

Monitoring the petrology and mineral chemistry of NWA 16080: Insights into the evolution of CV chondrites

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Abstract NWA 16080 is a representative reduced CV carbonaceous chondrite (CV_{red}), consisting mainly of chondrules (47 vol%) and matrix (42 vol%), along with minor quantities of calcium- and aluminum-rich inclusions (CAI) and amoeboid olivine aggregates (AOA) (CAI + AOA, 6 vol%) and opaque minerals (5 vol%). The chondrules exhibit well-preserved outlines and can be categorized into Type I (Fa < 10) and Type II (Fa > 10). They primarily consist of magnesium-rich olivine, along with both low-Ca and high-Ca pyroxenes, and contain minor amounts of secondary plagioclase. Olivines present in chondrules display compositional zoning characterized whereas the matrix is composed of fine-grained olivine. Nickel-rich metal and nickel-poor sulfides are also present, along with trace amounts of magnetite. In contrast to standard oxidized CV chondrites (CV_{ox}), the presence of high metal, Ni-poor sulfides, and

reduced magnetite in NWA 16080 indicates a more reduced parent-body environment. Shock metamorphism is classified as mild (S1), while terrestrial weathering is characterized as low (W2). Raman spectroscopy indicates a diverse spectrum of organic matter (OM) maturity: certain areas exhibit characteristics akin to other CV_{red} chondrites, whereas others reach maturity levels comparable to those observed in CV_{ox} chondrites. The Raman parameters indicate that this meteorite is classified as approximately type 3.4 to 3.5. The overlapping OM maturity with certain CV_{ox} chondrites provides a contradiction to the anticipated depth-thermal layering outlined in the onion-shell model. This suggests that the CV parent body probably experienced more intricate processes, including impacts and fluid-rock interactions, rather than merely depth-dependent heating.

Keywords CV chondrite · Parent body · Organic matter · Petrological type

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1 Introduction

Carbonaceous chondrites represent some of the most primitive meteorite types and are essential for comprehending the early formation history of the solar system (Wang 1987; Turner et al. 2021). Carbonaceous chondrites have not experienced substantial melting or differentiation, offering a distinctive viewpoint on planet formation and the early evolution of the solar system (Wang et al. 2005; Scott and Krot 2014). The Vigarano-type chondrite (CV) group is mainly made up of chondrules, which account for about 45 vol%, and matrix, comprising roughly 40 vol%. Additionally, calcium- and aluminum-rich inclusions (CAIs) and amoeboid olivine aggregates (AOAs) make up approximately 10 vol%

of the composition (Weisberg et al. 2006; Scott and Krot 2014).

CV chondrites are categorized into oxidized and reduced subgroups (CV_{ox} and CV_{red}) according to their petrographic and mineralogical characteristics. In CV_{ox} chondrites, the metal-to-magnetite ratio is below 0.2, and the matrix-to-chondrule ratio exceeds that of CV_{red} chondrites, with values between 0.6 and 1.2. In contrast, CV_{red} chondrites exhibit a relatively high metal-to-magnetite ratio, ranging from 2 to 46, while their matrix-to-chondrule ratio is lower, between 0.5 and 0.6. Additionally, the nickel (Ni) content in sulfides is less than 3 wt%, which is lower than the nickel content found in sulfides from CV_{ox} chondrites (Mcsween 1977; Weisberg et al. 1997, 2006).

CV_{ox} chondrites were further classified by Weisberg et al. (1997) into two subgroups: oxidized Allende-like (CV_{oxA}) and Bali-like (CV_{oxB}) chondrites. These subgroups, along with the broader category of CV_{ox} chondrites, display unique mineralogical and alteration characteristics when compared to the CV_{red} chondrites. CV_{ox} chondrites exhibit a greater prevalence of Ni-rich sulfides, magnetite, and Ni-rich metals (such as awaruite in CV_{oxA} chondrites) and show more significant secondary alteration. In contrast, CV_{red} chondrites primarily contain kamacite and taenite, suggesting a reduced level of alteration (Brearley and Krot 2013). Additionally, CV_{oxA} chondrites are characterized by the presence of Na- and K-rich secondary anhydrous minerals, including nepheline, which are produced through Fe-alkali-halogen metasomatism (Kimura and Ikeda 1995). CV_{oxB} chondrites contain abundant phyllosilicates (Tomeoka and Buseck 1990). The mineralogical features observed here are atypical for CV_{red} chondrites, which display reduced phyllosilicate abundances and infrequently show secondary anhydrous minerals (Brearley and Krot 2013).

Most CV chondrites experience thermal metamorphism, resulting in the re-equilibration of mineral assemblages (Trigo-Rodríguez et al. 2019). The classification of meteorites based on their petrologic characteristics, such as CV chondrites, range from type 3, indicating minimal metamorphism, to type 6, which signifies extensive metamorphism, thereby illustrating the extent of thermal metamorphism involved. Type 3 chondrites represent the most primitive category, exhibiting no signs of hydrous alteration or notable metamorphism; however, certain thermal metamorphic characteristics may still be observable.

Ordinary chondrites of petrologic type 3 have been further classified into subtypes, specifically from 3.0 to 3.9, based on mineralogical and chemical criteria. Petrologic type 3.0 indicates meteorites that have undergone minimal metamorphism, while type 3.9 refers to meteorites where specific minerals approach chemical equilibrium (Van Schmus and Wood 1967; Sears et al. 1980; Huss et al. 2006; Brearley and Krot 2013). The induced thermoluminescence

(ITL) technique has been employed to categorize the metamorphic grades of type 3 unequilibrated ordinary chondrites (Guimon et al. 1985, 1995; Benoit et al. 1991). Guimon et al. (1995) utilized the thermoluminescence (TL) method for the classification of petrologic types in CV3 chondrites. However, the petrologic types obtained from their research exhibited inconsistencies when juxtaposed with the petrologic and mineralogical attributes of CV3 chondrites, in addition to the inert gas data from presolar grains and the maturity levels of organic matter (OM) present in the samples (Mcsween 1977; Quirico et al. 2003; Bonal et al. 2006). CV3 chondrites demonstrate considerable complexity, and their petrologic classification within type 3 is not as well-defined or broadly accepted when compared to CO chondrites and ordinary chondrites (Sears et al. 1980; Kimura et al. 2008; Rubin and Li 2019). CO chondrites have established a well-defined 3.x petrologic classification system, primarily using techniques such as TL and electron probe microanalysis (EPMA) (Sears et al. 1991; Imae and Nakamura 2018). Raman spectroscopic analysis was conducted on CV chondrite samples to examine the organic materials within the matrix, adhering to the methodology established by Bonal et al. (2016), to propose a 3.x subclassification framework.

