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Almahata Sitta—Fragment MS-CH: Characterization of a new chondrite type

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Abstract–Among the several hundred, mostly small meteorite fragments, recovered within the Almahata Sitta strewn field, one fragment (MS-CH), weighing 5.68 g, was detected that represents a new type of chondritic meteorite. The detection of short-lived cosmogenic radionuclides clearly indicates that this chondrite fragment results from a fresh meteorite fall consistent with the Almahata Sitta event in October 2008. The fundamental mineralogical characteristics of the Almahata Sitta fragment MS-CH can be summarized as follows: (1) the almost equilibrated olivine has high Fa contents of about 36 mole%. The fragment is of petrologic type 3.8 ± 0.1; (2) the metal abundance of the rock is on the order of 2.5 vol%; (3) the mean chondrule size has been determined to be roughly 450 μm; (4) point-counting and imaging indicate that the matrix abundance is approximately 45 vol%; (5) Cr-spinels have much lower TiO_2 concentrations than typical spinels within R chondrites; (6) calcium-aluminum-rich inclusions are spinel-rich and severely altered having abundant Na- and/or Cl-rich alteration products. Spinel also contains significant concentrations of Fe and Zn; (7) magnetites and platinum-group element-rich phases (sulfides, tellurides, and arsenides) characteristic of both R and CK chondrites were not found in fragment MS-CH; and (8) the mean oxygen isotope composition of three small fragments of Almahata Sitta MS-CH is $\delta^{17}O = +4.35‰$, $\delta^{18}O = +4.94‰$, and $\Delta^{17}O = +1.76‰$. The oxygen isotopes relate MS-CH to R chondrites. No established chondrite group having all these characteristics exists.

INTRODUCTION

On October 7, 2008, the asteroid 2008 TC_3 was detected in space about 19 h before it impacted Earth in the Nubian Desert of northern Sudan. This was the first time ever that an asteroid was observed and studied before its fall on Earth. Several hundreds, mostly small, meteorite fragments were recovered and were subsequently named as the Almahata Sitta meteorite. Almahata Sitta has been classified as an anomalous polymict ureilite (Jenniskens et al. 2009) and described mineralogically by Zolensky et al. (2009) and Herrin et al. (2009).

In a detailed study, 40 small pieces from different quite fresh fragments collected within the Almahata Sitta strewn field were investigated and about 20 different lithologies were found (Bischoff et al. 2010a, 2010b; Horstmann and Bischoff 2010a, 2010b). Based on these findings, Bischoff et al. (2010a, 2010b) suggested that Almahata Sitta is not only a ureilitic meteorite but also a spectacular breccia containing clasts of chondritic and achondritic lithologies.

Among the small meteorite fragments recovered within the Almahata Sitta strewn field, a fragment (MS-CH) with a mass of 5.68 g was detected representing a new type of chondritic meteorite. In this study, we have characterized the mineralogical properties of this unique chondrite type and also present the oxygen isotopic composition and data on short-lived radionuclides analyzed within the rock.

SAMPLES AND ANALYTICAL TECHNIQUES

Almahata Sitta fragment MS-CH is a relatively fresh, complete meteorite fragment of 5.68 g found in the Almahata Sitta strewn field in July 2009. A small slice was selected for the preparation of three tiny thin sections (PL09301, PL09302, and PL09303) and a 5.1 g sample was used to measure the short-lived cosmogenic radionuclides at the Laboratori Nazionali del Gran Sasso (Italy). Small grains from three different areas of the fragment (with a mass collectively <5 mg) were prepared for oxygen isotope measurements at Universität Göttingen (Germany).

The mineralogy and texture of the fragments were studied by light and electron optical microscopy. A JEOL 6610-LV scanning electron microscope (SEM) with an attached Oxford Instruments EDS system was used to resolve the fine-grained textures and to analyze the mineral constituents. As analytical standards we used olivine (Mg, Fe, and Si), jadeite (Na), plagioclase (Al), sanidine (K), diopside (Ca), rutile (Ti), chromium oxide (Cr), rhodonite (Mn), pentlandite (Fe, Ni, and S), and Co-metal (Co).

Most quantitative mineral analyses were obtained using a JEOL JXA 8900 electron microprobe operated at 15 keV and a probe current of 15 nA. Natural and synthetic standards of well-known compositions were used as standards for wavelength dispersive spectrometry. These are jadeite (Na), sanidine (K), diopside (Ca), disthen (Al), fayalite (Fe), chromium oxide (Cr), pentlandite (Ni, S), hypersthene (Si), San Carlos olivine (Mg), rhodonite (Mn), rutile (Ti), Co-metal (Co), chalcopyrite (Cu), tugtupite (Cl), and willemite (Zn). The matrix corrections were made according to the $\Phi\rho(z)$ procedure of Armstrong (1991).

The oxygen isotope composition of three fragments (MS-CH-1: 0.88 mg; MS-CH-2: 2.139 mg; MS-CH-3: 0.754 mg) of Almahata Sitta MS-CH was analyzed by infrared laser fluorination (Sharp 1990) in conjunction with isotope ratio monitoring mass spectrometry. Samples were fluorinated in an atmosphere of approximately 20 mbar with purified F_2 gas. Excess F_2 was reacted to Cl_2 in a heated NaCl trap ($NaCl + 0.5\ F_2 \rightarrow NaF + 0.5\ Cl_2$) and Cl_2 was cryogenetically separated from sample O_2. Sample O_2 was collected on a molecular sieve trap from where it was transported by a He carrier gas flow via a second molecular sieve and a 5A gas chromatography column into the source of a ThermoElectron MAT253 triple collector gas mass spectrometer. Accuracy and precision were usually at $\pm 0.2‰$ for $\delta^{18}O$ and $\pm 0.06‰$ for $\Delta^{17}O$. Terrestrial rocks and minerals (~290 analyses) were used for the definition of the terrestrial fractionation line with a slope of 0.5250 ± 0.0007 (1σ).

