

Mineralogy, Petrology, and Stable Isotope Composition of NWA 13943 (CK5) Carbonaceous Chondrite (Post-print)

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Date: 2024-01-31T00:00:00+00:00

Abstract

CK-type meteorites are a class of highly oxidized carbonaceous chondrites, with a metal/magnetite ratio close to zero. Unlike other types of carbonaceous chondrites (petrologic types: 1-3), most CK-type meteorites experienced intense thermal metamorphism (550-1270;K) on their parent bodies, predominantly types 4-6. Multiple lines of evidence indicate that CK and CV3-type meteorites have a genetic relationship. However, minor differences still exist between the two in terms of petrographic structure and chemical composition. Therefore, finely distinguishing and comparing their geochemical characteristics is crucial for validating the CK-CV single parent body hypothesis. Northwest Africa (NWA) 13943 is a newly discovered meteorite that has experienced relatively intense thermal metamorphism. Using scanning electron microscopy and electron microprobe, the petrologic type of NWA 13943 was determined. And using mass spectrometry techniques, the whole-rock oxygen isotopic and chromium isotopic compositions of the NWA 13943 meteorite were measured as a focus. Integrating petrographic structure, mineral chemical composition, oxygen isotope anomalies ($\Delta^{17}\text{O}$, where Δ represents the isotopic fractionation value) and chromium isotope anomalies ($\varepsilon^{54}\text{Cr}$, where ε denotes 10^4 times the relative deviation of the isotopic ratio in the sample from that in the standard), the parent bodies of CK and CV-type meteorites may have formed in two similar but distinct chemical source regions in the protoplanetary disk.

Full Text

Petrology, Mineralogy and Stable Isotopic Composition of NWA 13943 (CK5) Carbonaceous Chondrite

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Abstract

CK-type meteorites represent a highly oxidized group of carbonaceous chondrites characterized by metal/magnetite ratios approaching zero. Unlike other carbonaceous chondrite groups, most CK meteorites have experienced intense thermal metamorphism on their parent bodies, with peak temperatures ranging from 400°C to 600°C. Multiple lines of evidence suggest genetic links between CK and CV-type meteorites, yet subtle differences remain in their petrographic textures and chemical compositions. Therefore, precise discrimination and comparison of their geochemical characteristics are crucial for testing the single-parent-body hypothesis for CK and CV meteorites. NWA 13943 is a newly discovered meteorite that has undergone relatively strong thermal metamorphism. Using scanning electron microscopy and electron probe microanalysis, we determined the petrologic type of NWA 13943, and through mass spectrometry, we measured its whole-rock oxygen and chromium isotopic compositions. Based on comprehensive analysis of petrographic textures, mineral chemistry, oxygen isotope anomalies ($\Delta^{17}\text{O}$, where Δ represents isotopic fractionation), and chromium isotope anomalies ($\delta^{54}\text{Cr}$, where δ denotes the relative deviation of an isotopic ratio in a sample from that in a standard, multiplied by 10^4), the parent bodies of CK and CV-type meteorites likely formed in two similar but distinct chemical reservoirs within the protoplanetary disk.

Keywords: astrochemistry; meteorites; CK-type carbonaceous chondrites

2. Experimental Methods

This study investigated the petrographic textures, mineral chemistry, and whole-rock isotopic composition of NWA 13943. Initial morphological information was obtained using scanning electron microscopy (SEM). Mineral modal abundances were determined through element mapping with an energy-dispersive spectrometer. Major and trace element analyses of olivine and magnetite were conducted via electron probe microanalysis (EPMA) at an accelerating voltage of 15 kV and a beam current of 20 nA. Counting times were typically 10 s on the peak and 5 s on backgrounds, reduced to 5 s and 2 s for Ni and Cr analyses, respectively. Standards consisted of natural minerals and synthetic compounds from the U.S. supplier Structure Probe, Inc., including hematite (Fe_2O_3), plagioclase ($\text{NaAlSi}_3\text{O}_8$), olivine (Mg_2SiO_4 and Fe_2SiO_4), pentlandite [$(\text{Fe,Ni})_9\text{S}_8$], vanadium metal, diopside ($\text{CaMgSi}_2\text{O}_6$), chromium oxide, rutile (TiO_2), and manganese wollastonite. Data were corrected using the ZAF (atomic number,

absorption, fluorescence) procedure. All experiments were performed at the Astrochemistry Laboratory of Purple Mountain Observatory.

