Supplementary Data (SD)

Petrography and mineral composition of 37 chondrule objects and CAIs

Petrography

Barred olivine chondrule (BOC)

BOC-01

The sample BOC-01 consists mainly of barred olivine, Al-rich clinopyroxene, and plagioclase, with minor amounts of nepheline. Barred olivine is generally forsterite: Mg/ (Mg+Fe^{2+}) atomic ratio [= X_{Mg}] being 0.98 to 0.99. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.93 to 0.98 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Al-rich clinopyroxene is characterized by high Al content (3.5–8.4 wt% Al_2O_3); X_{Mg} ranges from 0.98 to 0.99. It contains significant Ti (1.5–2.1 wt% TiO_2), Cr (0.39– 0.55 wt% Cr_2O_3), and Na (0.08–0.14 wt% Na_2O). Plagioclase has 90.9–91.9 mol.% anorthite component. Nepheline replacing fine-grained aggregates of plagioclase in mesostasis contains up to 2.2 wt% K_2O. Sodalite pinkish in color occurs as an accessory mineral in the mesostasis and contains up to 7.2 wt% Cl. Sodalite is closely associated with nepheline (Figure SD1).

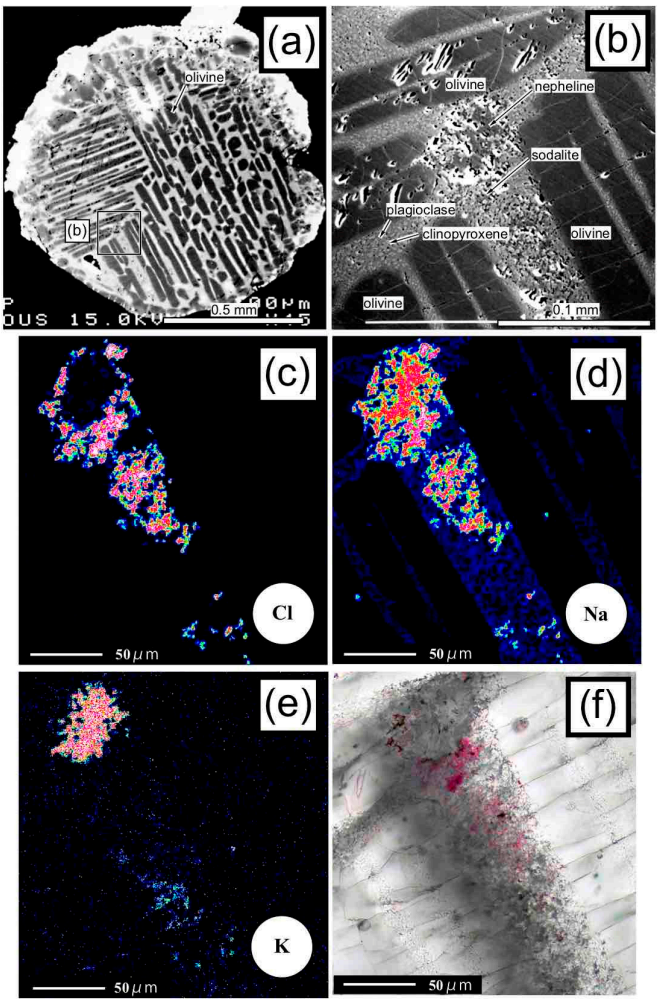


Figure SD1 Nepheline and sodalite in mesostasis (BOC-01). (a) Back-scattered electron images showing microtexture of analyzed barred olivine chondrules. (b) An enlarged image of a part of a showing occurrence of nepheline and sodalite. (c) Compositional map (Cl) of a part of b showing the occurrence of nepheline and sodalite. (d) Compositional map (Na) of a part of b. (e) Compositional map (K) of a part of b. (f) Microphotograph (Open-Nicol) of a part of b.

Sample BOC-02

The sample BOC-02 consists mainly of barred olivine with minor amounts of mesostasis. Barred olivine in this chondrule is

characterized by high Fe content; X_{Mg} ranges from 0.49 to 0.59 (ST1). The X_{Mg} values decrease towards the olivine of chondrule rim (SF2). Mesostasis is characterized by high Al content (4.9–30.2 wt% Al_2O_3). It contains significant Ca (0.5–5.7 wt% CaO), Ti (0.1–0.4 wt% TiO_2), Cr (0.0–1.2 wt% Cr_2O_3), and Na (1.4–15.3 wt% Na_2O).

BOC-03

The sample BOC-03 consists mainly of barred olivine and low-Ca pyroxene. Barred olivine shows chemical zoning in X_{Mg} ranging from 0.70 to 1.00 (ST1); the X_{Mg} value decrease towards the rim. This chondrule is further mantled by Fe-rich olivine (SF2). Low-Ca pyroxene contains 0.8-1.8 wt% Al_2O_3, 0.5–4.5 wt% CaO, and 0.5–1.0 wt% Cr_2O_3; X_{Mg} ranges from 0.92 to 0.99.

BOC-04

The sample BOC-04 consists mainly of barred olivine and Mg-Al spinel with minor amounts of nepheline and sodalite (Figure SD2). Mg-Al spinel contains 0.18–0.19 wt% Cr_2O_3; X_{Mg} ranges from 0.98 to 0.99. Nepheline contains 1.6 wt% K_2O. Sodalite contains 6.3–7.2 wt% Cl.

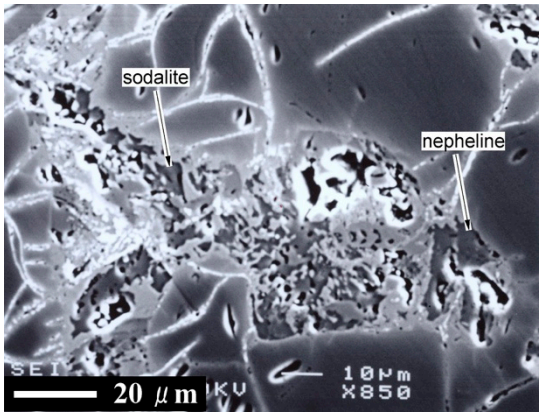


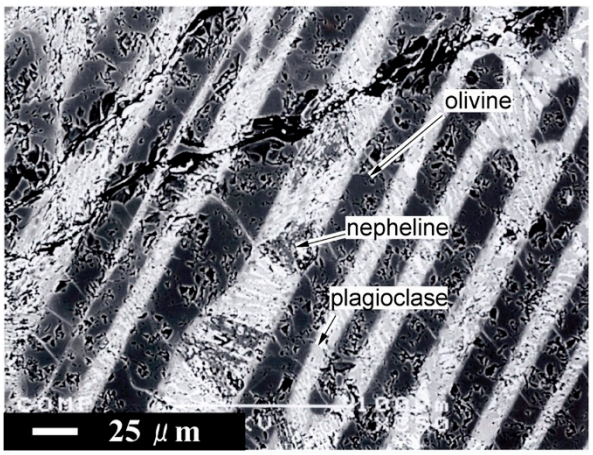
Figure SD2 An enlarged image (back-scattered electron images) showing the occurrence of nepheline and sodalite BOC-04.