The short-lived cosmogenic radioisotopes were measured at the Laboratori Nazionali del Gran Sasso (LNGS) (Italy) by means of gamma ray spectroscopy. The measurements were performed using high-purity Germanium (HPGe) detectors, in ultra low background configuration (25 cm of lead and an inner liner of 5 cm copper, Rn suppression system, inside an underground laboratory with 1400 m rock overburden). The counting efficiency was calculated with a thoroughly tested Monte Carlo code. The 5.1 g sample was measured during the time period from October 13 to 18, 2009.

RESULTS

Hand Specimen

The original individual specimen had a weight of 5.68 g and was covered by a black fusion crust. The black fusion crust is still visible in the remaining main mass (Fig. 1) after some parts of the fragment have been broken off or cut. The cut surface is grayish having abundant light rounded inclusions (mainly chondrules and chondrule fragments) embedded within abundant matrix. Metals at the surface have already obtained a very slight brownish staining due to oxidation reactions with terrestrial humidity between the fall and recovery of the rock fragment.

Mineralogy of the Unique Chondrite Fragment MS-CH

Texture

In thin section, MS-CH shows a well-preserved chondritic texture (Fig. 2a). Obviously, the sample has a relatively high abundance of matrix. Based on point-counting on photomicrographs, a matrix abundance of approximately 45 vol% has been determined, which is in the range of CO, CV, CK, and R chondrites (e.g., Grossman et al. 1988 and references therein; Kallemeyn et al. 1991; Rubin and Kallemeyn 1993; Bischoff 2000) and significantly higher than within ordinary chondrites (e.g., Grossman et al. 1988 and references therein). As coarse-grained constituents, fragment MS-CH contains abundant chondrules and chondrule fragments, as well as metals, sulfides, and some calcium-aluminum-rich inclusions (CAIs), which will be described below. No indication was found that the minerals in the clast have suffered reduction by reaction with the ureilite host.

Chondrules

Most chondrules or chondrule fragments are porphyritic, but all typical types of chondrules occur (Fig. 2). Barred-olivine chondrules appear to be more abundant than within ordinary chondrites (Fig. 2). A mean chondrule size of approximately 450 μm has been determined based on the analyses of the apparent diameter of 44 chondrules. The mean chondrule size is similar to that in R chondrites.

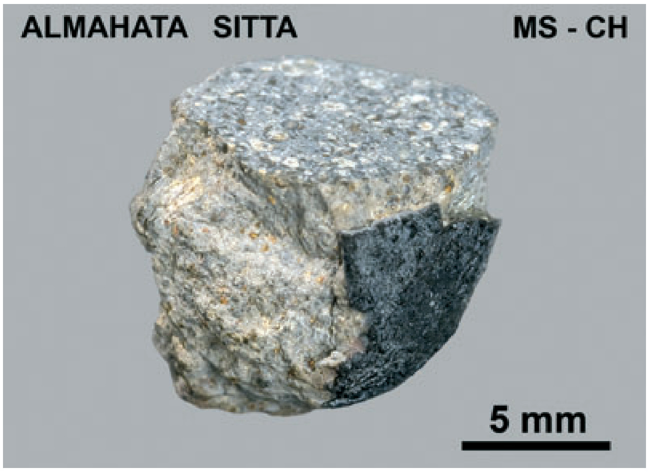

Fig. 1. Photomicrograph of the Almahata Sitta stone investigated in this study. The black fusion crust is still visible after some parts of the fragment have been broken off or cut. The grayish cut surface contains light chondrules and chondrule fragments embedded within abundant matrix.

Main Minerals

Olivine within chondrules and matrix is mainly Fa_{35-37}. Only a very limited number of olivines were encountered having lower Fa contents. These zoned olivines are large and the olivine with the highest, so far analyzed Mg concentration has a Fa content of 19 mole%. Random analyses of olivines revealed a mean olivine composition of 35.0 ± 3.6 mole% Fa. Thus, the olivine compositions indicate that the rock is almost equilibrated. The olivines do not contain NiO as found in R and CK chondrites (Table 1). On the other hand, the low-Ca pyroxenes are variable in composition (Fs_{3-26}). A small, weak peak in the Fs distribution can be found at about 24–26.5 mole% Fs, but low-Ca pyroxenes with Fs contents as low as 3 mole% exist (Fig. 3). The Cr-spinels have much lower TiO_2 concentrations than those within R chondrites. Representative analyses of the main silicates and oxides are given in Table 1. The rock has significant abundances of metals and troilites of about 2.5 and 5 vol%, respectively, as obtained by SEM surface-imaging using the analySIS software (Olympus Soft Imaging Solutions). Sulfides and metals as large as 460 × 360 and 280 × 160 μm, respectively, occur within the studied thin sections. Figure 4d shows an area within MS-CH having a relatively high abundance of metals and sulfides. The Fe,Ni-metal is mainly Ni-rich (Ni: ~40 wt%; Co: ~2 wt%; taenites). The less abundant kamacite has on the order of 7 wt% Ni and 1.5 wt% Co. Representative compositions of metals and sulfides are given in Table 2. Magnetites and platinum-group element (PGE)-rich phases (sulfides, tellurides, and arsenides) characteristic of R and CK chondrites were not found in fragment MS-CH.