Whole-rock oxygen isotope analysis was conducted on a Delta V Plus gas-source isotope ratio mass spectrometer at Nanjing University. Approximately 1.5 mg of powdered sample was used, following the methodology described in reference [23]. Oxygen isotope compositions are expressed as $\delta^{17}\text{O}$ and $\delta^{18}\text{O}$ values (δ representing the relative deviation of an isotopic ratio in a sample from that in a standard, multiplied by 10^3), defined as:

$$\delta X (\text{‰}) = 10^3 \times [(X^{16}\text{O}) / (X^{16}\text{O})_{\text{std}} - 1]$$

where $X = 17$ or 18 . The standard is Vienna Standard Mean Ocean Water (V-SMOW). Standard errors for $\delta^{18}\text{O}$ and $\delta^{17}\text{O}$ are $\pm 0.15\text{‰}$ and $\pm 0.08\text{‰}$, respectively. Oxygen-16 isotope anomalies are expressed as $\Delta^{17}\text{O}$ (Δ representing isotopic fractionation), defined as:

$$\Delta^{17}\text{O} = 10^3 \times \ln(\delta^{17}\text{O}/10^3 + 1) - 0.528 \times \ln(\delta^{18}\text{O}/10^3 + 1)$$

Whole-rock chromium isotopic composition was measured using a Triton thermal ionization mass spectrometer at the Institute of Geological Sciences, Free University of Berlin. Approximately 20 mg of powdered sample was used. Chromium isotope anomalies are expressed as ^{53}Cr or ^{54}Cr (δ representing the relative deviation of an isotopic ratio in a sample from that in a standard, multiplied by 10^4), defined as:

$$\delta X_{\text{Cr}} = 10^4 \times [(X_{\text{Cr}}/^{52}\text{Cr}) / (X_{\text{Cr}}/^{52}\text{Cr})_{\text{std}} - 1]$$

where $X = 53$ or 54 . The standard used was NIST SRM 979. Detailed analytical and data processing procedures are described in reference [24].

3.1. Overall Petrographic Characteristics

The hand specimen of NWA 13943 is shown in [Figure 1: see original paper]. The surface exhibits a black fusion crust, with a weathering rim approximately 1-2 mm thick around the cut surface. [Figure 2: see original paper] presents a backscattered electron (BSE) overview image and elemental distribution map (Si: green; Fe: red; Mg: blue) of a polished section. The interior contains sparse silicate chondrules (5 vol%) ranging from millimeter to submillimeter size (0.5 ± 0.2 mm) embedded in fine-grained matrix. Representative BSE images of chondrules are shown in [Figure 3: see original paper], while [Figure 4: see original paper] illustrates representative magnetite grains and coexisting minerals. Metal grains are rare; only minor Fe-Ni metal oxides or sulfides were observed ([Figure 4: see original paper]a). Secondary plagioclase grains range from 10 ± 5 μm in diameter, with abundances <10 vol%. The matrix shows relatively high degrees of recrystallization, with occasional calcite veins and fine-grained aqueous alteration minerals ([Figure 4: see original paper]b).

Modal abundance statistics indicate the sample comprises approximately 45 vol% olivine, 25 vol% pyroxene, 5 vol% plagioclase, 11.5 vol% magnetite, and 0.5 vol% carbonates. Chondrules in NWA 13943 show indistinct outlines, are mostly circular or elliptical, heavily fractured, and commonly display cracks ([Figure 3: see original paper]). Neither barred olivine nor radial pyroxene textures were observed. Chondrules are predominantly porphyritic olivine (PO) and porphyritic olivine-pyroxene (POP) types.

