical microscopy.
K4	I	A	K4 is a fragment (1mm in longest direction) of a porphyritic olivine-rich chondrule. Fine-grained (<50µm) subhedral olivine grains are embedded in mesostasis. Only a few low-Ca pyroxene grains are located close to chondrule margins. Mesostasis (partly altered) contains amongst others high-Ca pyroxene. Opaque phases unevenly distributed within chondrule.	Opaque phases are magnetite and Fe-Ni sulfides (SEM-EDS).

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K5	I	AB	K5 is a large (1.5mm) porphyritic olivine-pyroxene chondrule with an irregular-shaped rim (opaques-rich, not analyzed for oxygen isotopes). Small (300 μ m) chondrules are attached to K5 and are now part of this irregular-shaped rim. K5 contains anhedral olivine (<200 μ m), mainly subhedral pyroxenes (<100 μ m), and mesostasis phases (mainly plagioclase and high-Ca pyroxene). No phyllosilicates are present in mesostasis. Opaque phases accumulate at chondrule margins but are absent in the chondrule interior.	K5 contains two distinct pyroxenes (excluding the high-Ca pyroxene of the mesostasis): Low-Ca pyroxene (Wo ₁₋₂) is clinoenstatite (lamellar twinning); intermediate pyroxene (Wo ₄₋₅) shows no lamellar features. Plagioclase (An ₉₂₋₉₈) and aluminian augite (Wo ₃₅) are part of the mesostasis.
K6	I	A	K6 is an elongated, olivine-rich chondrule (1mm in longest direction) with platy olivine grains; some low-Ca pyroxenes along chondrule margins and a few in chondrule interior. Mesostasis is altered but still contains some high-Ca pyroxene. Small (<5 μ m), aligned opaque phases contained in olivine. Coarser-grained opaque phases along margins of chondrule.	K6 contains low-Ca and intermediate pyroxenes, as well as high-Ca pyroxenes (aluminian augites, mesostasis).
K7	I	A	K7 is a round (1mm diameter) porphyritic chondrule dominated by olivine. Olivine (300 μ m) is subhedral and grains show rounded edges. Low-Ca pyroxene is present in a small pocket (together with high-Ca pyroxene, altered mesostasis) close to the chondrule margin. Low-Ca pyroxene also forms a very thin rim (<50 μ m) or coating surrounding the chondrule. Mesostasis consists of plagioclase that is intergrown with high-Ca pyroxene; some hydrous alteration. Mesostasis assemblages are present in oval-shaped inclusions in olivine. A few opaque phases.	Chondrule contains relatively Ca-rich olivine grains (CaO > 0.5 wt%, All analyses: 0.35 - 0.53 wt%). High-Ca pyroxene is aluminian augite (Wo ₃₇). Opaque phases are Fe-Ni sulfides (SEM-EDS).
K8+9	I	AB	(K8+9) Chondrules 8 (left, fragmented by sectioning) and 9 are attached to each other and are enclosed by a fine-grained, low-Ca pyroxene- and opaque phases-rich rim (similar to the rim of K1). The compound object has an apparent size of 1.5mm. Individual chondrules are layered and contain olivine (<100 μ m), mesostasis, and opaque phases in their centers. These centers are mantled by coarse low-Ca pyroxene which contains only a few opaque phases. A few bigger (up to 200 μ m) blobs of opaque phases are embedded between individual chondrules and the rim. Mesostasis is unaltered and comprises mainly plagioclase and high-Ca pyroxene.	Low-Ca pyroxene is clinoenstatite (twinning). The compound chondrule contains intermediate pyroxenes in the chondrule interior (Wo ₅) and in the rim (Wo ₄₋₅); high-Ca pyroxene (aluminian augite, Wo ₃₇₋₃₈) in the mesostasis. Plagioclase is anorthite-rich (An _{>94}). Opaque phases are magnetite and Fe-Ni sulfides (SEM-EDS).

