Electron-microprobe analyses of Allende chondrules and CAIs: Implication to the argon isotope study of carbonaceous chondrite

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Abstract

Chemical compositions of major constituent minerals of Allende chondrules and CAIs were analysed using electron-microprobe. The analysed minerals include olivine, orthopyroxene, Al-rich clinopyroxene, Ca-poor clinopyroxene (pigeonite), Fe-rich clinopyroxene, plagioclase, gehlenite, nepheline, and sodalite; the results were summarized as eight tables with brief descriptions. This electron-microprobe analyses of the carbonaceous chondrite confirmed that the secondary nepheline is major sink of potassium in the Allende chondrule. Nepheline may play a crucial role to incorporate radiogenetic argon in the Allende chondrule. Close association of nepheline and sodalite was also observed.

Introduction

Understanding the formation of carbonaceous chondrite has considerably scientific importance as underscored by the abundance of recent task groups, workshops, conference sessions, and books devoted to the subject. In particular, chondrules in carbonaceous chondrite are the most important primitive component to evaluate the early evolution of the inner solar system (e.g., Kita et al., 2000; Alexander et al., 2001; Itoh and Yurimoto, 2003); they are believed to have formed by rapid cooling of silica melt early in the history of the solar system (Rubin, 2000). Chondrules also provide various information on the mantle process of the terrestrial planet (e.g., Agee et al., 1995; Kavner and Raymond, 1998). Most chondrule studies have focused on the Allende-like subgroup of CV3 chondrites. They are moderately metamorphosed and include various secondary minerals such as Fe-rich olivine, Ca-rich clinopyroxenes, andradite, gehlenite, wollastonite, nepheline, and sodalite (e.g., Fruland et al., 1978; Johnson et al., 1990; Kojima and Tomeoka, 1996; Buchanan et al., 1997, Kort et al., 1995, 1998). The nature of these metamorphic 'alternation' processes is a controversial point in the two different models: nebular (e.g., Johnson et al., 1990; Weisberg et al., 1996; Brenker et al., 2000) and asteroidal (e.g., Kojima and Tomeoka, 1996, Buchanan et al., 1997, Krot et al., 1998). Formation and subsequent 'alternation' processes of chondrule remain a most crucially scientific challenge for Earth and Planetary scientists.

The principal focus of our research on the Allende chondrite is the application of in-situ argon isotope analyses using pulse laser. High abundance of noble gases in the chondrite enables to perform microscale noble gas analyses (e.g., Nakamura et al., 1999; Okazaki et al., 2001). However, through our preliminary petrographic research of the Allende chondrules, we have identified significant chemical heterogeneities of chlorine and potassium that may obstruct accurate argon isotope analyses (Takeshima et al., 2003; Takeshima et al., 2004a, 2004b, 2004c). This report summarizes results of our electron microprobe analyses of Allende chondrules for argon age study. These data will be used to combine with further isotope study; and more detailed isotope study will be described elsewhere.

SAMPLE DESCRIPTION AND ANALYTICAL TECHNIQUE

The Allende chondrite specimen (ME-427H) was obtained from Mineralogical Research Co., San Jose, U.S.A. (http://www.minresco.com/). The culled slice measures about $50 \times 45 \times 5$ mm; the total weight of sample was 28.85 g. The sample contains abundant chondrules and CAIs (Fig. 1). In this study, small fragments (less than 2 mm size) of the Allende chondrules and CAIs were polished for back-scattered electron (BSE) imaging, and quantitative analyses. The investigated samples are divided mainly into three types: (1) barred olivine chondrule (19%), (2) Porphyritic olivine chondrule (55%), and (3) Ca-, Al-rich inclusion (CAI) (5%) (Fig. 2).

Electron microprobe analysis was carried out with a JEOL JXA-8900R at Okayama University of Science. The quantitative analyses were performed at 15kV accelerating voltage, 12 nA beam current and 3 μm beam size. Natural and synthetic silicates and oxides were used for calibration (Tsujimori et al., 1997). The ZAF method (oxide basis) was employed for matrix corrections.

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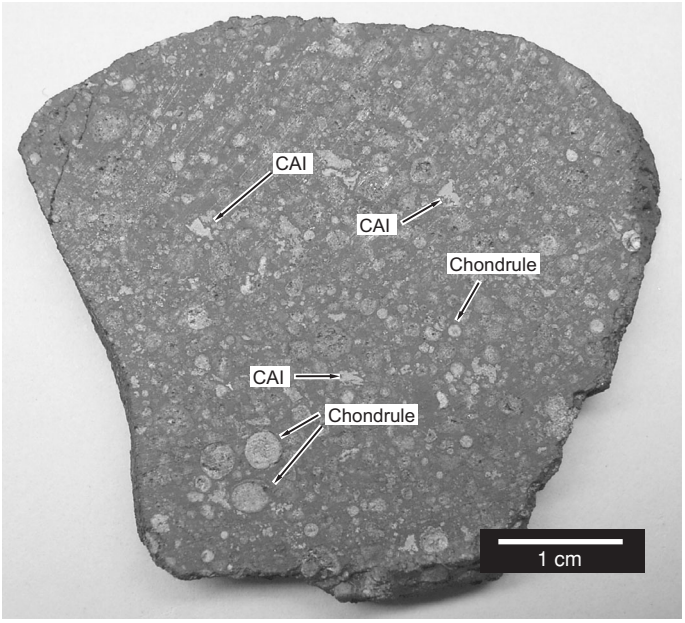

Fig 1: Photograph of the Allende chondrite specimen showing occurrences of chondrule and CAI.

SUMMARY OF MINERAL CHEMISTRY

SThe results of quantitative analysis are listed in Tables 1, 2, 3, 4, 5, 6, 7, and 8.

Table 1. Representative analyses of the analysed Allende chondrule (BOC-01).