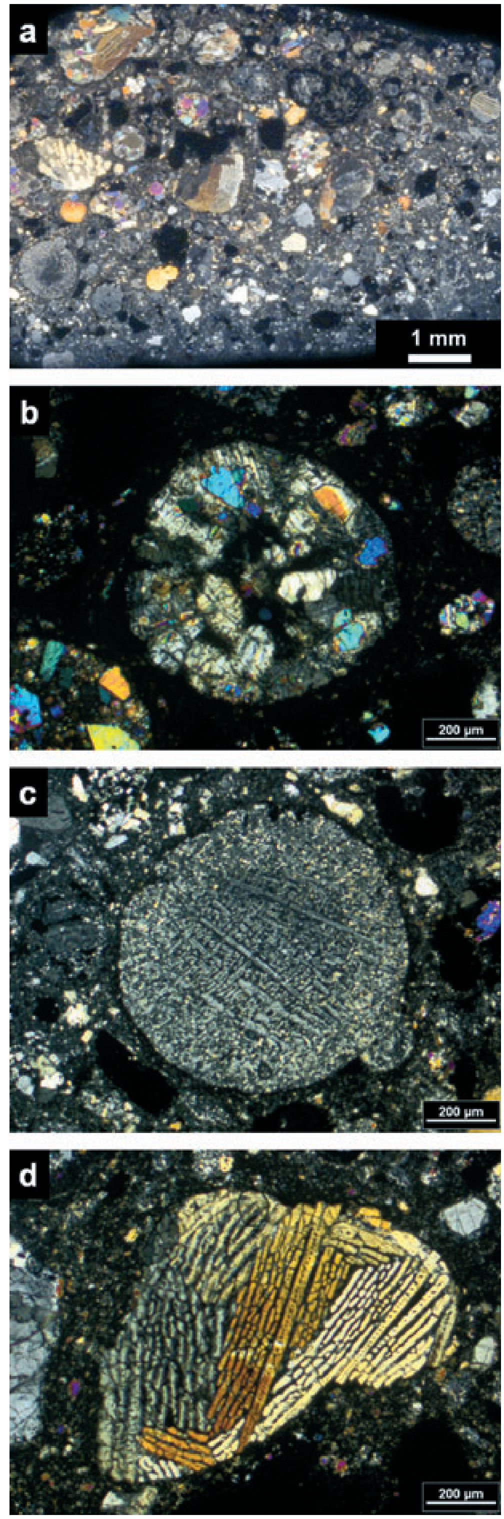

Fig. 2. Photomicrographs in transmitted light (crossed polars). a) Overview of the Almahata Sitta fragment MS-CH showing the chondritic texture and the abundance of matrix. b) Typical porphyritic olivine–pyroxene chondrule. c) Fine-grained pyroxene-rich chondrule. d) Barred-olivine chondrule fragment.

Table 1. Microprobe analyses (except as indicated) of the main phases as well as of chromite and ilmenite.

	Olivine		Pyroxene			Plagioclase			Chromite	Ilmenite
	Mean (n = 34)	Min.*	Mean (24)	Min.	Max.	Mean (5)	Min.	Max.		
SiO_2	36.5	39.2	55.9	58.1	53.9	66.9	67.4	65.8	0.17	< 0.02
Al_2O_3	< 0.01	n.d.	0.38	0.21	0.55	19.6	19.0	19.6	5.7	n.d.
Cr_2O_3	0.05	< 0.01	0.43	0.39	0.44	< 0.01	n.d.	n.d.	56.5	0.09
TiO_2	< 0.02	< 0.04	0.03	n.d.	0.07	< 0.02	n.d.	n.d.	1.35	54.8
FeO	31.3	18.2	9.4	3.2	17.1	0.89	0.93	1.20	31.5	43.6
NiO	< 0.02	< 0.10	< 0.01	< 0.01	n.d.	< 0.01	n.d.	0.04	n.d.	0.04
ZnO	< 0.03	n.a.	0.03	< 0.01	n.d.	< 0.02	n.d.	0.06	0.82	< 0.05
MgO	32.8	42.0	32.3	37.5	26.1	0.26	0.56	0.47	1.84	2.73
MnO	0.40	0.55	0.30	0.17	0.24	< 0.01	< 0.01	< 0.02	0.50	0.70
CaO	0.05	n.d.	0.50	0.21	0.84	1.27	0.96	1.50	0.11	n.d.
K_2O	< 0.01	< 0.01	< 0.01	n.d.	n.d.	0.60	0.68	0.55	n.d.	n.d.
Na_2O	< 0.01	< 0.04	0.04	n.d.	n.d.	10.4	10.5	10.3	0.11	n.d.
Total	101.10	99.95	99.31	99.78	99.24	99.92	100.03	99.52	98.60	101.96
Fa/Fs/An	35.0	19.6	14.4	4.57	26.5	6.1	4.7	7.2		

Note: All data in wt%. n.d. = not detected; n.a. = not analyzed; n = number of analyses.
*EDS analysis normalized to 100%.

Shock Effects

Almahata Sitta fragment MS-CH has been affected by shock metamorphism (Stöffler et al. 1988, 1991; Bischoff and Stöffler 1992). The olivine shows undulatory extinction and irregular fractures. In about 10–20% of the olivine grains, planar fractures are visible indicating an even higher degree of shock metamorphism. Using the shock classification scheme for ordinary chondrites by Stöffler et al. (1991), fragment MS-CH is very weakly shocked (S2).