BOC-05

The sample BOC-05 consists mainly of barred olivine, low-Ca pyroxene, and Al-rich clinopyroxene, with minor amounts of sodalite and mesostasis. Barred olivine is forsterite: X_{Mg} being 0.98 to 1.00 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Low-Ca pyroxene contains 1.7–2.0 wt% Al_2O_3, 0.7–2.0 wt% CaO, and 0.4–0.5 wt% Cr_2O_3; X_{Mg} ranges from 0.97 to 0.99. Al-rich clinopyroxene is characterized by high Al content (7.5–12.8 wt% Al_2O_3); X_{Mg} ranges from 0.85 to 0.99. It contains significant Ti (0.5–1.2 wt% TiO_2), Cr (0.07–0.43 wt% Cr_2O_3), and Na (0.00–2.67 wt% Na_2O). Sodalite contains 6.1 wt% Cl. Mesostasis is characterized by high Al content (6.7-23.8 wt% Al_2O_3). It contains significant Ca (1.7–19.2 wt% CaO), Ti (0.2-1.1 wt% TiO_2), Cr (0.0-0.7 wt% Cr_2O_3), and Na (0.0–2.0 wt% Na_2O).

BOC-06

The sample BOC-06 consists mainly of barred olivine, Al-rich clinopyroxene, and plagioclase, with minor amounts of nepheline, sodalite, and mesostasis (Figure SD3). Barred olivine is generally forsterite: X_{Mg} being 0.90 to 0.99. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.69 to 0.98 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Al-rich clinopyroxene is characterized by high Al content (6.0–14.0 wt%



Al_2O_3); X_{Mg} ranges from 0.74 to 0.98. It contains significant Ti (0.4–4.7 wt% TiO_2), Cr (0.27–1.25 wt% Cr_2O_3), and Na (0.21–1.48 wt% Na_2O). Plagioclase has 84.3–84.6 mol.% anorthite component. Nepheline contains 1.4–1.8 wt% K_2O. Sodalite contains 5.1 wt% Cl. Mesostasis is characterized by high Al content (6.6–22.1 wt% Al_2O_3). It contains significant Ca (13.3–28.4 wt% CaO), Ti (0.1–1.4 wt% TiO_2), Cr (0.1-0.4 wt% Cr_2O_3), and Na (0.1–1.5 wt% Na_2O).

Figure SD3 An enlarged image (back-scattered electron images) showing the occurrence of nepheline BOC-06.

BOC-07

The sample BOC-07 consists mainly of barred olivine, low-Ca pyroxene, Fe-rich clinopyroxene, and Al-rich clinopyroxene. Barred olivine is forsterite: X_{Mg} is 0.93 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Low-Ca pyroxene contains 1.2-2.2 wt% Al_2O_3, 1.8–2.4 wt% CaO, and 0.4–0.6 wt% Cr_2O_3; X_{Mg} ranges from 0.99 to 1.00. Fe-rich clinopyroxene is characterized by high Fe content (23.5 wt% FeO) with X_{Mg} = 0.19. Al-rich clinopyroxene is characterized by high Al content (3.7–4.9 wt% Al_2O_3); X_{Mg} = 0.99. It contains significant Ti (0.7–1.2 wt% TiO_2), Cr (0.53–0.59 wt% Cr_2O_3), and Na (0.04–1.18 wt% Na_2O).

BOC-08

The sample BOC-08 consists mainly of barred olivine, Fe-rich clinopyroxene, Al-rich clinopyroxene, and plagioclase, with minor amounts of nepheline and mesostasis. Barred olivine is forsterite: X_{Mg} being 0.89 to 0.98. The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Fe-rich clinopyroxene is characterized by high Fe content (23.5 wt% FeO) with X_{Mg} = 0.27. Al-rich clinopyroxene is characterized by high Al content (4.8–12.1 wt% Al_2O_3); X_{Mg} ranges from 0.97 to 0.99. It contains significant Ti (0.5–1.1 wt% TiO_2), Cr (0.38–0.71 wt% Cr_2O_3), and Na (0.22–0.64 wt% Na_2O). Plagioclase has 90.2 mol.% anorthite component. Nepheline contains 1.7 wt% K_2O. Mesostasis is characterized by high Al content (12.9–26.1 wt% Al_2O_3) and high Ca content (9.4-15.9 wt% CaO). It contains significant Ti (0.2–1.7 wt% TiO_2), Cr (0.1–0.4 wt% Cr_2O_3), and Na (0.6–15.9 wt% Na_2O).

BOC-09

The sample BOC-09 consists mainly of barred olivine with minor amounts of mesostasis. Barred olivine is forsterite: X_{Mg} being 0.76 to 1.00. Mesostasis is characterized by high Al content (7.2–26.2

wt% Al_2O_3). It contains significant Ca (6.6–14.4 wt% CaO), Ti (0.0–1.6 wt% TiO_2), Cr (0.0–0.6 wt% Cr_2O_3), and Na (0.3–10.2 wt% Na_2O).

BOC-10

The sample BOC-10 consists mainly of barred olivine, low-Ca pyroxene, clinopyroxene, and plagioclase, with minor amounts of sodalite. Barred olivine is forsterite: X_{Mg} being 0.68 to 0.94. Low-Ca pyroxene contains 1.0–2.1 wt% Al_2O_3, 1.9–4.8 wt% CaO, and 0.4–0.6 wt% Cr_2O_3; X_{Mg} ranges from 0.97 to 0.99. Clinopyroxene has a diopsidic composition with X_{Mg} = 0.99; it contains 1.0–3.7 wt% Al_2O_3, 0.6–1.9 wt% TiO_2, and 0.3–0.6 wt% Cr_2O_3. Plagioclase has 84.3–85.9 mol.% anorthite component. Sodalite contains 6.3 wt% Cl.

BOC-11

The sample BOC-11 consists mainly of barred olivine, Fe-rich clinopyroxene, and Al-rich clinopyroxene, with minor amounts of nepheline. Barred olivine shows chemical zoning in X_{Mg} ranging from 0.61 to 0.85 (ST1); the X_{Mg} value decrease towards the rim. This chondrule is further mantled by Fe-rich olivine (SF2). Fe-rich clinopyroxene is characterized by high Fe content (23.0 wt% FeO) with X_{Mg} = 0.49. Al-rich clinopyroxene is characterized by high Al content (5.9–8.2 wt% Al_2O_3); X_{Mg} ranges from 0.72 to 0.74. It contains significant Ti (0.5–0.6 wt% TiO_2), Cr (1.08–1.29 wt% Cr_2O_3), and Na (0.04–0.08 wt% Na_2O). Nepheline contains 1.4–2.0 wt% K_2O.

Porphyritic olivine chondrule (POC)

POC-01

The sample POC-01 consists mainly of porphyritic olivine, clinopyroxene, and plagioclase, with minor amounts of nepheline. Olivine is generally forsterite: X_{Mg} being 0.92 to 0.97. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.70 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Clinopyroxene is characterized by high Ca content (17.23 wt% CaO); X_{Mg} = 0.95. It contains significant Al (5.4 wt% Al_2O_3), Ti (1.4 wt% TiO_2), Cr (0.52 wt% Cr_2O_3), and Na (0.48 wt% Na_2O) contents. Plagioclase contains 80.8–84.1 mol.% anorthite component. Nepheline contains 1.3 wt% K_2O.