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K10	I	A	K10 is a teardrop-shaped (1.5mm in longest direction) olivine-rich porphyritic chondrule with a high mesostasis-to-phenocryst ratio. Olivine grains are anhedral and variably-sized (from 50 - 300 μ m). Intermediate pyroxenes are often subhedral and evenly distributed within chondrule and could be treated as a part of the mesostasis assemblage. Mesostasis phases are plagioclase and high-Ca pyroxene. Chondrule is rich in opaque phases (10 - 200 μ m).	No low-Ca pyroxenes present (intermediate pyroxenes, Wo_{4-5}). High-Ca pyroxene (mainly aluminian augite, Wo_{43}) and plagioclase (An_{91-95}) in mesostasis.
K11	I	B	K11 is a semi-round (1mm in longest direction) pyroxene-rich porphyritic chondrule with a low amount of mesostasis and a high amount of evenly distributed opaque phases. Coarse low-Ca pyroxene possesses fine-grained (usually <50 μ m) olivine inclusions. Mesostasis contains plagioclase and high-Ca pyroxene.	Low-Ca pyroxene is clinoenstatite (twinning). Opaque phases identified are magnetite and Fe-Ni sulfides. Plagioclase in mesostasis is An_{94} .
K12	I	AB	K12 is a large (2mm in longest direction) and irregular-shaped, pyroxene-olivine chondrule containing abundant fine-grained opaque phases. The texture resembles those of the fine-grained rims of K1 and K8+9. Fine- to medium-grained low-Ca pyroxene and fine-grained olivine (<50 μ m) form poikilitic texture. Medium-grained (50-80 μ m) olivine enclosed in low-Ca pyroxene on the right hand site of chondrule fragment. Low amount of mesostasis (mainly high-Ca pyroxene)	Low-Ca pyroxene is clinoenstatite (twinning). Opaque phases are Fe-Ni sulfides and magnetite (SEM-EDS).
K13	I	B	K13 is an irregular-shaped pyroxene-rich chondrule (1mm in longest direction). Coarse low-Ca pyroxene grains enclose olivine clusters (up to 100 μ m). Opaque phases are abundant in some parts of the chondrule; small amount of mesostasis (plagioclase and high-Ca pyroxene).	Low-Ca pyroxene is clinoenstatite (twinning). Opaque phases identified by SEM-EDS are magnetite and Fe-Ni sulfides.
K14	I	AB	K14 is a heart-shaped olivine-pyroxene chondrule (0.7mm) that contains a coarse (300 μ m) compound of opaque phases in its center. Usually euhedral low-Ca pyroxene (up to 200 μ m) often encloses anhedral olivine (50-100 μ m). Plagioclase and high-Ca pyroxene form radial intergrown textures.	Low-Ca pyroxene is clinoenstatite (twinning). High-Ca pyroxene is aluminian augite (Wo_{35}); Opaque phases: Fe-Ni sulfides and magnetite.
K15	I	B	K15 is a pyroxene-rich chondrule (0.8mm) containing only a few opaque phases. Low-Ca pyroxene is coarse (up to 300 μ m), subhedral and contains finer-grained olivine (<50 μ m). Mesostasis is heavily altered but some high-Ca pyroxenes (mainly euhedral) are still present.	Low-Ca pyroxene is clinoenstatite (twinning). High-Ca pyroxene is aluminian augite. Magnetite was identified by SEM-EDS.

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K16	I	A	K16 is an oval-shaped olivine-rich porphyritic chondrule (0.8mm) possessing a low amount of mesostasis. K16 has a thin (<50µm) rim that is rich in opaque phases. Olivine grains are anhedral, coarse (up to 150µm), and virtually free of opaque inclusions. Interstitial intermediate pyroxenes show irregular-shaped grain boundaries with plagioclase and high-Ca pyroxene in mesostasis. Low-Ca pyroxene is absent in the chondrule interior. A few bigger blobs of opaque phases are situated between chondrule interior and the thin rim.	High-Ca pyroxene is aluminian augite (Wo ₄₂); intermediate pyroxene: Wo ₅₋₆ .