OM constitutes roughly 50% of the total organic carbon found in carbonaceous chondrites; however, thermal metamorphism has the potential to degrade or alter these organic materials (Alexander et al. 2007). Raman spectroscopy serves as a precise method for evaluating the structural order of OM in the classification of type 3 chondrites (Bonal et al. 2016; Yesiltas et al. 2021). The analysis focuses on quantifying the carbonization and graphitization processes of OM by examining the D-band and G-band parameters. These parameters serve as indicators of the overall deterioration experienced by the meteorite (Quirico et al. 2003, 2005; Bonal et al. 2006, 2007). Prior research has demonstrated that meteorites classified within the same chemical group derive from a singular parent body (Krot et al. 1995; Greenwood et al. 2020). Supporting evidence comprises fragments from various CV subtypes identified in specific CV_{red} chondrites, including Mokoia, which exhibits both CV_{oxA} and CV_{oxB} lithologies, and Vigarano, which contains fragments of CV_{ox} chondrites (Krot et al. 1998, 2000).

The onion-shell model (OSM) was initially introduced by Wood (1967) to elucidate the thermal stratification of ordinary chondrite parent bodies. The concentric, layered structure exhibits an increase in metamorphic degree with depth: the core encounters the highest temperatures, which gradually decrease toward the outer layers, leading to a radial distribution of petrologic types. The central core is occupied by higher petrologic types, such as types 6 to 7, whereas lower types, including type 3, are located nearer to the surface. This concept is backed by multiple studies (e.g., Pellas and

Storzer 1981; Trieloff et al. 2003; Gail and Trieloff 2019). Numerous lines of evidence have subsequently corroborated the OSM in ordinary chondrite bodies, including ^{244}Pu Fission Track Thermometry (e.g., Pellas and Storzer 1981), thermo chronometric methods (Trieloff et al. 2003), and thermal history modeling (Gail and Trieloff 2019).

Expanding upon these ideas, numerous researchers have implemented the OSM framework in the study of CV chondrites (Davidson et al. 2014; Kooten et al. 2021). Carporzen et al. (2011) identified the unidirectional magnetization in CV3 chondrites as a result of radiogenic heating from the decay of ^{26}Al , which contributed to the partial differentiation and heating of the parent body's crust. Weiss and Elkins-Tanton (2013) proposed that carbonaceous chondrite parent bodies developed metallic cores and generated magnetic fields through dynamo processes. Rapid accretion accompanied by the decay of internal ^{26}Al may lead to a layered structure resembling that of OSM (Rubin 2025). This perspective indicates that CV chondrites could record unique layers of crust or mantle. Some researchers suggest that CK and CV chondrites may have a shared parent body, with CK chondrites deriving from deeper, more metamorphosed regions, whereas CV chondrites are thought to have formed in the crustal layers. CV_{red} chondrites would occupy the outmost crust, followed by CV_{oxB} chondrites at intermediate depths, and CV_{oxA} chondrites at greater depths (Wasson et al. 2013; Greenwood et al. 2010; Ganino and Libourel 2017).

However, more recent research challenges this concept, indicating a more intricate geological history and chemical evolution, which may even involve distinct parent bodies for CV_{ox} and CV_{red} chondrites (Ganino and Libourel 2017; Gattacceca et al. 2020). The present research focuses on improving the understanding of the NWA 16080 meteorite through the examination of its petrological, mineralogical, and Raman spectroscopic features utilizing scanning electron microscopy (SEM), EPMA, and micro-Raman spectroscopy. This study involves experimental analyses to classify the group and subtype of meteorite NWA 16080, characterize its petrological features, assess its degree of thermal metamorphism, and examine the environmental conditions that contributed to the formation of NWA 16080. This study thoroughly investigates the petrological and mineralogical features, in conjunction with Raman spectroscopic data of OMs in NWA 16080. It seeks to assess its alignment with the OSM and clarify the thermal evolution of the parent body as well as the processes of the early solar system.

2 Sample and analytical methods

NWA 16080 is classified as a carbonaceous chondrite and was obtained by Bingan Miao in July 2018 from Rex, a

meteorite dealer based in Beijing. The sample had a mass of 16.0 g and exhibited three smoothly cut surfaces, in addition to a partially preserved black-brown fusion crust (Fig. 1). The crust comprises sizable CAIs measuring approximately 5 mm, along with a few remaining chondrules. The cut surface displays clear chondrules measuring between 1 and 5 mm, along with small white refractory inclusions approximately 1 mm in size. The sample was processed into a polished section and a thin section approximately 0.03 mm in thickness.

The experiments detailed in this study were carried out at the Guangxi Key Laboratory of Exploration for Hidden Metallic Ore Deposits, located at Guilin University of Technology. The project primarily entailed utilizing an Axio Scope.