POC-02

The sample POC-02 consists mainly of olivine, low-Ca pyroxene, clinopyroxene, and plagioclase, with minor amounts of nepheline and sodalite. Olivine is generally forsterite: X_{Mg} being 0.82 to 0.97. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.49 to 0.73 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Low-Ca pyroxene contains 1.2 wt% Al_2O_3, 0.7 wt% CaO, and 0.5 wt% Cr_2O_3; X_{Mg} = 0.99. Clinopyroxene is characterized by high Ca content (18.1 wt% CaO); X_{Mg} = 0.62. It contains significant Al (3.4 wt% Al_2O_3),

Ti (1.1 wt% TiO_2), Cr (0.50 wt% Cr_2O_3), and Na (0.00 wt% Na_2O) contents. Plagioclase contains 84.8–88.6 mol.% anorthite component. Nepheline contains 1.9 wt% K_2O. Sodalite contains 5.1 wt% Cl.

POC-03

The sample POC-03 consists mainly of olivine, low-Ca pyroxene, clinopyroxene, and plagioclase, with minor amounts of nepheline and sodalite. Olivine is forsterite: X_{Mg} = 0.97. Low-Ca pyroxene contains 0.7 wt% Al_2O_3, 0.5 wt% CaO, and 0.2 wt% Cr_2O_3; X_{Mg} = 0.99. Clinopyroxene is characterized by high Ca content (19.4–21.3 wt% CaO); X_{Mg} = 0.96–0.99. It contains significant Al (2.9–3.3 wt% Al_2O_3), Ti (0.5–1.1 wt% TiO_2), Cr (0.5–0.6 wt% Cr_2O_3), and Na (0.01–0.03 wt% Na_2O) contents. Plagioclase contains 90.5–93.8 mol.% anorthite component. Nepheline contains 1.7 wt% K_2O. Sodalite contains 5.2-6.0 wt% Cl.

POC-04

The sample POC-04 consists mainly of olivine, clinopyroxene, and plagioclase. Olivine is forsterite-rich (magnesian); X_{Mg} = 0.93 to 0.99. Clinopyroxene is characterized by high Ca content (4.33–25.6 wt% CaO); X_{Mg} = 0.90–0.99. It contains significant Al (1.6–3.3 wt% Al_2O_3), Ti (0.0–0.9 wt% TiO_2), Cr (0.0–0.9 wt% Cr_2O_3), and Na (0.00–0.03 wt% Na_2O) contents. Plagioclase contains 83.3–87.8 mol.% anorthite component.

POC-05

The sample POC-05 consists mainly of olivine, low-Ca pyroxene, clinopyroxene, and plagioclase, with minor amounts of nepheline. Olivine is forsterite-rich (magnesian); X_{Mg} = 1.00. Low-Ca pyroxene contains 0.9–1.8 wt% Al_2O_3, 0.6–0.7 wt% CaO, and 0.3–0.4 wt% Cr_2O_3; X_{Mg} = 0.94–0.99. Clinopyroxene is characterized by high Ca content (6.37 wt% CaO); X_{Mg} = 0.99. It contains significant Al (2.5 wt% Al_2O_3), Ti (0.9 wt% TiO_2), Cr (0.6 wt% Cr_2O_3), and Na (0.04 wt% Na_2O) contents. Plagioclase contains 83.9–85.4 mol.% anorthite component. Nepheline contains 1.7–2.0 wt% K_2O.

POC-06

The sample POC-06 consists mainly of olivine, low-Ca pyroxene, and Al-rich clinopyroxene, with minor amounts of nepheline (Figure SD4). Olivine is generally forsterite: X_{Mg} being 0.91 to 1.00. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} = 0.64 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Low-Ca pyroxene contains 1.1 wt% Al_2O_3, 0.5 wt% CaO, and 0.5 wt% Cr_2O_3; X_{Mg} = 0.99. Al-rich clinopyroxene is characterized by high Al content (5.5–14.8 wt% Al_2O_3); X_{Mg} ranges from 0.96 to 0.99. It contains significant Ti (0.5–1.6 wt% TiO_2), Cr (1.02–1.36 wt% Cr_2O_3), and Na (0.03–1.29 wt% Na_2O). Nepheline contains 1.6–2.0 wt% K_2O.

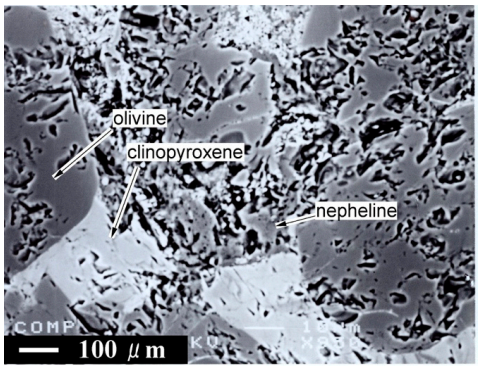


Figure SD4 An enlarged image (back-scattered electron images) showing the occurrence of nepheline POC-06.

POC-07

The sample POC-07 consists mainly of olivine, low-Ca pyroxene, clinopyroxene, and plagioclase. Olivine is forsterite-rich (magnesian); X_{Mg} = 0.91–0.99. Low-Ca pyroxene contains 0.4–0.9 wt% Al_2O_3, 0.3–2.3 wt% CaO, and 0.5 wt% Cr_2O_3; X_{Mg} = 0.96–0.99. Clinopyroxene is characterized by high Ca content (15.3–19.1 wt% CaO); X_{Mg} = 0.97. It contains significant Al (2.9–4.2 wt% Al_2O_3), Ti (1.1–1.2 wt% TiO_2), Cr (1.5–1.6 wt% Cr_2O_3), and Na (0.03–0.04 wt% Na_2O) contents. Plagioclase contains 81.7 mol.% anorthite component.

POC-08

The sample POC-08 consists mainly of olivine, low-Ca pyroxene, and clinopyroxene, with minor amounts of nepheline. Olivine is forsterite-rich (magnesian); X_{Mg} = 0.97. Low-Ca pyroxene contains 1.7 wt% Al_2O_3, 0.6 wt% CaO, and 0.6 wt% Cr_2O_3; X_{Mg} = 0.99. Clinopyroxene is characterized by high Ca content (5.9–16.9 wt% CaO); X_{Mg} = 0.98-0.99. It contains significant Al (1.5–2.3 wt% Al_2O_3), Ti (0.7 wt% TiO_2), Cr (0.8–0.9 wt% Cr_2O_3), and Na (0.0 wt% Na_2O) contents. Nepheline contains 2.0 wt% K_2O.

POC-09

The sample POC-09 consists mainly of olivine and Al-rich clinopyroxene, with minor amounts of nepheline. Olivine shows chemical zoning in X_{Mg} ranging from 0.81 to 0.98 (ST1); the X_{Mg} value decrease towards the rim. This chondrule is further mantled by Fe-rich olivine (SF2). Al-rich clinopyroxene contains up to 7.9 wt% Al_2O_3 and 0.8 wt% Cr_2O_3; X_{Mg} is 0.96. Nepheline contains 1.4–1.7 wt% K_2O.