Calcium-Aluminum-Rich Inclusions

Several CAIs were found having abundant spinel (Figs. 4a and 4b). Representative mineral analyses of the constituents are given in Table 3. CAI CH-1 is a concentric spinel-rich inclusion with a spinel-rich core surrounded by a porous nepheline-bearing layer (Fig. 4a; Table 3). The inclusion is almost completely rimmed by Ca-pyroxene and in some areas by an additional rim of olivine (~Fa_{36}). The spinels have high concentrations of ZnO (>2 wt%).

The CAI CH-2 is a complex spinel-rich aggregate and consists of three different units (Fig. 4b). The spinel has considerable concentrations of FeO and ZnO of ~20 and ~3 wt%, respectively (Table 3). The Cr concentration increases significantly toward the adjacent chondrite matrix in one area of the inclusion having no Ca-pyroxene rim (Fig. 4b). Here, the spinel has FeO, Cr_2O_3, and ZnO concentrations of ~30, ~35.5, and ~1.5 wt%, respectively (Table 3). In other areas, the spinel cores are surrounded by Na- and Cl-rich alteration products, probably sodalite (Table 3). Within the spinels, tiny inclusions of ilmenite and FeS were found as well as an Os-,Ru-bearing Fe,Ni-metal grain. Some

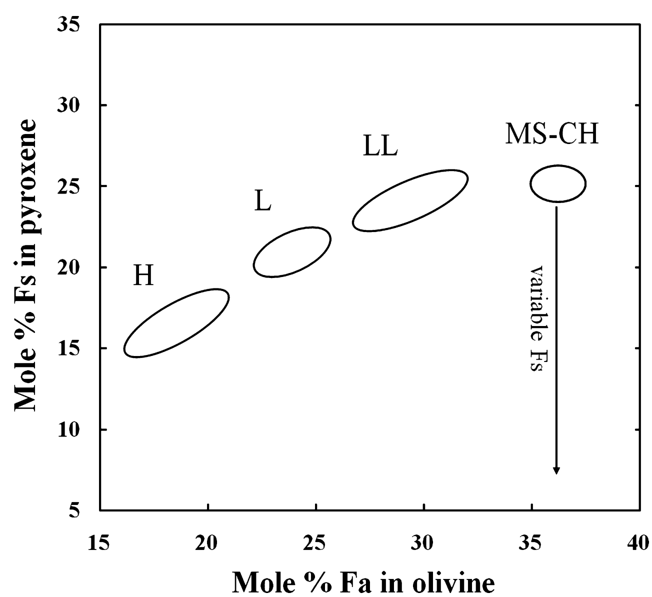

Fig. 3. Plot of the Fs content of low-Ca pyroxene versus Fa content of olivine for mineral compositions in the MS-CH fragment compared with those for equilibrated (types 4–6) ordinary chondrites. Note that in the case of the Almahata Sitta fragment, the olivines are almost equilibrated and that the pyroxenes have a weak maximum at $Fs_{24–26}$, and show a wide range of compositions (see text). Figure after Keil and Fredricksson (1964), Sears and Dodd (1988), and Brearley and Jones (1998).

representative analyses of the constituents are given in Table 3.

Matrix

The matrix is fine grained and strongly dominated by olivine (Fig. 4c). The olivine is rather uniform in