Analysis#	7	9	2	4	5	14	11	13	15	24	28	31	33
Mineral	Olivine (core)		Olivine (rim)			Al-rich clinopyroxene				Plagioclase		Nepheline	
SiO_2	41.97	41.97	40.88	41.09	41.50	53.07	52.06	53.16	52.81	47.65	47.73	45.00	45.69
TiO_2	0.09	0.05	0.01	0.03	0.10	1.69	1.47	2.10	1.65	0.11	0.13	0.09	0.04
Al_2O_3	0.06	0.04	0.10	0.00	0.14	5.59	8.14	3.50	4.48	30.66	31.07	32.86	31.83
Cr_2O_3	0.09	0.00	0.21	0.00	0.16	0.55	0.39	0.46	0.50	0.00	0.00	0.08	0.08
FeO *	1.95	1.43	6.89	4.46	2.93	0.47	0.71	0.45	0.46	0.60	0.58	0.14	0.31
MnO	0.04	0.06	0.04	0.04	0.05	0.09	0.03	0.07	0.07	0.00	0.00	0.00	0.06
MgO	55.83	56.47	52.01	53.76	55.11	20.72	18.54	20.76	20.34	0.93	0.89	0.77	0.78
CaO	0.30	0.27	0.19	0.28	0.20	17.69	19.01	20.14	20.14	17.10	17.49	3.16	2.74
Na_2O	0.00	0.00	0.00	0.02	0.00	0.12	0.14	0.08	0.13	1.76	1.75	15.41	16.54
K_2O	0.01	0.02	0.01	0.00	0.02	0.00	0.00	0.01	0.00	0.00	0.01	1.57	1.67
NiO	0.02	0.00	0.00	0.07	0.00	-	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	100.35	100.31	100.35	99.74	100.19	99.99	100.49	100.74	100.58	98.81	99.64	99.07	99.73
O=	4	4	4	4	4	6	6	6	6	8	8	6	6
Si	0.990	0.989	0.987	0.987	0.986	1.877	1.838	1.884	1.874	2.222	2.209	1.065	1.079
Ti	0.002	0.001	0.000	0.001	0.002	0.045	0.039	0.056	0.044	0.004	0.004	0.002	0.001
Al	0.002	0.001	0.003	0.000	0.004	0.233	0.339	0.146	0.187	1.685	1.695	0.917	0.886
Cr	0.002	0.000	0.004	0.000	0.003	0.015	0.011	0.013	0.014	0.000	0.000	0.002	0.002
Fe	0.038	0.028	0.139	0.090	0.058	0.014	0.021	0.013	0.014	0.023	0.023	0.003	0.006
Mn	0.001	0.001	0.001	0.001	0.001	0.003	0.001	0.002	0.002	0.000	0.000	0.000	0.001
Mg	1.964	1.983	1.871	1.925	1.951	1.092	0.976	1.097	1.076	0.064	0.061	0.027	0.027
Ca	0.008	0.007	0.005	0.007	0.005	0.670	0.719	0.765	0.766	0.854	0.867	0.080	0.069
Na	0.000	0.000	0.000	0.001	0.000	0.009	0.010	0.006	0.009	0.159	0.157	0.707	0.758
K	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.000	0.000	0.001	0.047	0.050
Ni	0.000	0.000	0.000	0.001	0.000	-	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	3.006	3.010	3.010	3.013	3.010	3.958	3.953	3.983	3.985	5.012	5.017	2.850	2.879

FeO*= total Fe as FeO.

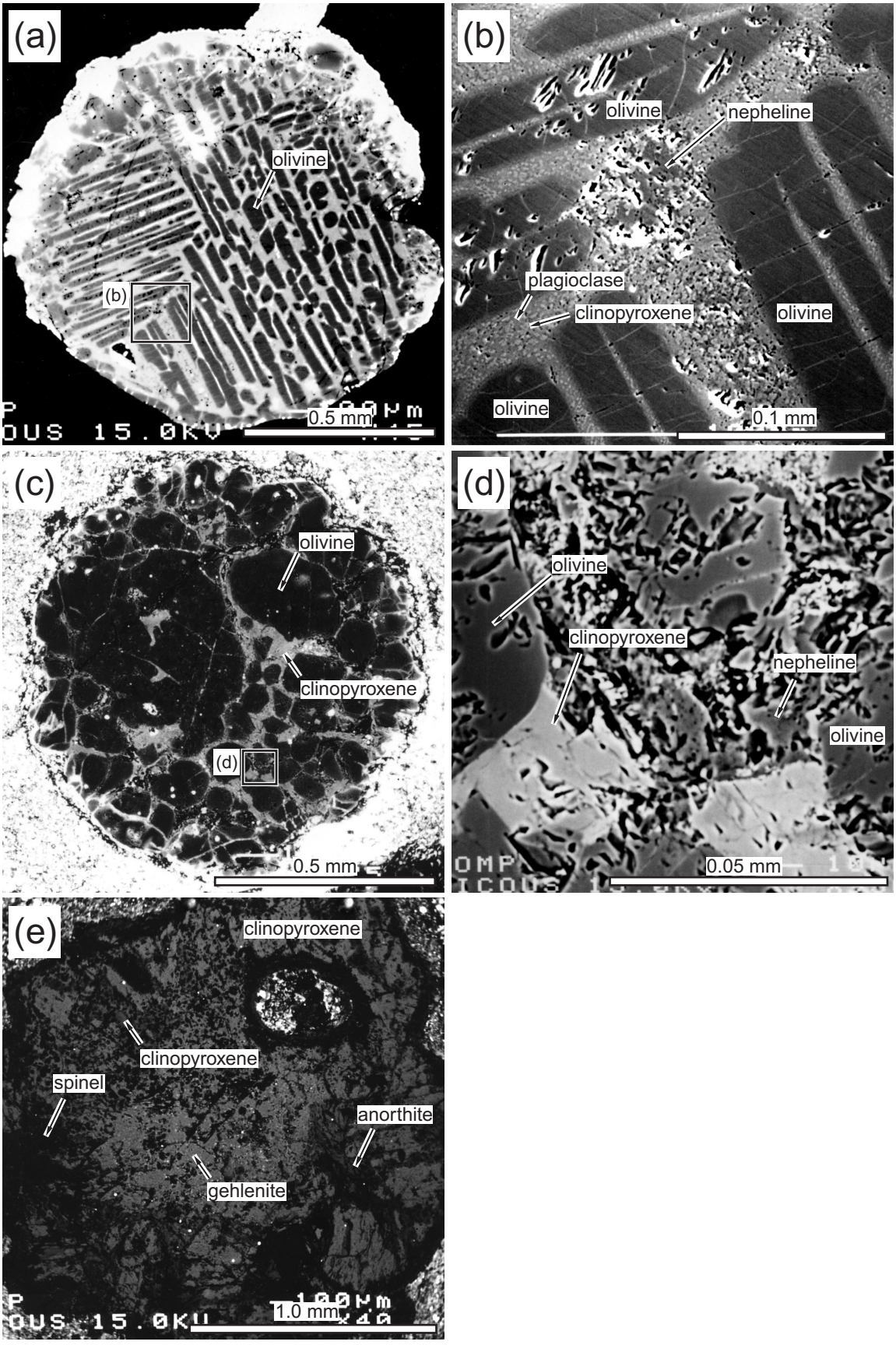

Fig 2: Back-scattered electron images showing microtexture of analysed chondorules of typical types. (2**a**) Barred olivine chondrule (sample BOC-01) (2**b**) Enlarged image in 2**a** showing occurrence of nepheline. (2**c**) Porphyritic olivine chondrule (sample POC-02). (2**d**) Enlarged view in 2**c** showing occurrence of nepheline. (2**e**) CAI (sample CAI-01).