K17	I	AB	K17 is a teardrop-shaped (0.6mm) olivine-pyroxene porphyritic chondrule with only a low amount of mesostasis (mainly plagioclase). Opaque phases surround lower half of chondrule. Olivine grains (<70µm) are anhedral and enclosed in low-Ca pyroxene.	High-Ca pyroxene in mesostasis is aluminian (subsilicic, Si < 1.75, Wo ₃₅₋₄₄) augite.
K18	I	A	K18 is a roundish, olivine-rich porphyritic chondrule (0.7mm) with abundant opaque phases. Anhedral and fine-grained (< 20µm) olivine occurs together with mesostasis in the center of chondrule; olivine coarsens towards chondrule margins. Some olivine grains show faint zoning in Fe content. Mesostasis is mainly plagioclase. Low-Ca pyroxene is present in minor amounts close to chondrule margins.	
K19	I	AB	K19 is a roundish and layered olivine-pyroxene chondrule (0.6mm). A fractured and massive olivine compound (300µm) in the center of chondrule is surrounded by low-Ca pyroxene which is partly rich in fine-grained opaque phases. Mesostasis phases (high-Ca pyroxene, plagioclase, and phyllosilicates) are present in small amounts.	Low-Ca pyroxene is clinoenstatite.
K20	I	AB	K20 is a roundish (0.8mm) and layered porphyritic olivine-pyroxene chondrule. The center of the chondrule is composed of anhedral olivine and mesostasis. The center is mantled by massive olivine. The center and mantle are surrounded by coarse and fractured low-Ca pyroxene with or without olivine inclusions (< 20µm) and with fine-grained opaque phases. The chondrule margin on the left is irregular-shaped.	Mesostasis is mainly composed of intermediate and high-Ca pyroxenes. Low-Ca pyroxene is clinoenstatite.
K21	I	AB	K21 is a fragment of a porphyritic olivine-pyroxene chondrule (0.7mm in longest direction). Anhedral olivine and mesostasis and some low-Ca pyroxenes are present. Mesostasis contains plagioclase and phyllosilicates. Opaque phases are of various sizes (<10 - 100µm).	Some low-Ca pyroxenes show twinning.

Chondrule			Brief petrographic description	Mineral chemistry, remarks
K22	I	AB	K22 is a roundish porphyritic olivine-pyroxene chondrule (0.8 mm). A fractured massive olivine compound dominates one half of the chondrule; fractured coarse-grained low-Ca pyroxene and mesostasis dominate the other half. Euhedral high-Ca pyroxene overgrowths on low-Ca pyroxene. Mesostasis contains phyllosilicates and no plagioclase. Some opaque phases are located at chondrule margins but opaques are absent in chondrule interior.	K22 contains relatively CaO-rich olivine (CaO: 0.23-0.52 wt%); high-Ca pyroxene is aluminian augite. Low-Ca pyroxene is clinoenstatite
K23	I	AB	K23 is an irregular-shaped, olivine-pyroxene porphyritic chondrule (0.7mm) with minor amounts of mesostasis and abundant opaque phases (similar to K18). Anhedral and fine-grained (< 20 μ m) olivine and mesostasis are situated in the center of the chondrule. Some olivine is coarser-grained (up to 80 μ m). Mesostasis contains high-Ca pyroxene. Low-Ca pyroxene is present close to chondrule margins.	
K24	I	AB	K24 is a olivine-pyroxene porphyritic chondrule (0.8mm). Olivine occurs in the form of small inclusions in subhedral to euhedral low-Ca pyroxene, in contact to the mesostasis, and as part of a fractured massive olivine compound (lower right). The mesostasis contains plagioclase and high-Ca pyroxene. Opaque phases are abundant (except within massive olivine compound).	
K25	II	B	K25 is porphyritic pyroxene-rich chondrule (0.6mm). Pyroxene grains are subhedral and possess thin (< 20 μ m) overgrows of olivine. Mesostasis is altered and contains only phyllosilicates.	Olivine overgrowths on pyroxene: Fo ₈₃ .
K26	II	A	Olivine in K26 (0.15mm) is chemically zoned and contains forsterite-rich relict grains.	Rims are fayalite-rich (Fo ₅₈) compared to the center of fragment (Fo ₆₆).