POC-10

The sample POC-10 consists mainly of olivine and low-Ca pyroxene with a minor amount of Al-rich clinopyroxene. Olivine is generally forsterite: X_{Mg} = 0.94. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.54 to 0.71 (ST1). The X_{Mg} values seem to decrease from the core part to the rim part of chondrule (SF2). Low-Ca pyroxene contains 1.9–2.1 wt% Al_2O_3 and 0.7–0.9 wt% Cr_2O_3; X_{Mg} ranges from 0.98 top 0.99. Al-rich clinopyroxene contains 8.2–10.4 wt% Al_2O_3 and 1.3–1.5 wt% Cr_2O_3; X_{Mg} ranges from 0.94 to 0.98.

POC-11

The sample POC-11 consists mainly of olivine, low-Ca pyroxene, and clinopyroxene. Olivine is Fe-rich; X_{Mg} = 0.58. Low-Ca pyroxene contains 1.3–2.2 wt% Al_2O_3 and 0.6 wt% Cr_2O_3; X_{Mg} ranges from 0.97

to 0.99. Clinopyroxene is characterized by high Ca content (17.6–18.7 wt% CaO); X_{Mg} = 0.97–0.98. It contains significant Al (2.6 wt% Al_2O_3), Ti (1.1–1.2 wt% TiO_2), Cr (0.5-0.6 wt% Cr_2O_3), and Na (0.03-0.07 wt% Na_2O) contents.

POC-12

The sample POC-12 consists mainly of olivine, low-Ca pyroxene, and clinopyroxene. Olivine shows chemical zoning in X_{Mg} ranging from 0.59 to 0.98 (ST1); the X_{Mg} value decrease towards the rim. This chondrule is further mantled by Fe-rich olivine (SF2). Low-Ca pyroxene contains 0.7–1.0 wt% Al_2O_3 and 0.6–0.7 wt% Cr_2O_3; X_{Mg} ranges from 0.97 to 0.98. Clinopyroxene is characterized by high Ca content (6.0–16.1 wt% CaO); X_{Mg} = 0.99. It contains significant Al (1.6–2.0 wt% Al_2O_3), Ti (0.4–0.9 wt% TiO_2), Cr (0.7–1.0 wt% Cr_2O_3), and Na (0.03 wt% Na_2O) contents.

POC-13

The sample POC-13 consists mainly of olivine, low-Ca pyroxene, Al-rich clinopyroxene, Fe-rich clinopyroxene, and plagioclase, with minor amounts of nepheline. Olivine is generally forsterite: X_{Mg} being 0.87 to 0.93. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.66 to 0.75 (ST1). Low-Ca pyroxene contains 1.4–2.7 wt% Al_2O_3, 1.8–3.5 wt% CaO, and 0.5–0.8 wt% Cr_2O_3; X_{Mg} = 0.97–0.99. Fe-rich clinopyroxene is characterized by high Fe content (19.2 wt% FeO) with X_{Mg} = 0.33. Al-rich clinopyroxene is characterized by high Al content (4.0–5.4 wt% Al_2O_3); X_{Mg} ranges from 0.95 to 0.97. It contains significant Ti (1.0–1.3 wt% TiO_2), Cr (0.59–0.70 wt% Cr_2O_3), and Na (0.04–0.13 wt% Na_2O). Plagioclase contains 83.3-91.4 mol.% anorthite component. Nepheline contains 1.7–2.2 wt% K_2O.

POC-14

The sample POC-14 consists mainly of olivine and plagioclase. Olivine is generally forsterite: X_{Mg} = 0.94. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} = 0.59 (ST1). Plagioclase contains 90.5 mol.% anorthite component.

POC-15

The sample POC-15 consists mainly of olivine, low-Ca pyroxene, clinopyroxene, and plagioclase with minor amounts of nepheline. Olivine is generally forsterite: X_{Mg} being 0.95 to 0.98. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} = 0.61 (ST1). Low-Ca pyroxene contains 1.1–2.2 wt% Al_2O_3, 0.4–1.8 wt% CaO, and 0.5–0.8 wt% Cr_2O_3; X_{Mg} ranges from 0.97 to 0.99. Clinopyroxene has a diopsidic composition with X_{Mg} = 0.97–0.98; it contains 1.5–2.2 wt% Al_2O_3, 1.4–1.9 wt% TiO_2, and 0.7–0.8 wt% Cr_2O_3. Plagioclase has 85.4-87.5 mol.% anorthite component. Nepheline contains 2.0 wt% K_2O. Sodalite contains 6.8 wt% Cl.

POC-16

The sample POC-16 consists mainly of olivine, low-Ca pyroxene, and clinopyroxene, with minor amounts of nepheline. Olivine is generally forsterite: X_{Mg} being 0.94 to 1.00. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.64 to 0.90 (ST1). Low-Ca pyroxene contains 1.2–1.6 wt% Al_2O_3, 0.5–1.9 wt% CaO, and 0.4–0.5 wt% Cr_2O_3; X_{Mg} ranges from 0.97 to 0.99. Clinopyroxene has a diopsidic composition with X_{Mg} = 0.96-0.99; it contains 1.6–3.4 wt% Al_2O_3, 0.5–1.5 wt% TiO_2, and 0.6–1.0 wt% Cr_2O_3. Nepheline contains 1.8–2.0 wt% K_2O. Sodalite contains 6.8 wt% Cl.

POC-17

The sample POC-17 consists mainly of olivine, low-Ca pyroxene, and plagioclase. Olivine is forsterite-rich (magnesian); X_{Mg} = 0.95. Low-Ca pyroxene contains 1.2–1.9 wt% Al_2O_3, 1.0–2.0 wt% CaO, and 0.5–0.6 wt% Cr_2O_3; X_{Mg} ranges from 0.97 to 0.99. Plagioclase contains 91.5–94.8 mol.% anorthite component.

POC-18

The sample POC-18 consists mainly of olivine and Al-rich clinopyroxene, with minor amounts of mesostasis. Olivine shows chemical zoning in X_{Mg} ranging from 0.66 to 0.96 (ST1); the X_{Mg} value decrease towards the rim. This chondrule is further mantled by Fe-rich olivine (SF2). Al-rich clinopyroxene is characterized by high Al content (3.0–5.9 wt% Al_2O_3); X_{Mg} ranges from 0.38 to 0.98. It contains significant Ti (0.0–0.9 wt% TiO_2), Cr (0.00–0.19 wt% Cr_2O_3), and Na (0.07–0.19 wt% Na_2O). Mesostasis is characterized by high Al content (4.2–18.6 wt% Al_2O_3) and high Ca content (0.7–17.3 wt% CaO). It contains significant Ti (0.1–0.8 wt% TiO_2), Cr (0.0–0.8 wt% Cr_2O_3), and Na (0.0–0.5 wt% Na_2O).