Table 2. Representative analyses of the analysed Allende chondrule (BOC-02).

Analysis#	1	3	4	5	6	7	10	11	9	13	16	21	22	24	19	39
Mineral	Olivine (core)								Olivine (rim)			Ca-poor clinopyroxene			Fe-rich Cpx	Plagioclase
SiO_2	42.08	41.03	43.03	42.88	42.15	41.79	42.37	42.79	40.04	41.46	40.10	54.39	54.48	55.16	49.86	45.99
TiO_2	0.12	0.06	0.02	0.06	0.03	0.04	0.01	0.10	0.06	0.00	0.02	0.46	1.06	1.07	0.02	0.08
Al_2O_3	0.06	0.81	0.05	0.02	0.01	0.03	0.03	0.12	0.21	0.02	1.54	7.51	7.14	6.74	1.13	32.85
Cr_2O_3	0.00	0.95	0.06	0.04	0.10	0.07	0.00	0.28	0.93	0.00	0.23	0.61	0.50	0.61	0.00	0.00
FeO *	5.86	4.60	1.89	1.06	3.22	3.86	3.87	2.05	9.79	8.63	9.47	0.65	0.61	0.59	20.38	0.16
MnO	0.00	0.10	0.04	0.11	0.00	0.05	0.06	0.11	0.00	0.07	0.06	0.00	0.03	0.00	0.57	0.00
MgO	52.32	51.17	55.31	54.38	54.25	53.37	54.35	54.75	47.93	49.96	47.40	23.01	23.17	25.20	4.30	0.69
CaO	0.21	0.29	0.27	0.26	0.07	0.14	0.13	0.15	0.20	0.19	0.29	12.21	12.67	10.62	22.71	18.21
Na_2O	0.00	0.10	0.00	0.00	0.01	0.04	0.01	0.03	0.01	0.02	0.10	0.29	0.32	0.22	0.16	1.08
K_2O	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02	0.00	0.01	0.03	0.01	0.03
NiO	0.00	0.00	0.07	0.03	0.04	0.04	0.00	0.03	0.09	0.08	0.05	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	100.65	99.16	100.73	98.85	99.87	99.43	100.83	100.40	99.27	100.43	99.26	99.13	99.99	100.23	99.13	99.09
O=	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Si	1.004	0.992	1.009	1.019	1.003	1.002	1.001	1.007	0.991	1.005	0.988	1.901	1.892	1.900	1.992	2.140
Ti	0.002	0.001	0.000	0.001	0.000	0.001	0.000	0.002	0.001	0.000	0.000	0.012	0.028	0.028	0.001	0.003
Al	0.002	0.023	0.001	0.001	0.000	0.001	0.001	0.003	0.006	0.001	0.045	0.309	0.292	0.273	0.053	1.802
Cr	0.000	0.018	0.001	0.001	0.002	0.001	0.000	0.005	0.018	0.000	0.004	0.017	0.014	0.017	0.000	0.000
Fe	0.117	0.093	0.037	0.021	0.064	0.077	0.076	0.040	0.203	0.175	0.195	0.019	0.018	0.017	0.681	0.006
Mn	0.000	0.002	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.001	0.001	0.000	0.001	0.000	0.019	0.000
Mg	1.862	1.845	1.932	1.927	1.924	1.908	1.915	1.921	1.769	1.805	1.742	1.199	1.200	1.294	0.256	0.048
Ca	0.005	0.007	0.007	0.006	0.002	0.003	0.003	0.004	0.005	0.005	0.008	0.457	0.471	0.392	0.972	0.908
Na	0.000	0.005	0.000	0.000	0.001	0.002	0.000	0.001	0.001	0.001	0.005	0.020	0.022	0.014	0.012	0.097
K	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.000	0.001	0.001	0.002
Ni	0.000	0.000	0.001	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.001	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	2.992	2.988	2.990	2.979	2.996	2.997	2.998	2.987	2.996	2.994	2.989	3.933	3.937	3.936	3.986	5.006

FeO*= total Fe as FeO.

Table 3. Representative analyses of the analysed Allende chondrule (POC-01).