3.2. Magnetite

Magnetite in NWA 13943 occurs in three settings: (1) dispersed in fine-grained matrix, (2) within chondrules, and (3) along chondrule rims. Most magnetite grains have rounded edges and corners, commonly contain inclusions of olivine and orthopyroxene, and show high porosity ([Figure 4: see original paper]a, b, c). Ilmenite and spinel exsolution are common internally ([Figure 4: see original paper]b). Minor magnetite occurs as subhedral grains without inclusions or pores ([Figure 4: see original paper]d). Grain sizes range from 5-100 μm .

Representative EPMA data for magnetite are presented in . Results show that NWA 13943 magnetite is Cr-rich, with Cr_2O_3 mass fractions (wt%) of 1-10%. Most magnetite contains 1.5-9.5 wt% Cr_2O_3 , 0.08-0.42 wt% TiO_2 , 0.14-1.22 wt% Al_2O_3 , 0.03-0.19 wt% MgO , and 0.31-1.44 wt% MnO . However, some magnetite shows compositional deviation with higher Cr_2O_3 (>10 wt%), TiO_2 (>1 wt%), Al_2O_3 (>2 wt%), and MgO (>1 wt%) but relatively lower Fe_2O_3 (<90 wt%). Petrographically, these highly Cr-rich magnetites also differ from most others, being more euhedral, internally clean, and less porous.

3.3. Olivine

Representative chemical compositions of chondrule and matrix olivine in NWA 13943 are given in . [Figure 5: see original paper] shows histograms of Fa (fayalite) frequency distribution for both chondrule and matrix olivine (Fa = $\text{FeO}/(\text{FeO}+\text{MgO})$ molar ratio $\times 100$). Neither olivine type shows zoning, with narrow Fa ranges and relatively homogeneous compositions. Chondrule olivine Fa values range from 29.4-30.0 (mean = 29.7), while matrix olivine Fa ranges from 30.1-31.3 (mean = 30.1).

3.4. Whole-Rock Oxygen and Chromium Isotopic Composition

NWA 13943 whole-rock oxygen isotope results are: $\delta^{17}\text{O} = -3.19 \pm 0.08\text{‰}$, $\delta^{18}\text{O} = 1.94 \pm 0.06\text{‰}$, $\Delta^{17}\text{O} = -3.47 \pm 0.08$. Whole-rock chromium isotopic

composition is: $^{53}\text{Cr} = 0.11 \pm 0.05$, $^{54}\text{Cr} = 0.64 \pm 0.03$ ($N = 3$, 2σ , where N is the number of analyses and 2σ represents two standard deviations).

4.1. Petrologic Classification of NWA 13943

Petrographically, NWA 13943 contains abundant magnetite (11.5 vol%), within the CK chondrite range (5–20 vol%, average 12 vol% [16]). Fe-Ni metal and sulfides are rare, consistent with the highly oxidized nature of CK chondrites. Chondrule diameters (0.5 ± 0.2 mm) match CK4–6 chondrites (0.5–1.2 mm, mean 0.8 mm [5]). The chondrule proportion (5 vol%) is significantly lower than in CK3 and CV3 chondrites (CV3: 45–65 vol%; CK3: 15–40 vol% [5]). Secondary plagioclase grain size (10 ± 5 μm) and abundance (<10 vol%) are consistent with CK4–6 meteorites ($2 \mu\text{m} < D < 60 \mu\text{m}$), contrasting with CK3 (no plagioclase) and CK6 ($D > 60 \mu\text{m}$) [8]. In summary, NWA 13943 is classified as a CK4–6 type carbonaceous chondrite.

4.2. Chemical Group Classification

Olivine is the most abundant mineral in NWA 13943, occurring in both chondrules and matrix. Chondrule olivine Fa values (29.7 ± 0.2) are consistent with those reported for CK4–6 meteorites (Fa = 29.8–30.3) but higher than CV3 meteorites (Fa < 15) and narrower than CK3 meteorites (Fa = 30.1–30.7 [5, 8, 20, 25–26]). Similarly, matrix olivine Fa values (30.1 ± 0.3) match CK4–6 matrix olivine (Fa = 30.2–31.1), are lower than CK3 matrix olivine (Fa = 31.2–31.7), and show narrower compositional ranges than CV3 meteorites (Fa = 0–99 [8, 25, 27–34]).