POC-19

The sample POC-19 consists mainly of olivine, Al-rich clinopyroxene, and plagioclase, with minor amounts of mesostasis. Olivine is generally forsterite: X_{Mg} being 0.96 to 0.98. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.89 to 0.94 (ST1). Al-rich clinopyroxene is characterized by high Al content (7.5–8.5 wt% Al_2O_3); X_{Mg} ranges from 0.96 to 0.99. It contains significant Ti (0.8–1.1 wt% TiO_2), Cr (0.9–1.1 wt% Cr_2O_3), and Na (0.02–0.18 wt% Na_2O). Plagioclase has 79.3 mol.% anorthite component. Mesostasis is characterized by high Al content (4.4–24.6 wt% Al_2O_3) and high Ca content (9.4–15.1 wt% CaO). It contains significant Ti (0.3–0.8 wt% TiO_2), Cr (0.0–1.1 wt% Cr_2O_3), and Na (0.2–1.2 wt% Na_2O).

Unclassified chondrule (UC)

UC-01

The sample UC-01 consists mainly of olivine, low-Ca pyroxene, Al-rich clinopyroxene, and plagioclase with minor amounts of nepheline and sodalite (Figure SD5). Olivine is generally forsterite: X_{Mg} = 0.75. However, olivine occurring in the rim part of chondrule is rich in Fe content: X_{Mg} being 0.58 to 0.62

(ST1). Low-Ca pyroxene contains 2.3–5.3 wt% Al_2O_3, 1.4–2.3 wt% CaO, and 0.6–1.1 wt% Cr_2O_3; X_{Mg} = 0.99. Al-rich clinopyroxene is characterized by high Al content (1.6–5.5 wt% Al_2O_3); X_{Mg} ranges from 0.96 to 0.98. It contains significant Ti (0.9–6.6 wt% TiO_2), Cr (0.8–2.3 wt% Cr_2O_3), and Na (0.03–0.14 wt% Na_2O) contents. Plagioclase contains 77.8–93.1 mol.% anorthite component. Nepheline contains 1.6–2.0 wt% K_2O. Sodalite contains up to 4.7 wt% Cl.

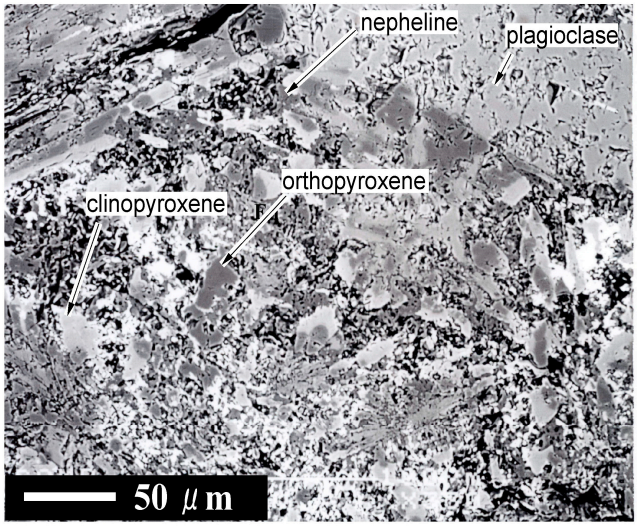


Figure SD5 An enlarged image (back-scattered electron images) showing the occurrence of nepheline UC-01.

UC-02

The sample UC-02 consists mainly of olivine, clinopyroxene, and plagioclase, with minor amounts of nepheline. Olivine is Fe-rich; X_{Mg} = 0.69. Clinopyroxene contains Al (2.4–4.0 wt% Al_2O_3), Ca (4.8–18.5 wt% CaO), Ti (0.4–1.7 wt% TiO_2), Cr (0.4-0.7 wt% Cr_2O_3), and Na (0.0–0.4 wt% Na_2O) contents; X_{Mg} ranges from 0.93 to 0.99. Plagioclase contains 96.8–97.1 mol.% anorthite component. Nepheline contains 1.4–1.9 wt% K_2O.

UC-03

The sample UC-03 consists mainly of olivine, Al-rich clinopyroxene, and plagioclase. Olivine is forsterite-rich (magnesian); X_{Mg} = 0.99. Al-rich clinopyroxene is characterized by high Al content (2.1–8.6 wt% Al_2O_3); X_{Mg} ranges from 0.94 to 0.99. It contains significant Ti (1.3–4.1 wt% TiO_2), Cr (0.5-1.0 wt% Cr_2O_3), and Na (0.00–0.15 wt% Na_2O) contents. Plagioclase contains 92.0–92.9 mol.% anorthite component.

Olivine fragment (OF)

OF-01

The sample OF-01 consists mainly of olivine and Al-rich phases. Olivine shows distinct chemical zoning in X_{Mg}; forsterite-rich (magnesian) cores (X_{Mg} = 0.90–1.00) are rimmed by Fe-rich olivine (X_{Mg} = 0.58–0.62). Al-rich phases are characterized by high Al content (23.7–29.0 wt% Al_2O_3). It contains significant Mg (0.9–22.8 wt% MgO), Ca (2.5–14.8 wt% CaO), Ti (0.2–0.8 wt% TiO_2), Cr (0.2–0.3 wt% Cr_2O_3), and Na (0.0–0.8 wt% Na_2O) contents.

OF-02

The sample OF-02 consists mainly of olivine and Mg-Al spinel. Olivine shows distinct chemical zoning in X_{Mg}; forsterite-rich (magnesian) cores (X_{Mg} = 0.97–1.00) are rimmed by Fe-rich olivine (X_{Mg} = 0.59–0.75). Mg-Al spinel contains 0.63 wt% Cr_2O_3; X_{Mg} = 0.93.

CAIs

CAI-01

The sample CAI-01 consists mainly of Fe-rich clinopyroxene with minor amounts of nepheline. Fe-rich clinopyroxene is characterized by high Fe content (12.4 wt% FeO) and Al content (2.0 wt% Al_2O_3) with X_{Mg} = 0.60. Nepheline contains 1.8 wt% K_2O.

CAI-02

The sample CAI-02 consists mainly of Al-rich clinopyroxene, gehlenite, Mg-Al spinel, and plagioclase, with minor amounts of Fe-rich clinopyroxene. Al-rich clinopyroxene is characterized by high Al content (5.9 wt% Al_2O_3) with X_{Mg} = 0.46. Fe-rich clinopyroxene is characterized by high Fe content (20.8–26.6 wt% FeO) with X_{Mg} = 0.02–0.25. Gehlenite contains 1.9–3.4 wt% MgO. Mg-Al spinel contains 0.09–0.32 wt% Cr_2O_3; X_{Mg} ranges from 0.82 to 1.00. Plagioclase is nearly end-member anorthite.

Mineral Chemistry

Olivine

Olivine of all chondrules and olivine fragments shows distinct chemical zoning in X_{Mg}; forsterite-rich (magnesian) cores (X_{Mg} = 0.51-1.00) are rimmed by Fe-rich olivine (X_{Mg} = 0.49–0.98). The olivine core is also rarely formed by Fe-rich olivine. Figure SD6 is a histogram of X_{Mg} of olivine. Olivine in chondrule core is characterized by minor elements up to 3.0 wt% CaO, 4.5 wt% Al_2O_3, 0.4 wt% MnO, and 1.0 wt% Cr_2O_3 (Figure SD7). Olivine in chondrule rim is characterized by minor elements up to 1.8 wt% CaO, 5.9 wt% Al_2O_3, 0.4 wt% MnO, and 1.7 wt% Cr_2O_3 (Figure SD8).