Analysis#	1	3	4	9	10	18	19	22	23	24	25	20	21	27	26
Mineral	Olivine (core)			Olivine (rim)		Orthopyroxene						Al-rich clinopyroxene			Fe-rich Cpx
SiO_2	40.59	41.85	41.66	35.08	37.78	58.95	58.04	57.57	57.45	57.50	58.31	52.87	52.70	52.77	49.31
TiO_2	0.01	0.06	0.02	0.08	0.14	0.13	0.19	0.50	0.55	0.48	0.38	1.11	1.33	1.09	0.08
Al_2O_3	0.15	0.10	0.03	2.80	1.27	1.69	1.36	2.65	2.71	2.33	1.86	4.28	5.43	3.98	1.00
Cr_2O_3	0.13	0.07	0.06	0.07	0.41	0.61	0.77	0.51	0.70	0.62	0.70	0.70	0.67	0.59	0.04
FeO *	11.93	6.87	8.30	28.68	22.85	0.69	0.92	1.86	1.02	1.18	0.92	1.97	1.30	1.69	19.18
MnO	0.00	0.03	0.08	0.28	0.12	0.14	0.09	0.15	0.07	0.09	0.12	0.08	0.08	0.25	0.73
MgO	46.68	51.45	50.13	31.65	37.86	36.63	36.05	34.37	34.83	35.02	36.06	22.26	20.63	20.54	5.40
CaO	0.28	0.21	0.25	0.18	0.15	1.85	2.19	3.13	3.45	3.00	2.26	16.18	18.52	18.84	22.27
Na_2O	0.00	0.00	0.00	0.04	0.04	0.00	0.03	0.04	0.06	0.04	0.03	0.13	0.02	0.04	0.14
K_2O	0.00	0.00	0.00	0.00	0.02	0.00	0.02	0.01	0.00	0.00	0.00	0.00	0.01	0.02	0.00
NiO	0.04	0.09	0.03	0.26	0.00	-	-	-	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	99.81	100.74	100.53	99.11	100.64	100.67	99.66	100.78	100.84	100.27	100.63	99.57	100.70	99.80	98.14
O=	4	4	4	4	4	4	4	4	4	4	4	6	6	6	6
Si	1.005	1.003	1.007	0.954	0.979	1.975	1.971	1.946	1.937	1.947	1.961	1.884	1.862	1.891	1.979
Ti	0.000	0.001	0.000	0.002	0.003	0.003	0.005	0.013	0.014	0.012	0.010	0.030	0.035	0.029	0.002
Al	0.004	0.003	0.001	0.090	0.039	0.067	0.054	0.106	0.108	0.093	0.074	0.180	0.226	0.168	0.047
Cr	0.003	0.001	0.001	0.002	0.008	0.016	0.021	0.014	0.019	0.017	0.019	0.020	0.019	0.017	0.001
Fe	0.247	0.138	0.168	0.652	0.495	0.019	0.026	0.052	0.029	0.034	0.026	0.059	0.038	0.051	0.644
Mn	0.000	0.001	0.002	0.006	0.003	0.004	0.003	0.004	0.002	0.003	0.003	0.002	0.002	0.007	0.025
Mg	1.723	1.839	1.806	1.282	1.462	1.830	1.825	1.732	1.751	1.768	1.808	1.182	1.087	1.097	0.323
Ca	0.007	0.005	0.006	0.005	0.004	0.066	0.080	0.113	0.125	0.109	0.081	0.617	0.701	0.723	0.958
Na	0.000	0.000	0.000	0.002	0.002	0.000	0.002	0.002	0.004	0.002	0.002	0.009	0.002	0.003	0.011
K	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.000	0.000	0.000	0.000	0.000	0.001	0.000
Ni	0.001	0.002	0.001	0.006	0.000	-	-	-	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	2.991	2.993	2.992	3.000	2.996	3.980	3.987	3.983	3.987	3.985	3.984	3.982	3.973	3.987	3.990

FeO*= total Fe as FeO.

Table 3. Representative analyses of the analysed Allende chondrule (POC-01). (Continued)

Analysis#	30	33	35	37	39	40	44	47	49	50	43
Mineral	Plagioclase				Nepheline						Sodalite
SiO_2	45.93	46.85	46.91	47.10	44.20	42.95	44.19	43.84	44.44	43.14	39.38
TiO_2	0.00	0.02	0.00	0.03	0.04	0.02	0.03	0.03	0.00	0.01	0.00
Al_2O_3	34.38	32.39	32.74	32.74	33.70	35.24	33.96	33.80	33.98	34.90	29.35
Cr_2O_3	0.02	0.02	0.00	0.00	0.03	0.00	0.00	0.00	0.00	0.07	0.03
FeO *	0.12	0.77	0.46	0.49	0.61	0.21	0.51	0.21	0.44	0.33	0.77
MnO	0.02	0.00	0.00	0.08	0.03	0.04	0.02	0.00	0.00	0.00	0.00
MgO	0.52	0.34	0.32	0.47	0.43	0.02	0.26	0.32	0.18	0.04	0.37
CaO	18.09	16.97	17.22	17.23	1.85	1.72	1.88	2.54	2.10	2.07	0.62
Na_2O	0.95	1.88	1.35	1.45	17.45	18.17	18.25	17.87	17.06	17.59	22.54
K_2O	0.00	0.00	0.01	0.01	1.83	2.24	1.79	1.99	1.74	1.97	0.05
NiO	-	-	-	-	-	-	-	-	-	-	0.00
Cl	-	-	-	-	-	-	-	-	-	-	6.79
Total	100.04	99.23	99.00	99.61	100.16	100.60	100.88	100.59	99.94	100.12	99.90
O=	8	8	8	8	4	4	4	4	4	4	12
Si	2.113	2.176	2.177	2.175	1.044	1.014	1.039	1.035	1.049	1.021	2.848
Ti	0.000	0.001	0.000	0.001	0.001	0.000	0.001	0.001	0.000	0.000	0.000
Al	1.864	1.773	1.790	1.782	0.938	0.981	0.941	0.940	0.945	0.974	2.502
Cr	0.001	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.001	0.002
Fe	0.005	0.030	0.018	0.019	0.012	0.004	0.010	0.004	0.009	0.007	0.046
Mn	0.001	0.000	0.000	0.003	0.001	0.001	0.000	0.000	0.000	0.000	0.000
Mg	0.036	0.023	0.022	0.032	0.015	0.001	0.009	0.011	0.006	0.002	0.040
Ca	0.892	0.844	0.856	0.853	0.047	0.044	0.047	0.064	0.053	0.052	0.048
Na	0.084	0.169	0.121	0.130	0.799	0.832	0.832	0.818	0.781	0.807	3.160
K	0.000	0.000	0.000	0.001	0.055	0.067	0.054	0.060	0.052	0.060	0.005
Ni	-	-	-	-	-	-	-	-	-	-	0.000
Cl	-	-	-	-	-	-	-	-	-	-	0.832
Total	4.996	5.017	4.985	4.997	2.912	2.944	2.932	2.933	2.895	2.924	9.483

FeO*= total Fe as FeO.

Table 4. Representative analyses of the analysed Allende chondrule (POC-02).