A Carl Zeiss A1 polarized microscope, designed for both transmitted and reflected light observation, was utilized to examine the petrological characteristics of the samples. Following the carbon coating of the meteorite's thin sections, a Zeiss Sigma field emission scanning electron microscope (SEM) was employed to examine the backscattered electron (BSE) images of the meteorites at an accelerating voltage of 15 keV. This facilitated the qualitative analysis of the minerals. A JEOL JXA-8230 EPMA, produced in Japan, was utilized to conduct quantitative mineral chemistry analyses, encompassing olivine, pyroxene, plagioclase, sulfides, and metallic minerals. EPMA analyses employed an accelerating voltage of 15 keV, a beam current of 20 nA, and a beam diameter of 3 μm . A beam diameter of 1 μm was chosen for smaller mineral particles and compositional zones. The matrix underwent analysis in an approach similar to that of olivine and pyroxene, with the exclusion of recrystallized regions. Standard natural samples obtained from the Institute of Mineral Resources, Chinese Academy of Geological Sciences, served as the reference materials. The peak counting

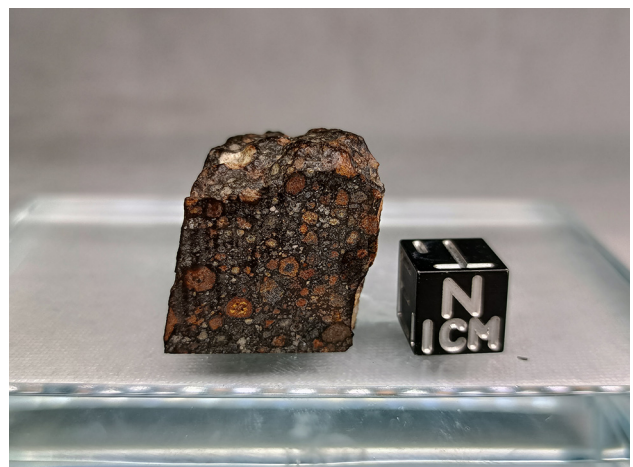


Fig. 1 Photograph of the NWA 16080 sample used in this study

times were 20 s for Na and K; 30 s for Al, Mg, Si, Fe, Ti, Ca, Ni, and Cr; and 60 s for Mn. The raw analytical data were corrected via the ZAF method (Chen et al. 2023) (i.e., atomic number, absorption effect, and fluorescence effect).

The OM in the thin section were analyzed using a Renishaw inVia laser Raman spectrometer, equipped with an Ar+ laser source operating at a wavelength of 514 nm and a power output of 50 mW. A 100× objective lens featuring a numerical aperture (NA) of 0.85 was employed, with an exposure time configured to 150 s. The analysis concentrated on areas with a high density of OM within the thin section, resulting in the collection of 50 spectra (Xia et al. 2024). The data were processed using Origin software, and a Gaussian and Lorentzian curve fitting method was employed to achieve the optimal fit.

3 Results

3.1 Petrological characteristics

NWA 16080 is composed of 47 vol% chondrules, 42 vol% matrix, and 6 vol% refractory inclusions (CAIs + AOAs). The mineralogical composition includes 95 vol% silicates and 5 vol% opaque minerals, as illustrated in Fig. 2. The ratio of matrix to chondrules in terms of modal abundance is 0.89. The primary opaque minerals include troilite, and Fe–Ni metal, along with minor amounts of magnetite. A total of 124 chondrules were identified in the thin section, with the majority exhibiting nearly spherical or elliptical shapes. The largest chondrule measures up to 1916 μm in diameter, exhibiting an average aspect ratio of around 1.43. The textures of the chondrules are mainly porphyritic, comprising approximately 99% of the total chondrules, while a minor fraction, less than 1%, consists of barred olivine chondrules (BO) as illustrated in Fig. 3a. The primary textures of porphyritic chondrules consist of porphyritic-olivine-pyroxene chondrules (POPs, Fig. 3b), porphyritic olivine chondrules (POs, Fig. 3c), and compound chondrules (CPCs, Fig. 3d).

Type I chondrules, which are noted for their high magnesium content in silicate minerals, make up 95% of the porphyritic chondrules. In contrast, the rare Type II chondrules, identified by their iron oxide-rich silicate minerals, represent only 5% of the total. Type II chondrules display a more dispersed arrangement of olivine phenocrysts, characterized by short prismatic forms and larger sizes, accompanied by distinct FeO-enriched rims. The mesostasis in Type II chondrules exhibits a larger size and shows partial devitrification (Fig. 3e).

The compound chondrule features a granular olivine (GO) chondrule texture that is enveloped by a layer of high-Ca pyroxene approximately 25 μm thick, which is subsequently encased by a porphyritic pyroxene (PP) chondrule

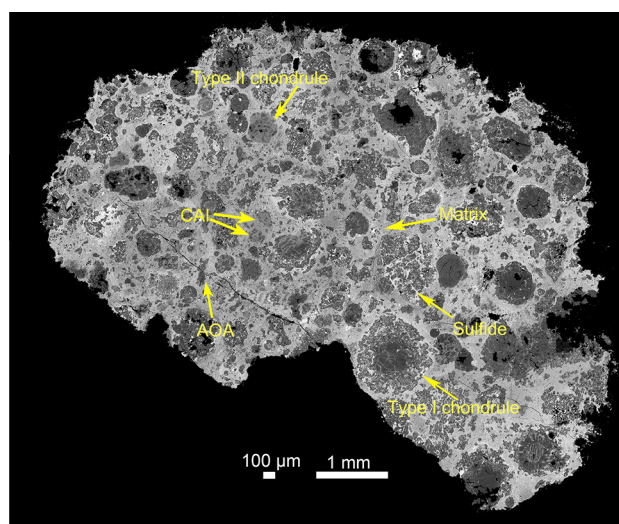


Fig. 2 Backscattered electron (BSE) image of the NWA 16080 thin section. CAI, calcium-aluminum-rich refractory inclusions; AOA, amoeboid olivine aggregates. CAIs and AOAs with diameters more than 150 μm . The matrix is primarily composed of FeO-rich granular silicate minerals. Sulfide and metal grains and aggregates are widely present in chondrules and the matrix. Type I chondrites: Mg-rich and FeO-poor minerals, generally with Fa < 10 mol%; Type II chondrites: More FeO-rich minerals, lighter in color in BSE images, generally with Fa > 10 mol%

texture. Pyroxene primarily consists of low-Ca varieties and exhibits large grain sizes, reaching widths of up to 80 μm . Several residuals, rounded olivine grains are observed encapsulated within pyroxene phenocrysts (Fig. 3d).

About 50% of the chondrules are found at the edges of igneous inclusions, with the maximum thickness reaching around 350 μm , encircled by igneous rims, with a maximum thickness of approximately 350 μm . The composition of these rims primarily includes olivine, low-Ca pyroxene, metal, and sulfides, with metal and sulfide grains frequently found at the boundaries of the rim and chondrule (Fig. 3f).