4.3. Magnetite

Magnetite in carbonaceous chondrites is generally considered a product of low-temperature aqueous alteration of metal [35]. Since magnetite is resistant to terrestrial weathering [36], its composition is essentially unaffected. However, parent body thermal metamorphism may have altered magnetite chemistry. Previous studies [37] demonstrated that magnetite composition can effectively discriminate CV, CK3, and CK4–6 meteorites. The major (Fe_2O_3) and trace element (MgO, Cr_2O_3 , TiO_2 , Al_2O_3) contents of NWA 13943 magnetite are compared with literature data for CK3 [6], CK4–6 [4, 7, 16, 20, 37], and CV [7, 38–40] meteorites in [Figure 6: see original paper]. Except for a few extremely Cr-rich grains, NWA 13943 magnetite compositions fall within the CK4–6 range.

Furthermore, from unequilibrated to equilibrated CK meteorites, MgO content in magnetite shows positive correlations with TiO_2 and Al_2O_3 , likely reflecting

exsolution of ilmenite and spinel during parent body cooling. This trend is not observed in CV meteorites, contradicting the hypothesis that CK and CV meteorites belong to the same thermal metamorphic sequence.

4.4. Oxygen and Chromium Isotopic Composition

As noted, CK and CV carbonaceous chondrites share many geochemical similarities in chondrule size [1], cosmic ray exposure age [19], and oxygen isotope composition [7], leading to proposed CK-CV co-genetic models [7, 18] to explain minor differences. However, while oxygen isotope compositions are sensitive to aqueous alteration [41-42] and terrestrial weathering [43], ^{54}Cr is unaffected, indicating that thermal metamorphism does not redistribute chromium isotopes [21]. Therefore, if CK and CV meteorites shared a parent body but experienced different thermal metamorphism, they should have similar ^{54}Cr values. Recent studies [21] show CK meteorites have $^{54}\text{Cr} = 0.12 \pm 0.03$ (2σ , $N = 3$), significantly lower than CV meteorites ($^{54}\text{Cr} = 0.39 \pm 0.04$, 2σ , $N = 4$), indicating distinct parent bodies.

[Figure 7: see original paper] shows triple oxygen isotope and $^{54}\text{Cr}-\Delta^{17}\text{O}$ diagrams for NWA 13943 and other carbonaceous chondrites. CK meteorites plot on or near the carbonaceous chondrite anhydrous mineral (CCAM) line, overlapping with CV3oxA meteorites. NWA 13943's whole-rock oxygen isotopes are similar to CK4-6 meteorite NWA 13954 ($\delta^{17}\text{O} = -3.12\text{‰}$, $\delta^{18}\text{O} = 1.97\text{‰}$, $\Delta^{17}\text{O} = -2.01$), both falling on the ^{16}O -poor end of CK variation. NWA 13943's ^{54}Cr plots between CK and CV meteorites but closer to the CK average. Its slightly higher $\Delta^{17}\text{O}$ compared to other CK meteorites may reflect aqueous alteration and/or terrestrial weathering.

Conclusion

Based on petrographic textures and mineral chemistry—including chondrule size and abundance, magnetite content, secondary plagioclase grain size, olivine Fa distributions in chondrules and matrix, and magnetite major and trace element compositions—NWA 13943 most closely resembles CK4-6 carbonaceous chondrites. Magnetite composition can discriminate CV, CK3, and CK4-6 meteorites. Combined oxygen isotope and chromium nucleosynthetic anomalies suggest CK and CV meteorite parent bodies formed in two chemically similar but distinct reservoirs in the protoplanetary disk.

Acknowledgments

We thank Jiang Yun, Li Ye, and Dr. Zhu Ke for guidance and suggestions. The NWA 13943 meteorite sample was provided by Mr. Zhang Bo of Shanghai Wuyunfang.

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