Analysis#	1	2	3	6	10	11	12	13	15	4	24	22	30	34	43	47	48
Mineral	Orthopyroxene									Fe-rich Cpx	Fe-rich Cpx	Al-rich clinopyroxene					
SiO_2	41.64	41.94	42.79	41.75	41.11	42.59	41.59	41.54	42.38	36.54	58.82	47.26	47.84	49.88	48.00	47.49	53.06
TiO_2	0.00	0.13	0.02	0.08	0.04	0.06	0.02	0.06	0.04	0.17	0.21	0.82	1.08	1.04	0.74	0.80	0.48
Al_2O_3	0.06	0.35	0.02	0.06	0.16	0.14	0.07	0.10	0.04	1.48	1.14	14.36	12.79	8.97	13.45	14.78	6.32
Cr_2O_3	0.02	0.14	0.00	0.02	0.13	0.18	0.01	0.16	0.11	0.58	0.53	1.19	1.02	0.95	1.21	1.07	1.06
FeO *	7.80	0.50	1.52	6.61	7.50	4.48	8.66	8.61	2.14	30.60	0.76	0.64	0.86	0.88	0.36	0.82	0.71
MnO	0.04	0.00	0.00	0.16	0.00	0.07	0.00	0.02	0.01	0.13	0.06	0.20	0.10	0.04	0.24	0.32	0.28
MgO	50.11	55.64	55.37	51.16	50.21	52.96	49.92	48.99	54.39	31.09	37.69	13.65	12.95	17.29	15.30	13.73	24.45
CaO	0.16	0.36	0.34	0.23	0.39	0.28	0.22	0.39	0.32	0.14	0.45	21.84	21.68	20.11	20.79	19.57	12.87
Na_2O	0.00	0.02	0.00	0.00	0.00	0.07	0.03	0.00	0.00	0.09	0.00	0.19	1.03	0.31	0.07	1.29	0.17
K_2O	0.02	0.01	0.00	0.01	0.00	0.02	0.01	0.00	0.00	0.02	0.00	0.01	0.09	0.00	0.02	0.10	0.03
NiO	0.03	0.00	0.00	0.02	0.02	0.04	0.12	0.04	0.00	0.00	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	99.88	99.09	100.06	100.10	99.56	100.88	100.65	99.89	99.43	100.83	99.66	100.16	99.42	99.46	100.17	99.96	99.42
O=	4	4	4	4	4	4	4	4	4	4	6	6	6	6	6	6	6
Si	1.010	0.995	1.008	1.006	1.001	1.009	1.006	1.012	1.007	0.981	1.983	1.696	1.734	1.795	1.714	1.703	1.867
Ti	0.000	0.002	0.000	0.001	0.001	0.001	0.000	0.001	0.001	0.003	0.005	0.022	0.029	0.028	0.020	0.022	0.013
Al	0.002	0.010	0.000	0.002	0.005	0.004	0.002	0.003	0.001	0.047	0.045	0.607	0.546	0.380	0.566	0.625	0.262
Cr	0.000	0.003	0.000	0.000	0.002	0.003	0.000	0.003	0.002	0.012	0.014	0.034	0.029	0.027	0.034	0.030	0.030
Fe	0.158	0.010	0.030	0.133	0.153	0.089	0.175	0.175	0.043	0.687	0.021	0.019	0.026	0.027	0.011	0.025	0.021
Mn	0.001	0.000	0.000	0.003	0.000	0.001	0.000	0.000	0.000	0.003	0.002	0.006	0.003	0.001	0.007	0.010	0.008
Mg	1.812	1.968	1.944	1.838	1.822	1.870	1.800	1.778	1.927	1.244	1.895	0.730	0.699	0.928	0.814	0.734	1.282
Ca	0.004	0.009	0.009	0.006	0.010	0.007	0.006	0.010	0.008	0.004	0.016	0.840	0.842	0.776	0.795	0.752	0.485
Na	0.000	0.001	0.000	0.000	0.000	0.003	0.001	0.000	0.000	0.005	0.000	0.013	0.072	0.021	0.005	0.089	0.011
K	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001	0.000	0.001	0.004	0.000	0.001	0.005	0.001
Ni	0.001	0.000	0.000	0.000	0.000	0.001	0.002	0.001	0.000	0.000	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	2.989	2.997	2.992	2.991	2.995	2.988	2.993	2.983	2.990	2.988	3.982	3.968	3.985	3.983	3.966	3.993	3.981

FeO*= total Fe as FeO.

Table 4. Representative analyses of the analysed Allende chondrule (POC-02). (Continued)

Analysis#	52	53	65	59	74	76	81
Mineral	Al-rich clinopyroxene				Nepheline		
SiO_2	53.52	48.81	47.77	47.75	45.75	44.72	43.56
TiO_2	0.92	1.64	0.96	1.04	0.19	0.22	0.07
Al_2O_3	5.46	10.64	12.43	12.43	33.78	32.17	35.05
Cr_2O_3	1.23	1.36	1.16	1.29	0.31	0.23	0.30
FeO *	0.69	0.56	0.55	0.48	0.64	0.54	0.42
MnO	0.36	0.16	0.23	0.08	0.00	0.00	0.00
MgO	23.70	17.02	14.98	15.05	0.70	0.85	0.17
CaO	14.00	19.70	21.42	21.33	2.96	3.23	2.44
Na_2O	0.09	0.03	0.07	0.11	14.28	14.74	16.33
K_2O	0.00	0.01	0.02	0.03	1.60	1.75	1.98
NiO	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-
Total	99.98	99.93	99.57	99.57	100.21	98.45	100.33
O=	6	6	6	6	4	4	4
Si	1.879	1.747	1.723	1.720	1.067	1.068	1.026
Ti	0.024	0.044	0.026	0.028	0.003	0.004	0.001
Al	0.226	0.449	0.528	0.528	0.928	0.905	0.972
Cr	0.034	0.038	0.033	0.037	0.006	0.004	0.006
Fe	0.020	0.017	0.017	0.014	0.012	0.011	0.008
Mn	0.011	0.005	0.007	0.002	0.000	0.000	0.000
Mg	1.240	0.908	0.806	0.808	0.024	0.030	0.006
Ca	0.527	0.755	0.828	0.823	0.074	0.083	0.062
Na	0.006	0.002	0.005	0.008	0.646	0.682	0.746
K	0.000	0.000	0.001	0.001	0.048	0.053	0.059
Ni	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-
Total	3.968	3.966	3.973	3.970	2.808	2.841	2.886

FeO*= total Fe as FeO.

Table 5. Representative analyses of the analysed Allende chondrule (POC-03).