CAIs include primarily compact Type A (CTA), fluffy Type A (FTA), hibonite-rich CAI, and spinel-pyroxene (sp-px) CAIs (e.g., Fig. 3g, h). The mineral compositions of Type A CAIs (CTA and FTA) are predominantly similar, consisting of 80–85 vol% melilite, spinel, high-Ca pyroxene, and perovskite. All of these inclusions are encased in thin layers of high-Ca pyroxene. In contrast, melilite is largely absent in the sp-px CAI, which features relatively coarse high-Ca pyroxene and spinel grains in the core, measuring approximately 20 and 17 μm , respectively. The inclusions rich in hibonite exhibit a greater structural complexity compared to Type A CAIs, with the primary minerals identified as hibonite, spinel, high-Ca pyroxene, melilite, feldspathoid, and perovskite. AOAs primarily display irregular, worm-like textures characterized by a disordered mineral framework, which includes olivine, high-Ca pyroxene, and spinel

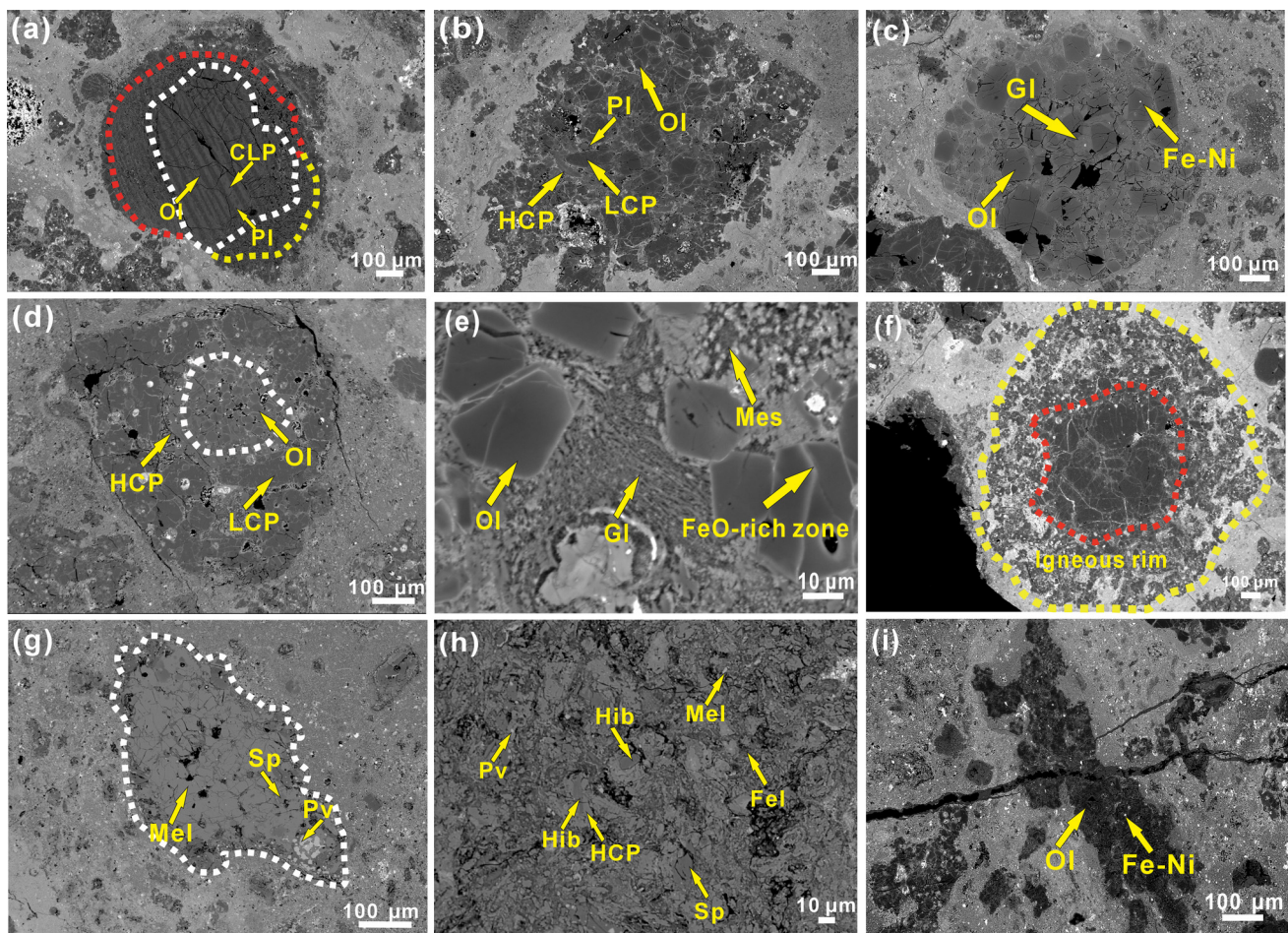


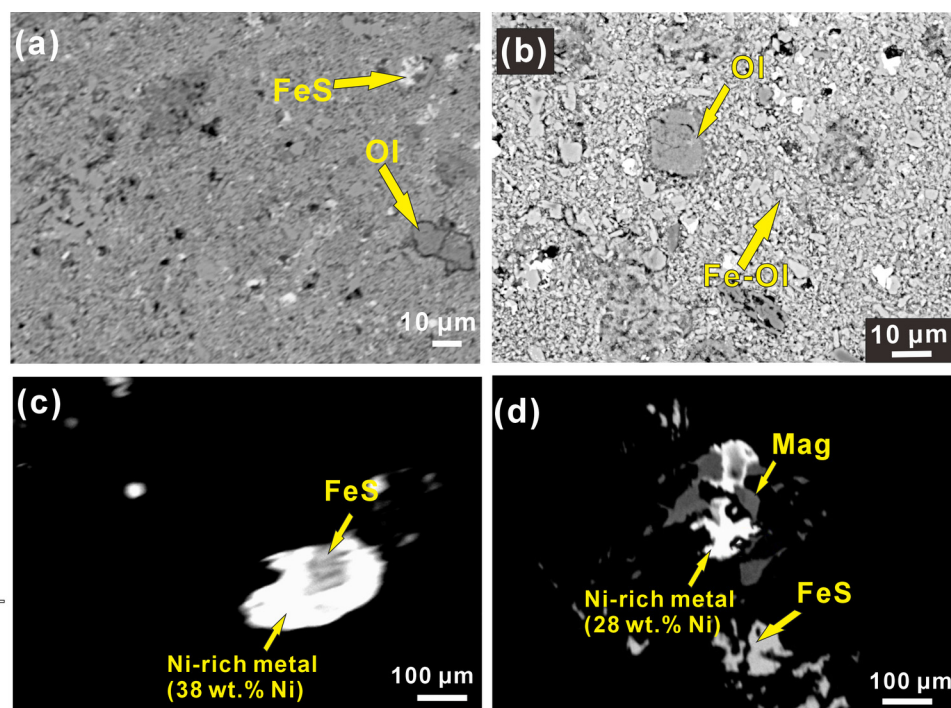
Fig. 3 BSE images of major chondrules, CAIs, and the AOA of NWA 16080. **a** BO chondrule: barred olivine chondrule, composed of three BO chondrules in a comb-like texture; **b** Type I POP chondrule: porphyritic-olivine-pyroxene chondrule, elliptical, surrounded by an irregular igneous rim, with large olivine phenocrysts (~85 μm), distinct high- and low-Ca pyroxenes, and some plagioclase grains; **c** Type II PO chondrule: porphyritic olivine chondrule, subhedral to euhedral olivine with short prismatic shapes; **d** CPC chondrule: Combination of a porphyritic pyroxene and a granular olivine chondrule, with granular olivine encircled by high-Ca pyroxene; **e** Slight recrystallization of the mesostasis in Type II chondrules, with clear compositional zoning at the olivine rims; **f** The largest igneous inclusion observed in the chondrules, approximately 350 μm in thickness; **g** A representative region of a hibonite-rich CAI, with anhedronal to subhedronal hibonite and slightly darker spinel; **h** A representative region of a hibonite-rich CAI, with anhedronal to subhedronal hibonite and slightly darker spinel; **i** AOA: Worm-like feature and irregular shape with clustered texture. Ol, olivine; HCP, high-Ca pyroxene; LCP, low-Ca pyroxene; Pl, plagioclase; Px, pyroxene; Sp, spinel; Mel, melilite; Mes, mesostasis; Pv, perovskite; Fel, feldspathoid-like mineral; Hib = hibonite; Fe–Ni, Fe–Ni metal; FeO-rich zone, FeO-rich olivine zone

(Fig. 3i). The olivine present in AOAs exhibits a compositional gradient, transitioning from magnesium-rich cores to iron-rich rims.

The matrix of the NWA 16080 displays a fine-grained texture, predominantly consisting of FeO-rich silicate minerals. In BSE images, the olivine grains exhibit a relatively dark appearance, averaging less than 2 μm in size; however, larger olivine grains are also observed, with dimensions reaching up to 6 μm (Figs. 4a, b). The matrix predominantly consists of opaque minerals, including troilite, sulfides, and Fe–Ni alloys, along with minor oxides like magnetite. These opaque minerals primarily display fine-grained and irregular textures and are extensively found within the chondrules, refractory inclusions, and matrix.