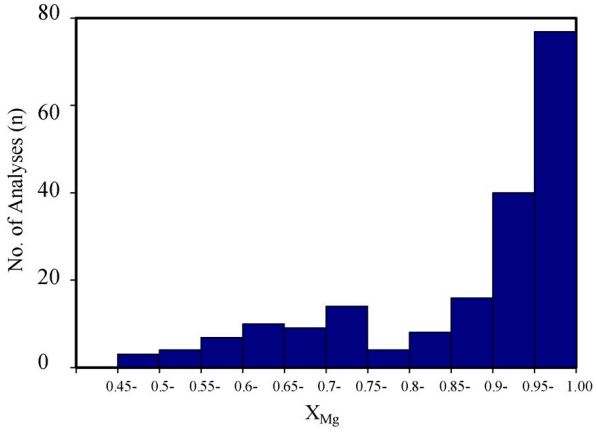


Figure SD6 Histogram of X_{Mg} of olivine

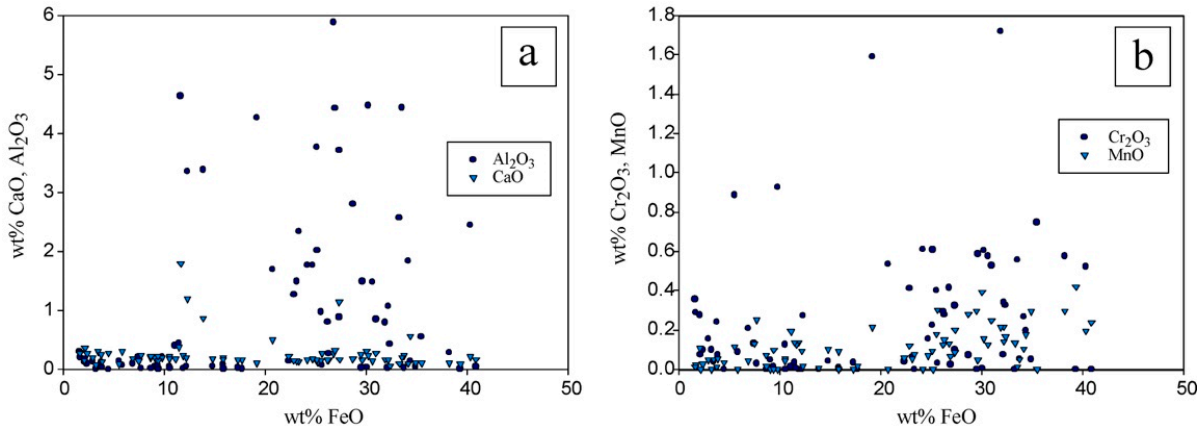


Figure SD7 Minor element variation plots for olivine in chondrule core

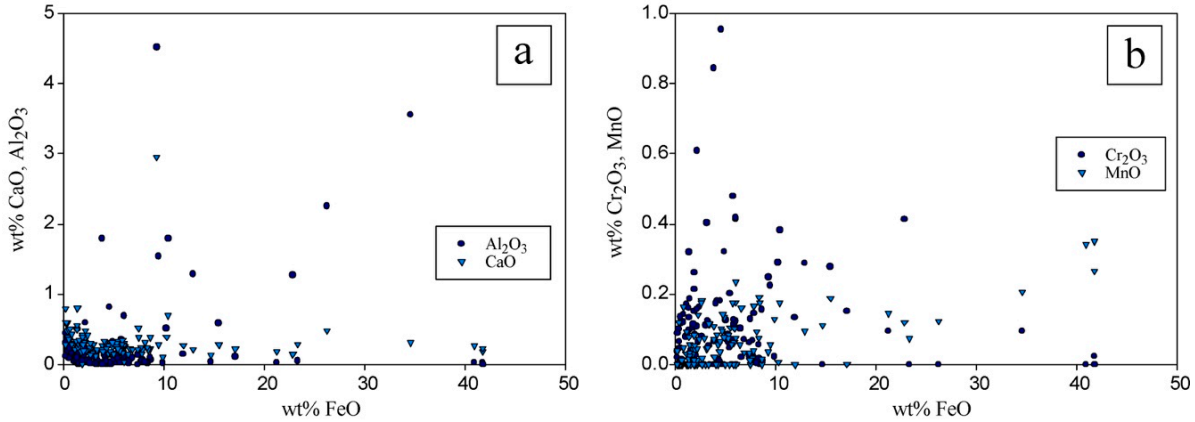


Figure SD8 Minor element variation plots for olivine in chondrule rim

Pyroxene

Figure SD9 shows chemical compositions of low-Ca pyroxene and clinopyroxene plotted on a Wo-En-Fs diagram. Low-Ca pyroxene is characterized by minor element content up to 4.8 wt% CaO, 5.3 wt% Al_2O_3, 0.4 wt% MnO, 1.1 wt% Cr_2O_3, and 1.2 wt% TiO_2 with X_{Mg} = 0.92-1.00 (Figure SD10). Clinopyroxene is characterized by high Ca and Al content up to 25.6 wt% CaO, 14.8 wt% Al_2O_3, and minor element content up to 0.7 wt% MnO, 2.3 wt% Cr_2O_3, and 6.6 wt% TiO_2 with X_{Mg} = 0.19-0.99 (Figure SD11).

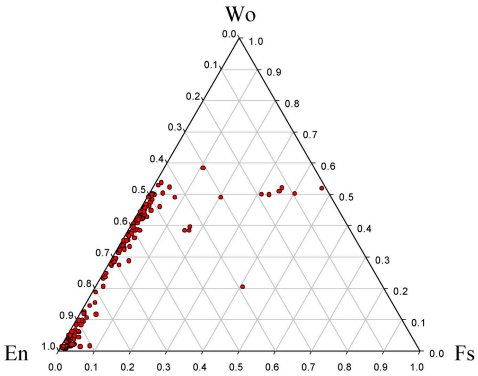


Figure SD9 Chemical compositions of low-Ca pyroxene and clinopyroxene plotted on a Wo–En–Fs diagram (Wo: wollastonite, En: enstatite, Fs: ferrosilite)