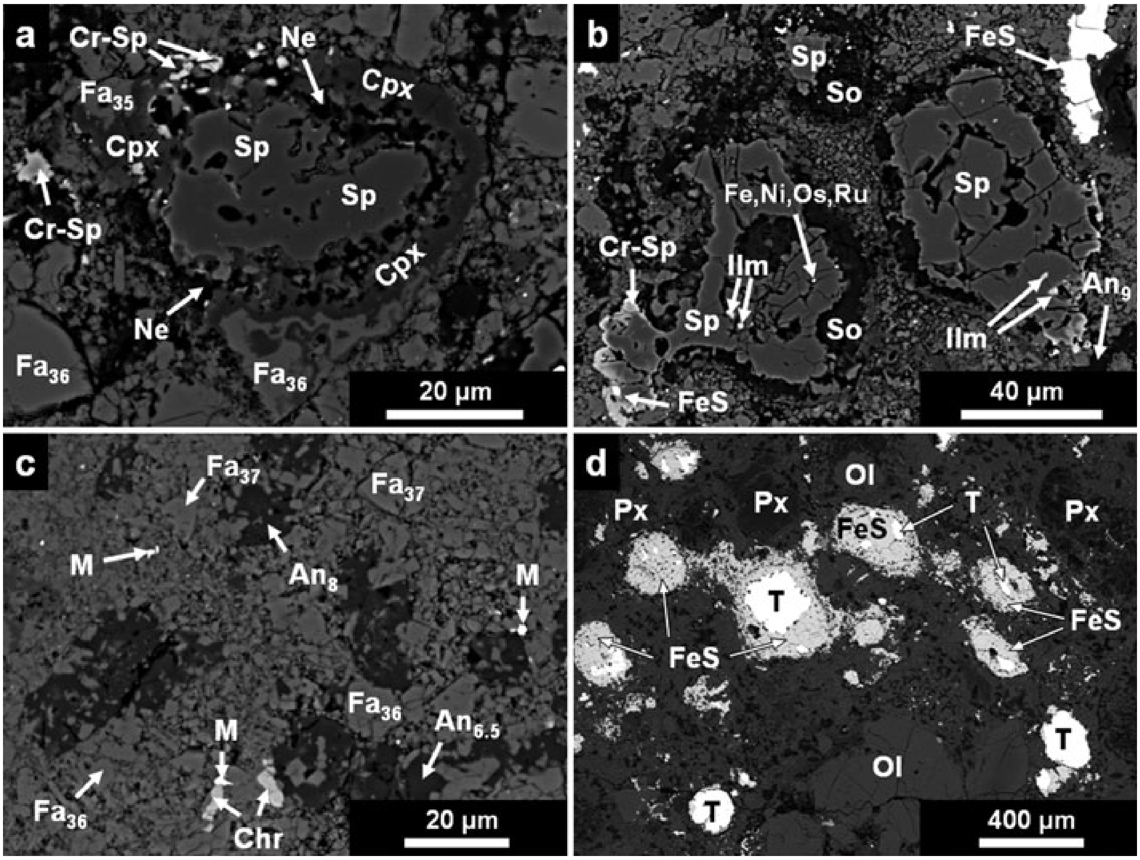

Fig. 4. Backscattered electron micrographs of calcium-aluminum-rich inclusions (CAIs) in the MS-CH fragment. a) CAI CH-1 is a concentric spinel-rich inclusion. A spinel-rich core (Sp) is surrounded by a porous nepheline-bearing layer (Ne), an almost complete rim of Ca-pyroxene (Cpx), and in some areas by an additional rim of olivine ($\sim Fa_{36}$); Cr-Sp = Cr-spinel. b) CAI CH-2 is a complex spinel-rich aggregate with three different units. The Cr concentration of spinel (Sp) increases significantly toward the chondrite matrix (Cr-Sp; lower left). Spinel cores are surrounded by Na- and Cl-rich alteration products, probably sodalite (So). Within the spinels, tiny inclusions of ilmenite (Ilm) and FeS were found as well as an Os-,Ru-bearing Fe,Ni-metal. Note the porous olivine-rich matrix surrounding the CAI. An = anorthite. c) The fine-grained matrix is strongly dominated by Fa-rich, mostly anhedral olivine locally intergrown with patches of plagioclase ($An_{5–10}$); Cr = chromite, M = metal. d) The distribution of metals (T = taenite) and sulfides (FeS) within fragment MS-CH. Taenite is often enclosed within troilite. Olivine (Ol; gray) and zoned low-Ca pyroxene (Px; dark to medium gray) dominate the silicate matrix; Ilm = ilmenite.

Table 2. Representative microprobe analyses (except as indicated) of metal and troilite in Almahata Sitta MS-CH.

	Metal						Sulfide				
	Taenite				Kamacite*		Troilite				
Si	n.d.	< 0.01	n.d.	< 0.01	< 0.14	< 0.06	n.d.	n.d.	n.d.	n.d.	n.d.
S	n.d.	< 0.01	< 0.02	0.07	n.d.	n.d.	36.0	36.0	36.4	36.3	35.9
Ca	< 0.02	< 0.03	n.d.	0.04	n.a.	n.a.	n.d.	0.05	< 0.01	n.d.	n.d.
Cr	< 0.02	< 0.04	0.14	n.d.	n.d.	< 0.03	n.d.	n.d.	0.05	n.d.	0.04
Mn	n.d.	n.d.	n.d.	n.d.	n.d.	n.d.	0.11	< 0.01	n.d.	< 0.03	< 0.01
Fe	56.8	57.7	57.1	75.9	91.3	91.4	61.8	62.5	62.6	62.4	62.3
Ni	40.9	40.4	40.6	21.6	6.8	6.9	1.18	0.15	n.d.	0.22	0.88
Cu	0.13	0.11	0.26	< 0.04	n.a.	n.a.	n.d.	0.09	0.15	< 0.03	n.d.
Zn	< 0.04	0.19	0.08	0.12	n.a.	n.a.	< 0.04	0.18	< 0.03	0.07	n.d.
Co	1.75	1.76	1.80	1.74	1.71	1.59	0.31	0.14	0.06	0.17	0.12
Total	99.66	100.25	100.00	99.52	99.95	99.98	99.44	99.12	99.30	99.22	99.25

Note: All data in wt%. n.d. = not detected; n.a. = not analyzed.
*EDS analyses normalized to 100%.

Table 3. Representative microprobe analyses of phases within two calcium-aluminum-rich inclusions (CAI 1 and CAI 2).