Opaque minerals are frequently located at the peripheries of the chondrules. The chondrules contain opaque minerals mostly composed of sulfides (4 vol%), with minor metals (1 vol%) and trace amounts of magnetite present. The sulfides consist primarily of troilite, display irregular shapes, and are largely concentrated within the matrix of type I chondrules. A limited amount of the rounded metallic minerals is located on the surfaces of the silicate minerals (Fig. 4b). The metals in question are primarily rich in nickel (nickel metal), while a minor fraction consists of nickel-poor variants (such as iron metal or metallic iron) (Figs. 4c, d).

Fig. 4 Backscattered electron images of the NWA 16080 matrix and opaque minerals. **a** and **b** Images of the matrix in the NWA 16080 thin section, showing anhedral, granular FeO-rich olivine as the main mineral. **c** and **d** Images of metal and sulfides in the NWA 16080 thin section, displaying irregular texture. Fe-Ol, FeO-rich olivine; Mag, Magnetite; FeS, Sulfide



3.2 Mineral chemistry

Tables 1 and 2 provide a summary of the major element compositions found in silicates, metals, and sulfides within the NWA 16080 meteorite. The olivine present in the chondrules is primarily forsterite, exhibiting Fa values [molar $100 \times \text{Fe}/(\text{Mg} + \text{Fe})$] that range from 0% to 45% (Fig. 5). Type I chondrules generally exhibit olivine cores with a Fa content that is usually below 10%, presenting an average Fa# value of $3.86\% \pm 1.62\%$. Olivine cores in Type II chondrules exhibit Fa values greater than 10%, with an average Fa value of $12.7\% \pm 4.2\%$. The Fa values in the rim regions of Type II olivine phenocrysts are typically higher, measuring $26.4\% \pm 7.9\%$, compared to the rims of Type I olivine phenocrysts, which are at $16.0\% \pm 7.4\%$.

The olivine present in the AOAs exhibits Mg-rich cores and Fe-rich rims, displaying Fa values that range from 1.69% to 18.8%, with an average Fa value of $5.84\% \pm 5.03\%$. The Fe-rich olivine exhibits trace quantities of MnO. The matrix primarily consists of fine-grained FeO-rich

olivine, exhibiting a broad compositional range. The Fa values span from 53.9% to 69.0%, yielding an average of $59.2\% \pm 4.2\%$. The low-calcium pyroxene found in chondrules is mainly made up of enstatite, while the high-calcium pyroxene is chiefly characterized by augite. The majority of pyroxenes are rich in magnesium, with a minor proportion showing slight enrichment in iron. These pyroxenes also demonstrate considerable compositional variability, ranging from $\text{En}_{51.0-98.6}\text{Fs}_{0.71-10.9}\text{Wo}_{0.89-41.0}$. Additionally, the low-Ca and high-Ca pyroxene found in the chondrules exhibit comparable MnO concentrations (refer to Table 2). In CAIs, the predominant pyroxenes are high-Ca pyroxenes that consist of fassaite. Furthermore, this study identified hedenbergite in CAIs, with relatively high FeO (25.1 to 28.9 wt%) and CaO (21.6 to 30.1 wt%) contents. In AOAs, the pyroxenes are predominantly high-Ca pyroxenes, with a small proportion of fassaite enriched in aluminum and titanium. Likewise, the FeO and CaO contents of the high-Ca pyroxenes in AOA are lower than those in the high-Ca pyroxenes found in CAIs. The Na_2O content in all the pyroxenes is