Analysis#	1	2	4	3	7	11	12	13	20	30	31	34	35	9	17	32
Mineral	Clinopyroxene			Mineral	Plagioclase									Olivine (rim)		
SiO_2	54.39	54.48	55.16	49.86	42.08	42.08	41.03	43.03	42.88	42.15	41.79	42.37	42.79	40.04	41.46	40.10
TiO_2	0.46	1.06	1.07	0.02	0.12	0.12	0.06	0.02	0.06	0.03	0.04	0.01	0.10	0.06	0.00	0.02
Al_2O_3	7.51	7.14	6.74	1.13	0.06	0.06	0.81	0.05	0.02	0.01	0.03	0.03	0.12	0.21	0.02	1.54
Cr_2O_3	0.61	0.50	0.61	0.00	0.00	0.00	0.95	0.06	0.04	0.10	0.07	0.00	0.28	0.93	0.00	0.23
FeO *	0.65	0.61	0.59	20.38	5.86	5.86	4.60	1.89	1.06	3.22	3.86	3.87	2.05	9.79	8.63	9.47
MnO	0.00	0.03	0.00	0.57	0.00	0.00	0.10	0.04	0.11	0.00	0.05	0.06	0.11	0.00	0.07	0.06
MgO	23.01	23.17	25.20	4.30	52.32	52.32	51.17	55.31	54.38	54.25	53.37	54.35	54.75	47.93	49.96	47.40
CaO	12.21	12.67	10.62	22.71	0.21	0.21	0.29	0.27	0.26	0.07	0.14	0.13	0.15	0.20	0.19	0.29
Na_2O	0.29	0.32	0.22	0.16	0.00	0.00	0.10	0.00	0.00	0.01	0.04	0.01	0.03	0.01	0.02	0.10
K_2O	0.00	0.01	0.03	0.01	0.00	0.00	0.04	0.00	0.00	0.00	0.00	0.01	0.00	0.01	0.00	0.02
NiO	-	-	-	-	0.00	0.00	0.00	0.07	0.03	0.04	0.04	0.00	0.03	0.09	0.08	0.05
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	99.13	99.99	100.23	99.13	100.65	100.65	99.16	100.73	98.85	99.87	99.43	100.83	100.40	99.27	100.43	99.26
O=	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4	4
Si	1.901	1.892	1.900	1.992	1.004	1.004	0.992	1.009	1.019	1.003	1.002	1.001	1.007	0.991	1.005	0.988
Ti	0.012	0.028	0.028	0.001	0.002	0.002	0.001	0.000	0.001	0.000	0.001	0.000	0.002	0.001	0.000	0.000
Al	0.309	0.292	0.273	0.053	0.002	0.002	0.023	0.001	0.001	0.000	0.001	0.001	0.003	0.006	0.001	0.045
Cr	0.017	0.014	0.017	0.000	0.000	0.000	0.018	0.001	0.001	0.002	0.001	0.000	0.005	0.018	0.000	0.004
Fe	0.019	0.018	0.017	0.681	0.117	0.117	0.093	0.037	0.021	0.064	0.077	0.076	0.040	0.203	0.175	0.195
Mn	0.000	0.001	0.000	0.019	0.000	0.000	0.002	0.001	0.002	0.000	0.001	0.001	0.002	0.000	0.001	0.001
Mg	1.199	1.200	1.294	0.256	1.862	1.862	1.845	1.932	1.927	1.924	1.908	1.915	1.921	1.769	1.805	1.742
Ca	0.457	0.471	0.392	0.972	0.005	0.005	0.007	0.007	0.006	0.002	0.003	0.003	0.004	0.005	0.005	0.008
Na	0.020	0.022	0.014	0.012	0.000	0.000	0.005	0.000	0.000	0.001	0.002	0.000	0.001	0.001	0.001	0.005
K	0.000	0.000	0.001	0.001	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.001
Ni	-	-	-	-	0.000	0.000	0.000	0.001	0.000	0.001	0.001	0.000	0.001	0.002	0.002	0.001
Cl	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-	-
Total	3.933	3.937	3.936	3.986	2.992	2.992	2.988	2.990	2.979	2.996	2.997	2.998	2.987	2.996	2.994	2.989

FeO*= total Fe as FeO.

Table 5. Representative analyses of the analysed Allende chondrule (POC-03). (Continued)

Analysis#	44	45	46	47	50	4
Mineral	Al-rich clinopyroxene				Nepheline	Nepheline
SiO_2	46.83	46.45	46.35	46.48	44.10	38.91
TiO_2	0.02	0.01	0.01	0.01	0.00	0.01
Al_2O_3	32.65	33.41	33.46	32.92	33.91	30.64
Cr_2O_3	0.00	0.00	0.00	0.00	0.00	0.00
FeO *	0.67	0.37	0.65	0.79	0.84	0.85
MnO	0.00	0.00	0.00	0.00	0.00	0.00
MgO	0.42	0.45	0.40	0.42	0.33	0.05
CaO	17.59	17.56	18.05	17.93	2.66	1.48
Na_2O	1.65	1.47	1.45	1.41	17.27	20.25
K_2O	0.02	0.00	0.00	0.00	2.05	0.02
NiO	-	-	-	-	-	0.03
Cl	-	-	-	-	-	6.79
Total	99.83	99.71	100.36	99.96	101.15	99.04
O=	8	8	8	8	4	12
Si	2.164	2.145	2.134	2.148	1.035	2.821
Ti	0.001	0.000	0.000	0.000	0.000	0.001
Al	1.778	1.819	1.816	1.793	0.938	2.618
Cr	0.000	0.000	0.000	0.000	0.000	0.000
Fe	0.026	0.014	0.025	0.030	0.016	0.051
Mn	0.000	0.000	0.000	0.000	0.000	0.000
Mg	0.029	0.031	0.027	0.029	0.012	0.005
Ca	0.871	0.869	0.890	0.888	0.067	0.115
Na	0.148	0.131	0.130	0.127	0.786	2.846
K	0.001	0.000	0.000	0.000	0.061	0.002
Ni	-	-	-	-	-	0.002
Cl	-	-	-	-	-	0.834
Total	5.016	5.010	5.022	5.015	2.916	9.294

FeO*= total Fe as FeO.

Table 6. Representative analyses of the analysed Allende chondrule (POC-04).