	Nepheline-dominating alteration product	Spinel		Ca-Px	Sodalite		Spinel				Cr-spinel
	CAI 1	CAI 1	CAI 1	CAI 1	CAI 2	CAI 2	CAI 2	CAI 2	CAI 2	CAI 2	CAI 2
SiO_2	41.9	0.06	0.04	54.4	38.9	38.5	0.04	< 0.03	< 0.02	< 0.03	0.19
Al_2O_3	30.2	64.3	63.9	0.82	31.5	30.8	63.4	63.1	62.9	63.2	26.8
Cr_2O_3	0.07	0.21	0.41	0.09	0.05	0.47	0.22	0.26	0.47	0.24	35.5
TiO_2	0.20	0.04	0.06	0.05	< 0.01	0.16	0.06	< 0.03	0.06	0.12	0.77
FeO	0.92	20.5	20.6	1.28	0.84	1.81	19.8	20.4	20.5	20.3	29.9
NiO	< 0.03	0.05	0.05	< 0.02	< 0.01	n.d.	0.09	< 0.03	0.05	0.05	n.d.
ZnO	0.07	2.20	2.53	< 0.03	0.07	0.12	3.4	2.40	2.77	2.64	1.52
MgO	1.44	12.8	12.4	19.0	0.11	1.13	12.5	12.7	12.8	12.5	4.3
MnO	< 0.03	0.12	0.16	< 0.02	n.d.	n.d.	0.11	0.15	0.11	0.08	0.36
CaO	2.47	0.07	0.08	23.4	0.19	0.31	< 0.02	< 0.02	n.d.	0.04	0.05
K_2O	1.53	n.d.	< 0.03	< 0.03	0.45	0.10	n.d.	< 0.01	< 0.03	< 0.03	< 0.02
Na_2O	16.6	0.19	0.10	< 0.03	20.4	17.1	0.25	0.17	0.21	0.26	0.20
Cl	2.88	< 0.02	n.d.	n.d.	8.4	8.4	< 0.03	< 0.02	n.d.	< 0.03	n.d.
Total	98.28	100.54	100.36	99.1	100.91	98.90	99.87	99.18	99.87	99.43	99.59
			Fs/En/Wo	2.0/52.0/46.0							

Note: All data in wt%. n.d. = not detected.

composition (~Fa_{36}); some grains are lath-like, but most are anhedral. The olivine grains do not show any indication (e.g., zoning, tiny metal inclusions) that they have suffered reduction at grain boundaries. In parts of the matrix, patches of plagioclase ($An_{5–10}$) occur intergrown with olivine (Fig. 4c). Small particles of chromite, ilmenite, troilite, and metal are additional distinct constituents of the matrix. Some representative analyses of the plagioclases and oxides are given in Table 1.

Oxygen Isotopes

Three aliquots were used for oxygen isotope analyses. The fragments MS-CH-1 to -3 had $\delta^{17}O$ of +4.6‰, +5.1‰, and +3.4‰ and $\delta^{18}O$ of +5.5‰, +5.6‰, and +3.7‰, respectively. The corresponding $\Delta^{17}O$ values were +1.7‰, +2.1‰, and +1.4‰. The mean $\delta^{17}O$ is +4.35‰, the mean $\delta^{18}O$ is +4.94‰, and the mean $\Delta^{17}O$ is +1.76‰ (Fig. 5). Thus, the mean value is similar to values for bulk R chondrites.

Cosmogenic Radioisotopes

The determination of the short-lived cosmogenic radioisotopes in MS-CH revealed the detection of ^{46}Sc (half-life: 83.788 days), of ^{54}Mn (half-life: 312.13 days) and ^{57}Co (half-life: 271.8 days). The value for ^{46}Sc clearly indicates that the fragment MS-CH results from a very recent meteorite fall, 335–420 days prior to the measurement, consistent with the Almahata Sitta fall in October 2008. Data are presented in Table 4.

DISCUSSION

Classification and Origin of Almahata Sitta Fragment MS-CH

The main mineral olivine is almost equilibrated and only a small number of large zoned grains exist; olivine is mainly $Fa_{35–37}$. Matrix olivine is equilibrated and has a similar composition compared with most olivine within chondrules and fragments (~Fa_{36}). On the other hand, low-Ca pyroxenes are much more heterogeneous in composition than olivine, because equilibration of olivine is significantly faster than that of pyroxene. Based on the compositional data of olivine and pyroxene, the MS-CH chondrite is a high-grade type 3 chondrite. Considering the olivine analyses and the deviation from the mean Fa content (35.0 ± 3.6 mole%), fragment MS-CH is of type 3.8. The higher type 3 petrologic type is also indicated by a slightly translucent fine-grained matrix instead of an opaque matrix found in type 3 chondrites of lower petrologic type. As discussed in the following paragraph, Almahata Sitta fragment MS-CH is mineralogically different to rocks known from other chondrite groups and must therefore be considered as a unique, new type of chondritic rock.

Based on the oxygen isotopes, Almahata Sitta fragment MS-CH should be classified as a R chondrite

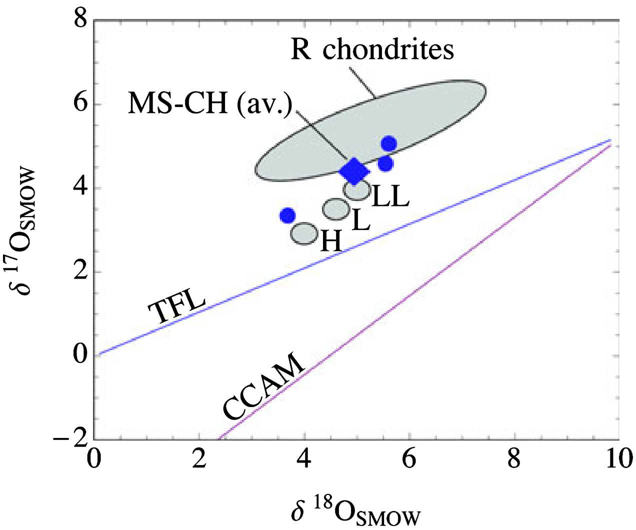

Fig. 5. Oxygen three-isotope plot ($\delta^{17}O$ versus $\delta^{18}O$) of analyses of three fragments (small circles) and the mean (large diamond) of Almahata Sitta fragment MS-CH. The fields for R and ordinary chondrites (H, L, and LL) are shown for reference. CCAM = carbonaceous chondrite anhydrous mixing line; TFL = terrestrial fractionation line.