Table 1 EMPA composition data of typical metals and sulfides in meteorite NWA 16080 (wt%)

	Troilite		Kamacite		Taenite	
	Range	Mean	Range	Mean	Range	Mean
Fe	62.1–63.4	62.3 ± 0.43	89.8–96.3	94.4 ± 2.43	52.5–63.0	61.2 ± 2.51
Cr	0–0.06	0.02 ± 0.02	0.01–0.35	0.26 ± 0.12	0–1.15	0.2 ± 0.34
Ni	0–0.21	0.06 ± 0.07	4.04–9.21	5.09 ± 1.87	34.6–44.1	37.6 ± 2.14
S	35.2–36.4	35.8 ± 0.34	0–0.02	0.01 ± 0.01	0.04	0.01 ± 0.01
Total	97.6–99.5	98.5 ± 0.62	97.7–100.8	99.8 ± 1.07	96.7–100	99.0 ± 1.05

Table 2 EMPA composition data of major silicate minerals in meteorite NWA 16080 (wt%)

	Olivine			Pyroxene			Plagioclase		
	Type I chondrules		Type II chondrules	AOA (Olivine)		chondrules	CAI	AOA	chondrules
	Core	Zone	Core	Zone		LCP	HCP	HCP	
Na ₂ O	0.01 ± 0.01	0.02 ± 0.02	0.02 ± 0.02	0.02 ± 0.03	b, d	0.01 ± 0.01	0.08 ± 0.17	0.05 ± 0.05	1.52 ± 0.23
MgO	57.0 ± 1.16	45.0 ± 7.21	49.4 ± 3.71	38.7 ± 6.03	52.1 ± 5.90	40.4 ± 0.55	25.0 ± 6.20	9.38 ± 9.31	0.83 ± 0.56
Al ₂ O ₃	0.08 ± 0.06	0.30 ± 0.55	0.03 ± 0.02	3.19 ± 3.50	1.22 ± 3.84	0.95 ± 0.32	3.36 ± 0.93	7.75 ± 8.20	35.7 ± 0.72
SiO ₂	40.4 ± 2.29	39.7 ± 1.49	38.9 ± 0.61	35.8 ± 3.39	39.6 ± 1.83	57.2 ± 0.18	51.9 ± 2.81	41.6 ± 8.92	44.8 ± 0.55
K ₂ O	0.01 ± 0.01	0.01 ± 0.02	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.01 ± 0.01	0.02 ± 0.00	0.01 ± 0.02
FeO	0.08 ± 1.70	14.9 ± 6.12	12.8 ± 4.04	24.4 ± 5.36	6.29 ± 5.31	0.77 ± 0.16	2.03 ± 2.50	14.0 ± 14.4	1.35 ± 0.55
Cr ₂ O ₃	0.15 ± 0.14	0.08 ± 0.05	0.11 ± 0.06	0.13 ± 0.15	0.20 ± 0.38	0.53 ± 0.14	0.78 ± 0.45	0.23 ± 0.33	0.03 ± 0.03
TiO ₂	0.07 ± 0.06	0.03 ± 0.03	0.06 ± 0.05	0.06 ± 0.12	0.10 ± 0.17	0.15 ± 0.09	1.10 ± 0.96	1.60 ± 3.48	0.09 ± 0.21
CaO	0.23 ± 0.06	0.19 ± 0.07	0.13 ± 0.07	0.34 ± 0.63	0.63 ± 1.25	0.78 ± 0.40	15.1 ± 5.43	24.7 ± 4.74	17.0 ± 0.55
MnO	0.12 ± 0.05	0.19 ± 0.11	0.02 ± 0.02	0.28 ± 0.09	0.12 ± 0.06	0.15 ± 0.06	0.19 ± 0.13	0.11 ± 0.13	0.01 ± 0.01
NiO	0.01 ± 0.01	0.21 ± 0.36	0.04 ± 0.03	0.07 ± 0.03	0.20 ± 0.30	0.06 ± 0.05	0.37 ± 0.76	0.16 ± 0.10	0.07 ± 0.06
Total	102.2 ± 0.4	100.7 ± 0.95	101.7 ± 0.42	101.1 ± 0.4	100.4 ± 0.47	101.1 ± 0.57	99.9 ± 1.16	99.4 ± 0.37	101.5 ± 0.38
Fa/En/An	3.86 ± 1.62	16.0 ± 7.40	12.7 ± 4.22	26.4 ± 7.85	6.27 ± 5.64	97.6 ± 0.65	66.9 ± 12.7	70.9 ± 11.7	86.0 ± 2.15

b, d = below the detection limit; Fa = 100 × molar FeO/(MgO + FeO); En = 100 × molar MgO/(CaO + MgO + FeO); An = 100 × molar CaO/(CaO + Na₂O + K₂O)

*At high resolution, the focus position of the electron beam of the electron probe may drift slightly, resulting in slight errors in the data