Analysis#	1	2	5	7	10	12
Mineral	Olivine		Al-rich Cpx	Nepheline		
SiO_2	42.86	39.56	50.56	45.78	46.06	45.55
TiO_2	0.01	0.04	0.97	0.12	0.11	0.12
Al_2O_3	0.08	0.01	7.93	31.20	30.21	30.47
Cr_2O_3	0.12	0.00	0.82	0.00	0.03	0.00
FeO *	1.80	17.71	1.31	0.95	0.97	0.53
MnO	0.01	0.02	0.00	0.00	0.00	0.00
MgO	54.67	41.54	18.72	1.25	2.08	2.06
CaO	0.18	0.16	19.69	3.68	3.16	4.55
Na_2O	0.00	0.01	0.05	16.13	15.63	14.09
K_2O	0.00	0.00	0.00	1.40	1.45	1.74
NiO	0.00	0.00	-	-	-	-
Cl	-	-	-	-	-	-
Total	99.72	99.05	100.04	100.50	99.70	99.10
O=	4	4	6	4	4	4
Si	1.013	1.014	1.808	1.077	1.089	1.083
Ti	0.000	0.001	0.026	0.002	0.002	0.002
Al	0.002	0.000	0.334	0.865	0.842	0.853
Cr	0.002	0.000	0.023	0.000	0.001	0.000
Fe	0.036	0.380	0.039	0.019	0.019	0.011
Mn	0.000	0.000	0.000	0.000	0.000	0.000
Mg	1.927	1.586	0.998	0.044	0.073	0.073
Ca	0.005	0.004	0.755	0.093	0.080	0.116
Na	0.000	0.000	0.003	0.736	0.717	0.649
K	0.000	0.000	0.000	0.042	0.044	0.053
Ni	0.000	0.000	-	-	-	-
Cl	-	-	-	-	-	-
Total	2.984	2.986	3.987	2.877	2.867	2.839

FeO*= total Fe as FeO.

Table 7. Representative analyses of the analysed Allende chondrule (POC-05).

Analysis#	4	2	5	6	12	13	9	10	11	15
Mineral	Olivine (core)	Olivine (rim)			Ortopyroxene		Al-rich clinopyroxene			
SiO_2	41.50	35.87	36.46	37.76	58.29	57.75	49.31	49.70	49.57	50.23
TiO_2	0.04	0.05	0.13	0.04	0.39	0.46	0.68	1.31	1.38	1.33
Al_2O_3	0.15	0.28	3.77	0.89	1.88	2.10	10.37	8.19	9.63	9.33
Cr_2O_3	0.12	0.58	0.23	0.10	0.73	0.92	1.42	1.28	1.47	1.28
FeO *	5.88	38.23	25.12	27.33	0.73	1.28	0.72	1.93	0.69	0.58
MnO	0.06	0.30	0.09	0.09	0.17	0.23	0.33	0.33	0.17	0.27
MgO	51.63	24.94	34.01	31.41	36.72	35.82	16.50	17.90	16.92	16.80
CaO	0.35	0.11	0.16	1.15	0.60	0.78	20.45	19.66	19.89	20.05
Na_2O	0.03	0.04	0.42	0.24	0.00	0.11	0.08	0.01	0.08	0.09
K_2O	0.00	0.02	0.06	0.04	0.00	0.05	0.00	0.00	0.00	0.03
NiO	0.03	0.14	0.00	0.05	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-
Total	99.77	100.57	100.43	99.09	99.51	99.49	99.86	100.32	99.80	99.99
O=	4	4	4	4	6	6	6	6	6	6
Si	1.001	1.006	0.957	1.017	1.970	1.962	1.770	1.785	1.778	1.795
Ti	0.001	0.001	0.003	0.001	0.010	0.012	0.018	0.035	0.037	0.036
Al	0.004	0.009	0.117	0.028	0.075	0.084	0.439	0.347	0.407	0.393
Cr	0.002	0.013	0.005	0.002	0.020	0.025	0.040	0.036	0.042	0.036
Fe	0.119	0.896	0.551	0.615	0.021	0.036	0.022	0.058	0.021	0.017
Mn	0.001	0.007	0.002	0.002	0.005	0.007	0.010	0.010	0.005	0.008
Mg	1.857	1.042	1.330	1.261	1.851	1.814	0.883	0.958	0.905	0.895
Ca	0.009	0.003	0.004	0.033	0.022	0.028	0.786	0.756	0.764	0.768
Na	0.001	0.002	0.021	0.012	0.000	0.007	0.005	0.001	0.006	0.006
K	0.000	0.001	0.002	0.002	0.000	0.002	0.000	0.000	0.000	0.001
Ni	0.001	0.003	0.000	0.001	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-
Total	2.996	2.984	2.992	2.974	3.972	3.976	3.974	3.987	3.964	3.956

FeO*= total Fe as FeO.

Table 8. Representative analyses of the analysed Allende CAI (CAI-01).

Analysis#	1	2	3	5	7	10	11	13	16	12	18
Mineral	Al-rich Cpx	Fe-rich clinopyroxene			Mg-Al spinel			Gehlenite		Plagioclase	Nepheline
SiO_2	50.04	49.10	49.58	50.04	0.05	0.02	0.15	25.06	27.51	42.83	45.42
TiO_2	0.21	0.00	0.10	0.21	0.28	0.22	0.15	0.00	0.04	0.03	0.00
Al_2O_3	1.99	0.25	2.46	1.99	70.64	70.12	67.77	31.11	26.71	35.20	32.97
Cr_2O_3	0.00	0.00	0.00	0.00	0.32	0.09	0.21	0.00	0.02	0.00	0.02
FeO *	12.41	26.56	20.85	12.41	0.06	1.00	8.64	0.29	0.01	0.12	0.91
MnO	0.42	0.29	0.07	0.42	0.00	0.00	0.00	0.00	0.00	0.01	0.00
MgO	10.41	0.37	3.95	10.41	27.81	26.84	21.46	1.94	3.44	0.08	0.38
CaO	23.16	22.83	23.57	23.16	0.18	0.14	0.20	39.61	40.84	19.98	2.61
Na_2O	0.11	0.01	0.04	0.11	0.02	0.00	0.01	0.13	0.00	0.04	16.62
K_2O	0.00	0.00	0.01	0.00	0.00	0.00	0.01	0.00	0.00	0.00	1.79
NiO	-	-	-	-	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-
Total	98.74	99.40	100.63	98.74	99.35	98.43	98.59	98.13	98.57	98.30	100.72
O=	6	6	6	6	4	4	4	24	24	8	4
Si	1.866	2.015	1.953	1.929	0.001	0.001	0.004	3.987	4.366	2.020	1.109
Ti	0.003	0.000	0.003	0.006	0.005	0.004	0.003	0.000	0.005	0.001	0.004
Al	0.250	0.012	0.114	0.090	1.988	1.998	1.997	5.833	4.996	1.957	0.746
Cr	0.002	0.000	0.000	0.000	0.006	0.002	0.004	0.000	0.003	0.000	0.000
Fe	0.071	0.912	0.687	0.400	0.001	0.020	0.181	0.038	0.001	0.005	0.033
Mn	0.000	0.010	0.002	0.014	0.000	0.000	0.000	0.000	0.000	0.000	0.002
Mg	0.863	0.022	0.232	0.598	0.990	0.967	0.800	0.459	0.813	0.006	0.117
Ca	0.946	1.004	0.995	0.957	0.005	0.004	0.005	6.754	6.946	1.010	0.175
Na	0.007	0.001	0.003	0.008	0.001	0.000	0.000	0.039	0.000	0.003	0.611
K	0.000	0.000	0.001	0.000	0.000	0.000	0.000	0.000	0.000	0.000	0.044
Ni	-	-	-	-	-	-	-	-	-	-	-
Cl	-	-	-	-	-	-	-	-	-	-	-
Total	4.008	3.976	3.989	4.003	2.996	2.996	2.993	17.110	17.129	5.002	2.841

FeO*= total Fe as FeO.