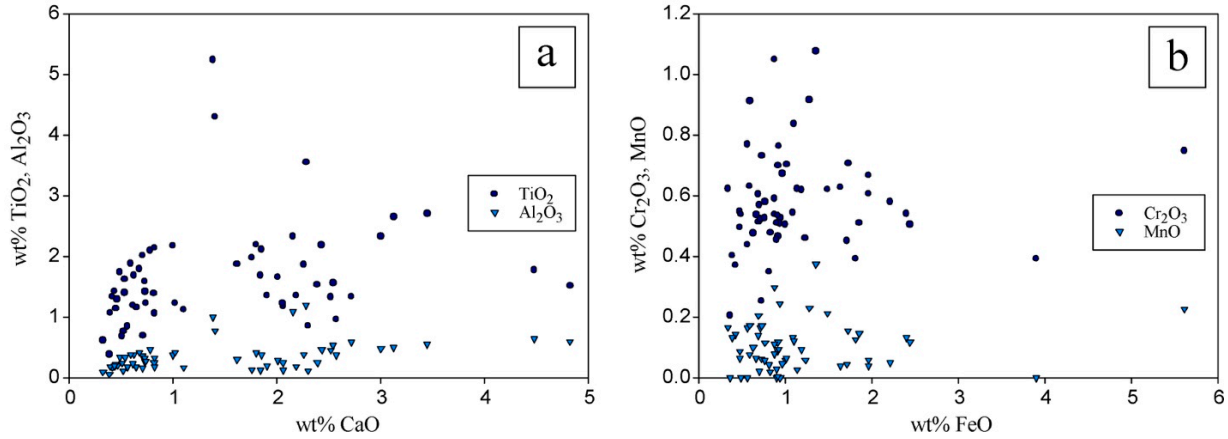


Figure SD10 Minor element variation plots for low-Ca pyroxene

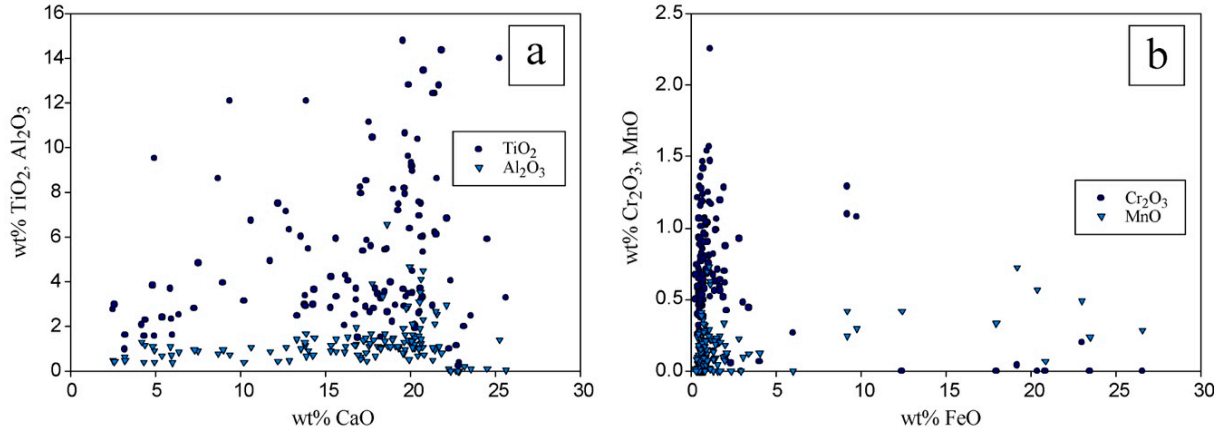


Figure SD11 Minor element variation plots for clinopyroxene

Plagioclase

Figure SD12 shows chemical compositions of plagioclase plotted on an Or–Ab–An diagram. Plagioclase contains 77.8–99.7 mol.% anorthite component. Figure SD13 shows chemical compositions of plagioclase, nepheline, sodalite, and mesostasis plotted on an Al–(Na+K) –Ca diagram.

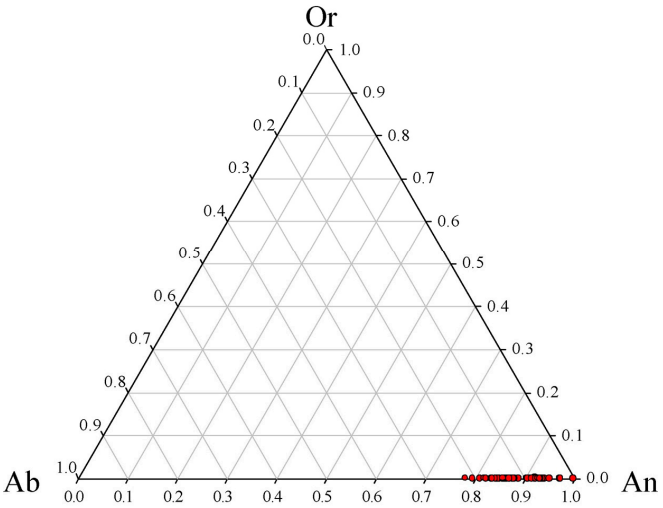


Figure SD12 Chemical compositions of plagioclase plotted on an Or–Ab–An diagram (Or: orthoclase, Ab: albite, An: anorthite)

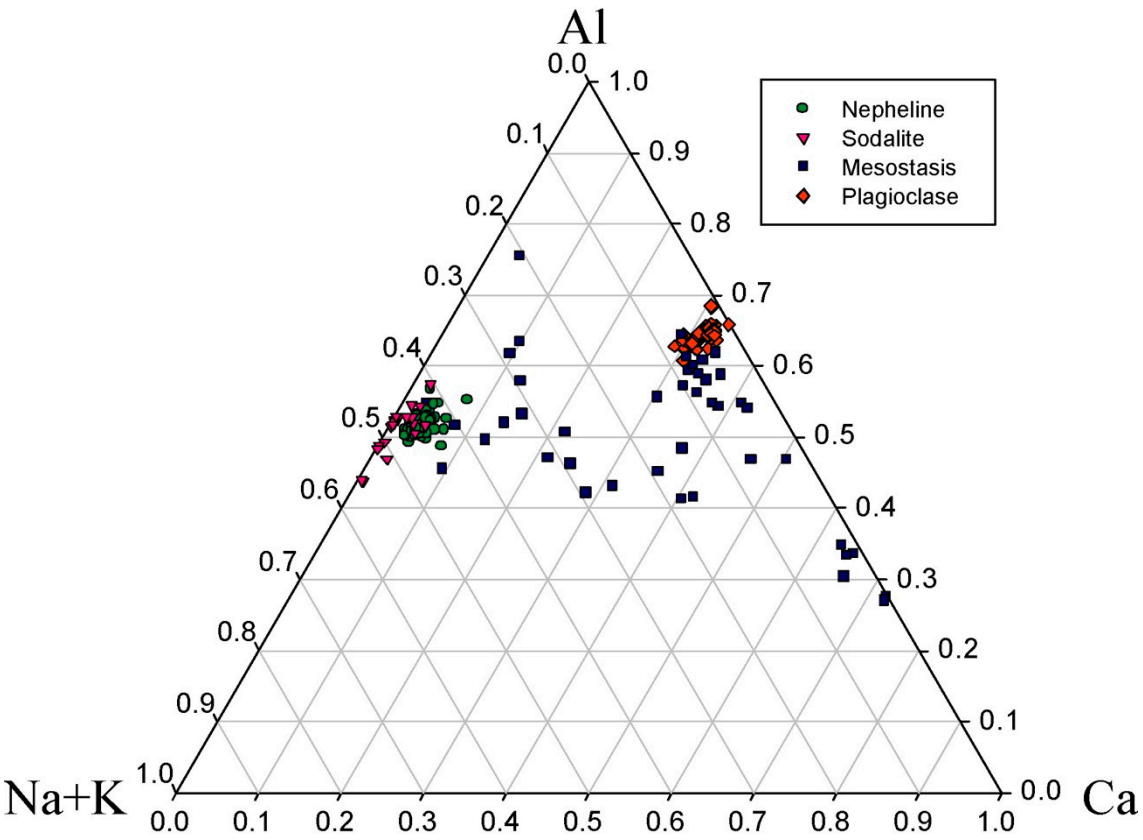
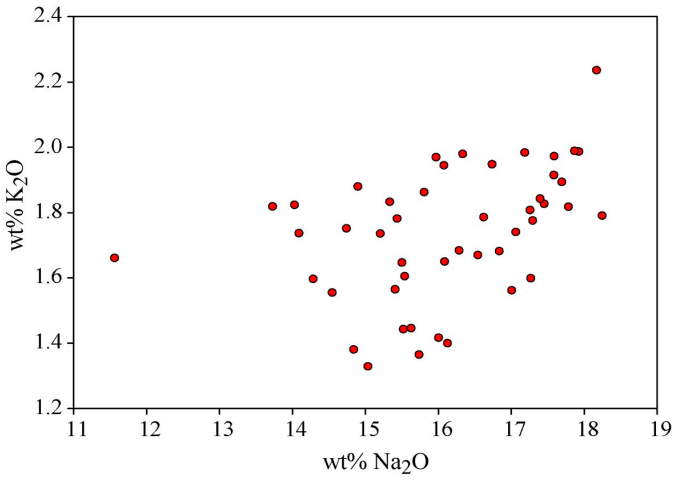