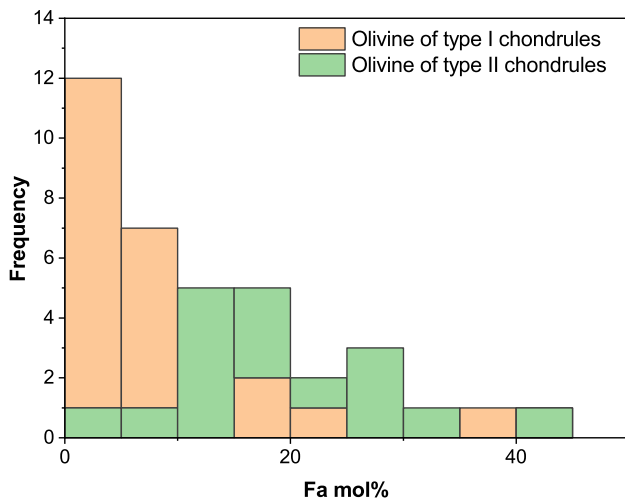


Fig. 5 Fa value histogram of olivine in chondrules in the NWA 16080 thin section. The Fa values of olivine in Type I chondrites are mainly less than 10 mol%, whereas those in Type II chondrites have a wider range, concentrated between 10 and 30 mol%. In the Fa₂₀ to Fa₄₀ range, Type II chondrites have a higher frequency, indicating that they generally contain more FeO

very low (mostly below the detection limit). Feldspars are predominantly located in the chondrites and CAIs of the NWA 16080 meteorite. The primary feldspar present is plagioclase, mainly bytownite (An_{83.1–92.0}Or_{0.00–0.40}Ab_{7.95–16.8}), characterized by a consistent composition and trace quantities of anorthite.

The primary metallic phases identified in NWA 16080 include taenite, exhibiting nickel content between 34.6 and 44.1 weight percent, and kamacite, which contains nickel at levels not exceeding 10.0 weight percent. The metal composition shows significant variation, with Ni contents varying from 4.04 wt% to almost 44.1 wt%. The main sulfide phase identified is troilite (FeS), exhibiting a nickel content that ranges from approximately 0.03 wt% to 0.21 wt%. The atomic ratio of Fe/S in troilite ranges from 1.00 to 1.01, while a minor presence of pyrrhotite exhibits a Fe/S atomic ratio between 0.97 and 1.09.

3.3 Raman spectroscopy of OM_s

50 Raman spectra of OM_s were acquired from various matrix locations in thin section samples of the NWA 16080 meteorite, following the experimental methods detailed in prior literature (Bonafant et al. 2006). The D-band and G-band of carbonaceous material were identified within the range of 850–2100 cm⁻¹ (Fig. 6). The spectra conformed to a Lorentzian distribution, consistently exhibiting first-order D- and G-band characteristics at around 1350 cm⁻¹ and 1580–1600 cm⁻¹, respectively (Tuinstra and Koenig 1970; Ferrari and Robertson 2000). The D and G

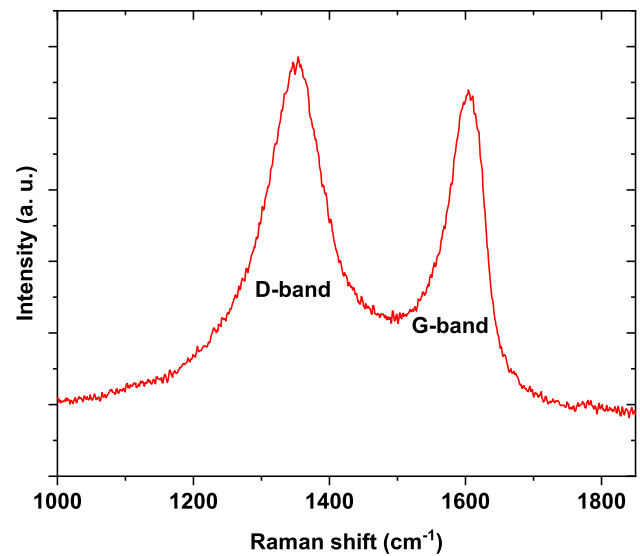


Fig. 6 Typical Raman spectra of OM_s in NWA 16080 matrix and the presence of D and G bands in the OM_s

bands exhibited comparable intensities, resulting in an I_D/I_G ratio of 1.00 ± 0.05 . The Raman shifts of the D and G bands (ω_D and ω_G , respectively) exhibited stability, with $\omega_D = 1354 \pm 1.69$ cm⁻¹ and $\omega_G = 1595 \pm 1.29$ cm⁻¹. However, the full width at half maximum (FWHM) values for the D-band and G-band (Γ_D and Γ_G , respectively) exhibited minor fluctuations, especially for $\Gamma_D = 141 \pm 23.8$, indicating a significant range of variation, which in turn influences the computation of the OM peak metamorphic temperature (PMT). The PMT was determined to be 396 ± 65.9 °C (refer to Table 3), while certain OM peak temperatures were observed to surpass 500 °C. The Γ_G value ($\Gamma_G = 85 \pm 6.78$) was smaller than Γ_D , and the $FWHM_D/FWHM_G$ ratio (1.65 ± 0.20) was greater than 1.

4 Discussion

4.1 Classification and subtypes of the NWA 16080 meteorite

NWA 16080 is identified as a CV carbonaceous chondrite due to its significant presence of chondrules, matrix, and refractory inclusions, aligning with the characteristic traits of CV chondrites (Mcsween 1977; Kimura and Ikeda 1998; Krot et al. 1999; Hezel et al. 2013). These abundances exceed those typically found in CR chondrites (Komatsu et al. 2015). The detection of trace amounts of magnetite reinforces its categorization as a CV chondrite, thereby ruling out its classification as CK chondrite (Dunn et al. 2016).