Table 4. Data summary for the detected cosmogenic radionuclides in the sample MS-CH of the Almahata Sitta meteorite. The reported uncertainties in the last digits (in parentheses) are expanded uncertainties with $k = 1$.

Radionuclide	Half-life	Activity concentrations in [dpm kg^{-1}]
^{26}Al	717000 yr	57 (12)
^{60}Co	5.2710 yr	22 (5)
^{54}Mn	312.13 days	114 (19)
^{22}Na	2.6027 yr	78 (15)
^{46}Sc	83.788 days	19 (8)
^{57}Co	271.8 days	22 (10)

(Fig. 5). The analyses of the fragments, however, show a considerable scatter with the average falling toward the lower $\delta^{17}O$ part of the R chondrite field, close to the field of LL chondrites. The small amount of sample material analyzed (<5 mg) may also not be entirely representative for the bulk composition of the fragment. The heterogeneity in oxygen isotope composition shows that isotopic equilibration of Almahata Sitta fragment MS-CH has not been reached.

The detection of the short- and medium short-lived cosmogenic radionuclides ^{46}Sc, ^{57}Co, and ^{54}Mn clearly indicates that the chondritic fragment MS-CH results from a recent meteorite fall consistent with the Asteroid 2008 TC$_3$ event in October 2008. Therefore, we have strong evidence that fragment MS-CH belongs to the Almahata Sitta meteorite fall.

Mineralogical Similarities of Fragment MS-CH to Other Chondrite Groups

Based on the mineral compositions, chondrule sizes, and matrix abundances, some similarities exist between the Almahata Sitta fragment MS-CH and LL-group ordinary chondrites, CK chondrites, and Rumuruti (R) chondrites. These similarities and the differences will be discussed in the following:

1. *Similarities to and differences from LL chondrites.* Among the ordinary chondrites, the LL chondrites are the most oxidized group having high Fa- and Fs contents in olivine and pyroxene (roughly 27–32 and 22–25 mole%, respectively). Olivine in fragment MS-CH is nearly equilibrated and has about 36 mole% Fa, which is far above the value for LL-group ordinary chondrites. On the other hand, the Co concentrations in metals are very similar to those in LL-group ordinary chondrites. Kamacite in LL chondrites has mean Co contents above approximately 1.4 wt% and taenite has up to 2 wt% Co (e.g., Afiattalab and Wasson 1980; Brearley and Jones 1998). A relationship between Almahata Sitta fragment MS-CH and LL-group ordinary chondrites is precluded by the high matrix abundance of about 45 vol% and the chondrule diameter of about 450 μm. The matrix abundance in ordinary chondrites is about 10–15 vol% and LL chondrites have mean chondrule sizes on the order of 900 μm (e.g., Grossman et al. 1988 and references therein). However, more recently Nelson and Rubin (2002) determined a revised mean chondrule size for LL chondrites of 570 μm.
2. *Similarities to and differences from CK chondrites.* CK chondrites are commonly metamorphosed and have equilibrated olivine with compositions of approximately Fa$_{28–34}$ (e.g., Kallemeyn et al. 1991; Geiger and Bischoff 1995). Thus, the olivine compositions of CK chondrites are very similar to those in Almahata Sitta fragment MS-CH; however, olivine in MS-CH does not contain significant NiO as observed in CK chondrites. In addition, the fragment studied here contains about 2.5 vol% metals. This is not the case for CK chondrites, which typically contain abundant magnetite (e.g., Geiger and Bischoff 1995). The chondrule size of approximately 450 μm in MS-CH is also significantly smaller than that found for CK chondrites (close to 1 mm; Kallemeyn et al. 1991). In addition, fragment MS-CH does not contain magnetite and PGE-rich sulfides, tellurides, and arsenides typically present in CK chondrites.
3. *Similarities to and differences from Rumuruti (R) chondrites.* The equilibrated Rumuruti (R) chondrites

have homogeneous Fa contents in olivine of about 36–40 mole% (e.g., Bischoff et al. 1994; Rubin and Kallemeyn 1994; Schulze et al. 1994; Kallemeyn et al. 1996; Rout and Bischoff 2008). This is in the same range as olivine within the Almahata Sitta fragment MS-CH ($Fa_{35–37}$). Rubin and Kallemeyn (1993) characterized the R chondrites as having 42 ± 11 vol% matrix, besides chondrules and large mineral and lithic fragments. Bischoff (2000) estimated the chondrule-to-matrix ratio in unequilibrated type 3 fragments of R chondrites to be approximately 1:1. The chondrule size of R chondrites is on the order of 400 μm (e.g., Bischoff et al. 1994; Rubin and Kallemeyn 1994; Schulze et al. 1994; Kallemeyn et al. 1996; Imae et al. 1999; Rout and Bischoff 2008). Thus, the matrix abundance and the chondrule size of R chondrites are in the same range as those of the Almahata Sitta fragment MS-CH. A relationship to the R chondrites is also indicated by similar oxygen isotope compositions. But distinct differences exist: R chondrites do not contain abundant metals as observed in MS-CH. The very few metals described from R chondrites usually exist enclosed and protected within forsteritic olivines that occur mainly in chondrules of type 3 lithologies. Olivines in R chondrites have significant NiO in their structures, which is not the case for olivines of the Almahata Sitta fragment (Table 1). R chondrites typically contain PGE-rich sulfides, tellurides, and/or arsenides, which are lacking in fragment MS-CH. Also, the Cr-spinels have much lower TiO_2 concentrations than those within R chondrites. These characteristics also clearly speak against a common origin of the fragment MS-CH and R chondrites.