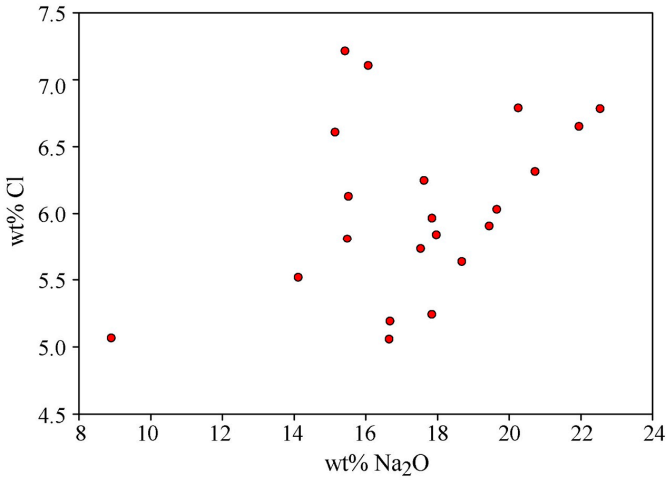
Figure SD13 Chemical compositions of plagioclase, nepheline, sodalite, and mesostasis plotted on an Al–(Na+K)–Ca diagram



Nepheline

Nepheline contains 2.2 wt% K_2O and 1.6–5.1 wt% CaO. It also contains excess Si (1.00–1.11 for 4 oxygens). Figure SD14 is K_2O and Na_2O content plots for nepheline.

Figure SD14 K_2O and Na_2O content plots for nepheline



Sodalite

Sodalite contains up to 7.22 wt% Cl. It contains up to 22.5 wt% Na_2O and 1.5 wt% CaO and K_2O less than 0.3 wt%. Figure SD15 is Cl and Na_2O content plots for sodalite.

Figure SD15 Cl and Na_2O content plots for sodalite

Other minerals

Gehlenite contains 1.9–3.4 wt% MgO. Mg-Al spinel contains 0.0 wt% Cr_2O_3; X_{Mg} ranges from 0.71 to 1.00. EMP and XRD analyses were not successful in identifying clearly the mesostasis due to their sizes (Takeshima et al., 2004). Mesostasis is characterized by high Ca, Al, and Na content up to 28.4 wt% CaO, 30.2 wt% Al_2O_3, 15.3 wt% Na_2O, minor element content up to 0.3 wt% MnO, 1.2 wt% Cr_2O_3, and 1.7 wt% TiO_2 (Figure SD16). Some chondrules include Ni–Fe-rich phases.

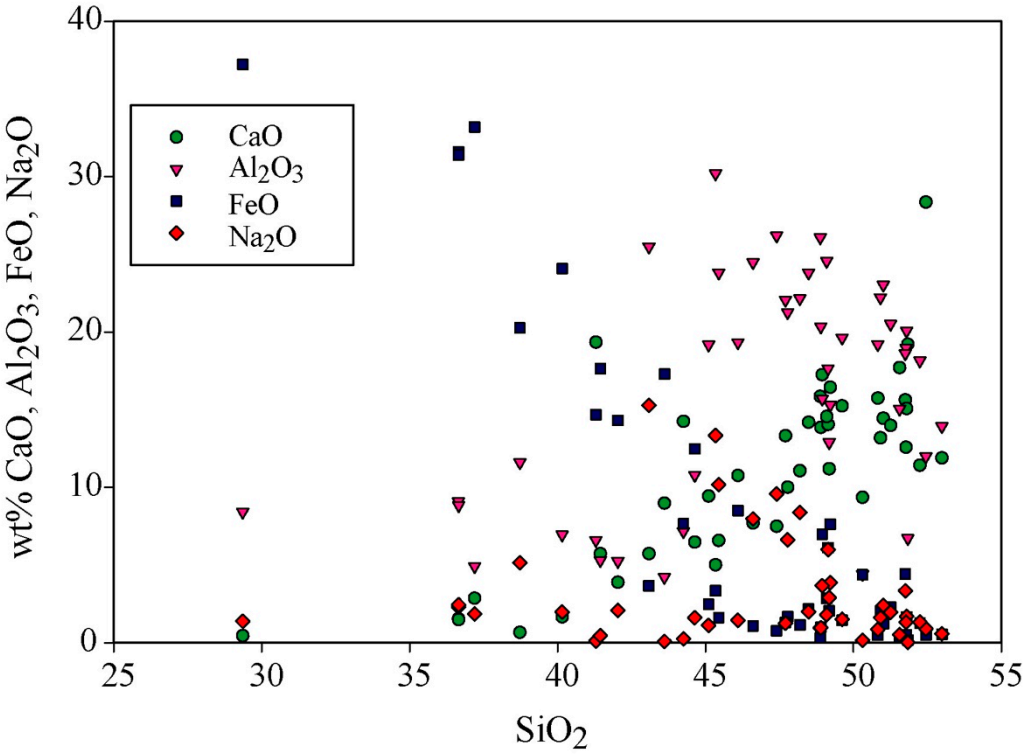


Figure SD16 Minor element variation plots for mesostasis

Takeshima, Y.; Tsujimori, T.; Hyodo, H. Electron-microprobe analyses of Allende chondrules and CAIs: Implication to the argon isotope study of carbonaceous chondrite. Bulletin of Research Institute of Natural Sciences, Okayama University of Science **2004**, no. 30, 51-60.