Barred olivine chondrule (BOC)

Sample BOC-01 (Table 1)

The BOC-01 consists mainly of barred olivine, Al-rich clinopyroxene, and plagioclase, with minor amounts of nepheline. Barred olivine shows chemical zoning in Mg/(Mg+Fe^{2+}) atomic ratio [= X_{Mg}] ranging from 0.93 to 0.99; the X_{Mg} value decrease towards the rim. Al-rich clinopyroxene is characterized by high Al content (3.5-5.6 wt% Al_2O_3); X_{Mg} ranges from 0.98 to 0.99. It contains significant Ti (1.5-2.1 wt% TiO2), Cr (0.39-0.55 wt% Cr_2O_3), and Na (0.08-0.14 wt% Na_2O). Plagioclase has 84.3-84.6 mol.% anorthite component. Nepheline replacing fine-grained aggregates of plagioclase contains up to 1.7 wt% K_2O.

Sample BOC-02 (Table 2)

The BOC-02 consists mainly of barred olivine, Ca-poor clinopyroxene with minor amounts of Fe-rich clinopyroxene, and plagioclase. Barred olivine shows chemical zoning in X_{Mg} ranging from 0.94 to 0.98; the X_{Mg} value decrease towards the rim. Ca-poor clinopyroxene has pigeonitic composition containing 10.6-12.7 wt% CaO; X_{Mg} ranges from 0.98 to 0.99. Fe-rich clinopyroxene is characterized by low X_{Mg} (0.27), and poor Al content (1.1 wt% Al_2O_3). Plagioclase contains 94.4 mol.% anorthite component.

Porphyritic olivine chondrule

Sample POC-01 (Table 3)

The POC-01 consists mainly of porphyritic olivine, orthopyroxene, and Al-rich clinopyroxene, with minor amounts of Fe-rich clinopyroxene, plagioclase, nepheline, and sodalite. Olivine shows distinct chemical zoning in X_{Mg}; forsterite-rich (magnesian) cores (X_{Mg} = 0.87-0.92) are rimmed by Fe-rich olivine (X_{Mg} = 0.66-0.75). Orthopyroxene contains 1.4-2.7 wt% Al_2O_3, 1.9-3.5 wt% CaO, and 0.6-0.8 wt% Cr_2O_3; X_{Mg} ranges from 0.97 to 0.99. Al-rich clinopyroxene is characterized by high Al content (4.0-5.2 wt% Al2O3); X_{Mg} ranges from 0.95 to 0.97. It contains significant Ti (1.1-1.3 wt% TiO_2), Cr (0.59-0.70 wt% Cr_2O_3), and Na (0.02-0.13 wt% Na_2O) contents. Fe-rich clinopyroxene is characterized by low X_{Mg} (0.33), and poor Al content (1.0 wt% Al_2O_3). Plagioclase contains 83-91 mol.% anorthite component. Nepheline contains 1.7-2.4 wt% K2O. Sodalite contains up to 6.8 wt% Cl.

Sample POC-02 (Table 4)

The sample POC-02 consists mainly of olivine, and Al-rich clinopyroxene with minor amounts of orthopyroxene, and nepheline. Olivine is characterized by forsterite-rich composition with X_{Mg} ranging from 0.92 to 0.99; less magnesian olivine (X_{Mg} = 0.64) rarely rims forsterite-rich core. Al-rich clinopyroxene is characterized by high Al content (5.5-14 wt% Al_2O_3); X_{Mg} ranges from 0.96 to 0.99. It contains significant Ti (0.4-1.6 wt% TiO_2), and Cr (1.0-1.4 wt% Cr_2O_3), and Na (0.03-1.0 wt% Na_2O). Nepheline contains 1.6-2.0 wt% K_2O.

Sample POC-03 (Table 5)

The sample POC-03 consists mainly of olivine, orpthopyroxene, clinopyroxene, and plagioclase with minor amounts of nepheline and sodalite. Olivine shows distinct chemical zoning in X_{Mg}; forsterite-rich (magnesian) cores (X_{Mg} = 0.95-0.98) are rarely rimmed by Fe-rich olivine (X_{Mg} = 0.61). Orthopyroxene 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 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 85-87 mol.% anorthite component. Nepheline contains 2.1 wt% K_2O.

Sample POC-04 (Table 6)

The sample POC-04 consists mainly olivine with minor amounts of Al-rich clinopyroxene, and nepheline. Olivine shows chemical zoning in X_{Mg} ranging from 0.81 to 0.98; the X_{Mg} value decreases towards the rim. 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.

Sample POC-05 (Table 7)

The sample POC-05 consists mainly olivine and orthopyroxene with minor amount of Al-rich clinopyroxene. Olivine shows distinct chemical zoning in X_{Mg}; forsterite-rich (magnesian) cores (X_{Mg} = 0.94) are thoroughly replaced by Fe-rich olivine (X_{Mg} = 0.54-0.71). Orthopyroxene 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 wt% Al_2O_3, and 1.3-1.5 wt% Cr_2O_3; X_{Mg} ranges from 0.94 to 0.98.

CAIs

Sample CAI-01 (Table 8)

The CAI-01 consists mainly of Al-rich clinopyroxene, gehlenite, Mg-Al spinel, plagioclase, with minor amounts of Fe-rich clinopyroxene, and nephelite. Al-rich clinopyroxene is characterized by high Al content (5.9 wt% Al_2O_3) with X_{Mg} = 0.92. Gehlenite contains 1.9-3.4 wt% MgO. Mg-Al spinel contains 0.09-0.32 Cr_2O_3; X_{Mg} ranges from 0.82 to 1. Plagioclase is nearly end-member anorthite. Nepheline contains up to 1.8 wt% K_2O.

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