In summary, Almahata Sitta fragment MS-CH is mineralogically clearly different to rocks known from other chondrite groups. Therefore, it has to be considered as a unique, new type of chondritic rock. However, based on some mineralogical and isotopic aspects (oxygen isotopes), a certain affinity to R chondrites may exist.

Secondary Alteration by Metamorphism and/or Nebular Processes

As stated above, olivine is almost equilibrated and only a small number of large zoned grains exist. Olivine in chondrules and fragments is mainly $Fa_{35–37}$, similar in composition to equilibrated matrix olivine ($\sim Fa_{36}$). Based on the compositional data of olivine, the MS-CH chondrite is quite equilibrated due to parent body metamorphism and is a high-grade petrologic type 3 chondrite. The CAIs have also been altered by metamorphic processes and/or by interactions in the solar nebula. They all contain considerable Fe, Zn, and Cr in spinel and have ilmenite instead of perovskite. The formation of nepheline and/or sodalite in the outer areas of the CAIs (Fig. 4) may be due to nebular alteration as also found in other chondrite groups. It should be mentioned that other scientists do not regard nepheline as being a nebular product in meteorites (e.g., Krot et al. 1995; Russell et al. 1998; Tomeoka and Itoh 2004), but formed during parent body alteration. Melilite has probably been replaced by nepheline/sodalite.

It is also known from other somewhat metamorphosed, high-grade type 3 or type 4 ordinary chondrites, R chondrites, CV, CO, and CK chondrites that CAIs often have ilmenite instead of perovskite and Fe-rich spinel (e.g., Bischoff and Keil 1983a, 1983b, 1983c, 1984; Geiger et al. 1993; Brearley and Jones 1998 and references therein; Bischoff and Schmale 2007; Rout and Bischoff 2007, 2008). CaO in perovskite is replaced by FeO to form ilmenite during secondary alteration. Similarly, Mg in spinel is replaced by Fe and Zn. Considering the replacement processes within spinels and perovskites, it is suggested that the chemical exchange processes started in the nebula (in many chondrites, CAIs containing ilmenite coexist with CAIs containing perovskite), followed by chemical alteration by diffusion during parent body metamorphism. In analogy to the spinels studied here, Fe-rich spinel is a typical mineral in CAIs from the metamorphosed CK chondrites as a result of metamorphic processes (e.g., MacPherson and Delaney 1985; Noguchi 1993; Geiger and Bischoff 1995).

The Significance of Breccias

To reveal information on the evolution of asteroidal parent bodies, it is very important to study meteorite breccias (e.g., Bischoff et al. 1983, 1993, 2006; Stöffler et al. 1988). Especially, the existence and abundance of foreign and exotic fragments in certain meteorites give fundamental information on the degree of mixing among asteroids in the asteroidal belt. The mixing of fragments of different types in chondrites and achondrites is summarized in Bischoff et al. (2006). In this respect, Almahata Sitta is a complex breccia offering potentially new and interesting xenolithic fragments (Bischoff et al. 2010a). Previous reports on polymict ureilites show that ordinary chondrite fragments (e.g., Jaques and Fitzgerald 1982; Prinz et al. 1986, 1987, 1988; Ikeda et al. 2000, 2003; Ross et al. 2010) and angrite-like clasts have been found within several meteorites (e.g., Jaques and Fitzgerald 1982; Prinz et al. 1986, 1987; Ikeda et al. 2000; Goodrich and

Keil 2002; Cohen et al. 2004; Kita et al. 2004). In addition, fine-grained dark clasts, mineralogically similar to fine-grained carbonaceous chondrite material, are known to occur in some ureilites (e.g., Prinz et al. 1987; Brearley and Prinz 1992; Ikeda et al. 2000, 2003; Goodrich and Keil 2002). Thus, chondritic clasts in ureilites are well-known; however, the huge variety of different chondrites found in Almahata Sitta is exceptional. These clasts are characterized and summarized in detail by Bischoff et al. (2010a). In this respect, one of the most complicated meteorite breccias is Kaidun, which contains various kinds of chondritic and achondritic fragments and Zolensky and Ivanov (2003) characterized Kaidun as a "harvest from the inner and outer asteroid belt." Thus, after the polymict breccia Kaidun, Almahata Sitta is a new extraordinary breccia for future studies on the complex evolution of small asteroidal planetesimals.

SUMMARY AND CONCLUSIONS

The fundamental mineralogical characteristics of the Almahata Sitta fragment MS-CH can be summarized as follows: (1) the almost equilibrated olivine has high Fa contents of about 36 mole%; (2) the metal abundance of the rock is on the order of 2.5 vol%; (3) the mean chondrule size has been determined to be roughly 450 μm; (4) point-counting indicates that the matrix abundance is about 45 vol%; (5) magnetites and PGE-rich phases, characteristic for R and CK chondrites, were not found; (6) the detected CAIs are spinel-rich and contain abundant Na- and/or Cl-rich alteration phases; and (7) the oxygen isotope composition of Almahata Sitta fragment MS-CH suggests that it is closely linked to R chondrites. Isotopic heterogeneity shows that equilibration of O isotopes has not been reached.

The significant metal abundance and other mineralogical characteristics discussed above clearly rule out a close relationship to CK and R chondrites, which also have similar high Fa values in olivine. The detection of short-lived cosmogenic radionuclides clearly indicates that the chondritic fragment MS-CH results from a fresh meteorite fall consistent with the Almahata Sitta event in October 2008.

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