NWA 16080 chondrite is additionally categorized as a CV_{red} chondrite. The NWA 16080 chondrite is distinguished

Table 3 Typical Raman parameters (cm^{-1}) of OMs and peak temperature calculations for NWA 16080

Γ_D	Γ_G	ω_D	ω_G	I_D/I_G	$\text{FWHM}_D/\text{FWHM}_G$	PMT($^{\circ}\text{C}$)
171	89	1353	1595	0.99	1.92	325
148	85	1353	1594	0.99	1.74	376
168	90	1353	1595	0.99	1.87	331
163	91	1353	1594	0.99	1.79	341
151	85	1353	1595	0.99	1.78	368
151	87	1354	1595	1.00	1.74	368
151	91	1355	1594	1.00	1.66	368
147	88	1354	1594	1.00	1.67	378
140	90	1355	1594	1.00	1.56	395
152	90	1354	1594	1.00	1.69	366
89	66	1352	1598	1.00	1.35	549
143	87	1356	1594	1.00	1.64	388
168	86	1352	1594	1.01	1.95	331
147	89	1357	1594	1.01	1.65	378
155	87	1352	1595	1.01	1.78	359

The PMT ($^{\circ}\text{C}$) is calculated via the formula $\text{PMT} = 931 - 5.10 \times \Gamma_D + 0.0091 \times \Gamma_D^2$, based on data from Busemann et al. (2007)

FWHM, Full width at half maximum; Γ_D , the value of FWHM-D; Γ_G , the value of FWHM-G; ω_D , Position of the D peak; ω_G , Position of the G peak

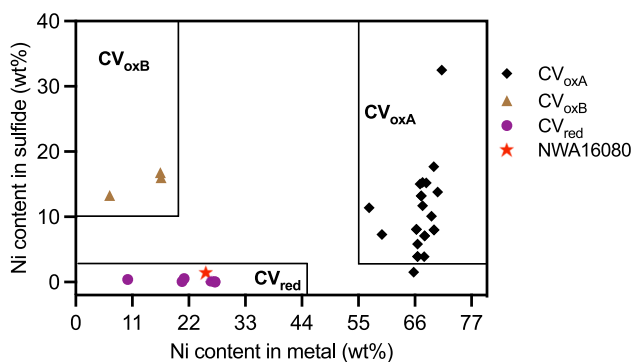


Fig. 7 Ratios of metal and sulfide Ni contents in the NWA 16080 to CV meteorite subgroup. Based on data from Richter et al. (2023), the NWA 16080 meteorite contains Ni-rich metal and Ni-poor sulfides, with parameters falling within the CV_{red} chondrite range

by its high-Ni metals and low-Ni sulfides, with the ratio of Ni content in metals to sulfides (Fig. 7) categorizing it within the CV_{red} chondrites field (Richter et al. 2023). NWA 16080 exhibits a high metal content, features only trace amounts of magnetite, and is devoid of nickel-rich minerals ($\text{Ni} > 50 \text{ wt\%}$). Additionally, the mineralogical characteristics provide further evidence for its classification. The chondrule minerals exhibit a magnesium-rich composition, suggesting a primitive origin, and are devoid of secondary minerals that are usually produced by iron-alkali halogen metasomatism and aqueous alteration processes. The independent Fe-rich olivine crystals that are typically found in CV_{ox} chondrites (Krot et al. 1998) were not detected in the

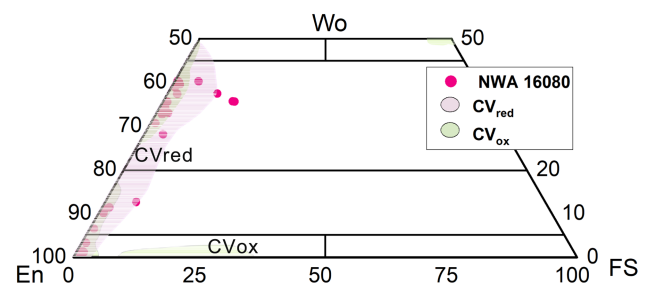


Fig. 8 Compositional range of pyroxene in the NWA 16080 chondrite. The shaded areas are derived from the data presented by Kimura and Ikeda (1997), Takaaki (1989), and Krot et al. (1998). The pyroxene in the chondrules of NWA 16080 is Mg-rich and Fe-poor, with no hedenbergite, aligning with the CV_{red} chondrite range

NWA 16080 chondrite. The matrix olivine in NWA 16080 exhibits a fine-grained and anhedral structure, contrasting with the coarse, lath-shaped olivine typically observed in numerous CV_{ox} chondrites. The Fa contents range from 53.9% to 69.0%, which is higher than those found in Leoville (Fa_{45-60}), and Vigarano (Fa_{35-45}) but lower than those in CV_{ox} chondrites ($\text{Fa}_{<90}$) (e.g., Kaba and Mokoia) (Krot et al. 1995). Pyroxene compositions are also consistent with CV_{red} characteristics. The pyroxenes found in the chondrules primarily display low-Ca, Mg-rich, and Fe-poor compositions, with Wo values concentrated in two specific ranges: $\text{Wo} < 20$ and $\text{Wo} 30-45$. Pyroxene in the NWA 16080 chondrite has a composition that aligns more closely with that of the CV_{red} chondrites (Fig. 8). Unlike CV_{ox} chondrites, no hedenbergite grains are found in the chondrules of NWA 16080. Instead,

hedenbergite is limited to CAIs, consistent with the characteristics of CV_{red} chondrites.

The classification of the shock deformation stage of meteorites is typically based on microscopic structural features (Stöffler et al. 1991; Rubin 1997). This classification system, while primarily designed for ordinary chondrites, has also seen partial application in the context of CV chondrites (e.g., Rubin 2012). In thin-section observations of NWA 16080, the manner of extinction in olivine and pyroxene is not readily apparent. The outlines of chondrules are distinctly defined, and the structural relationship between chondrules and the matrix is maintained effectively. Furthermore, there was no indication of plastic deformation or the presence of shock-induced melt pockets, while certain minerals displayed notable fractures. From these observations, it can be inferred that NWA 16080 underwent low shock pressure, resulting in its classification as shock stage S1. The degree of terrestrial weathering in meteorites is mainly

determined by the oxidation processes affecting metallic phases and sulfides (Wlotzka 1993). In NWA 16080 (Fig. 9), certain metal grains exhibit slight oxidation, resulting in the formation of dark oxide rims, whereas others maintain their original, unaltered condition. The matrix exhibits no notable darkening, and there are no extensive indications of oxide-filled fractures. The observations indicate that NWA 16080 has experienced minimal terrestrial weathering, resulting in negligible effects on its mineralogy and structure. As a result, the weathering grade is designated as W2.

4.2 Thermal metamorphic and petrologic types

The chondrules present in the NWA 16080 meteorite display distinct, almost translucent outlines. The lack of coarse-grained plagioclase and additional mineralogical characteristics further suggest that this meteorite is classified as a type 3 chondrite. The criteria for classifying the petrologic types

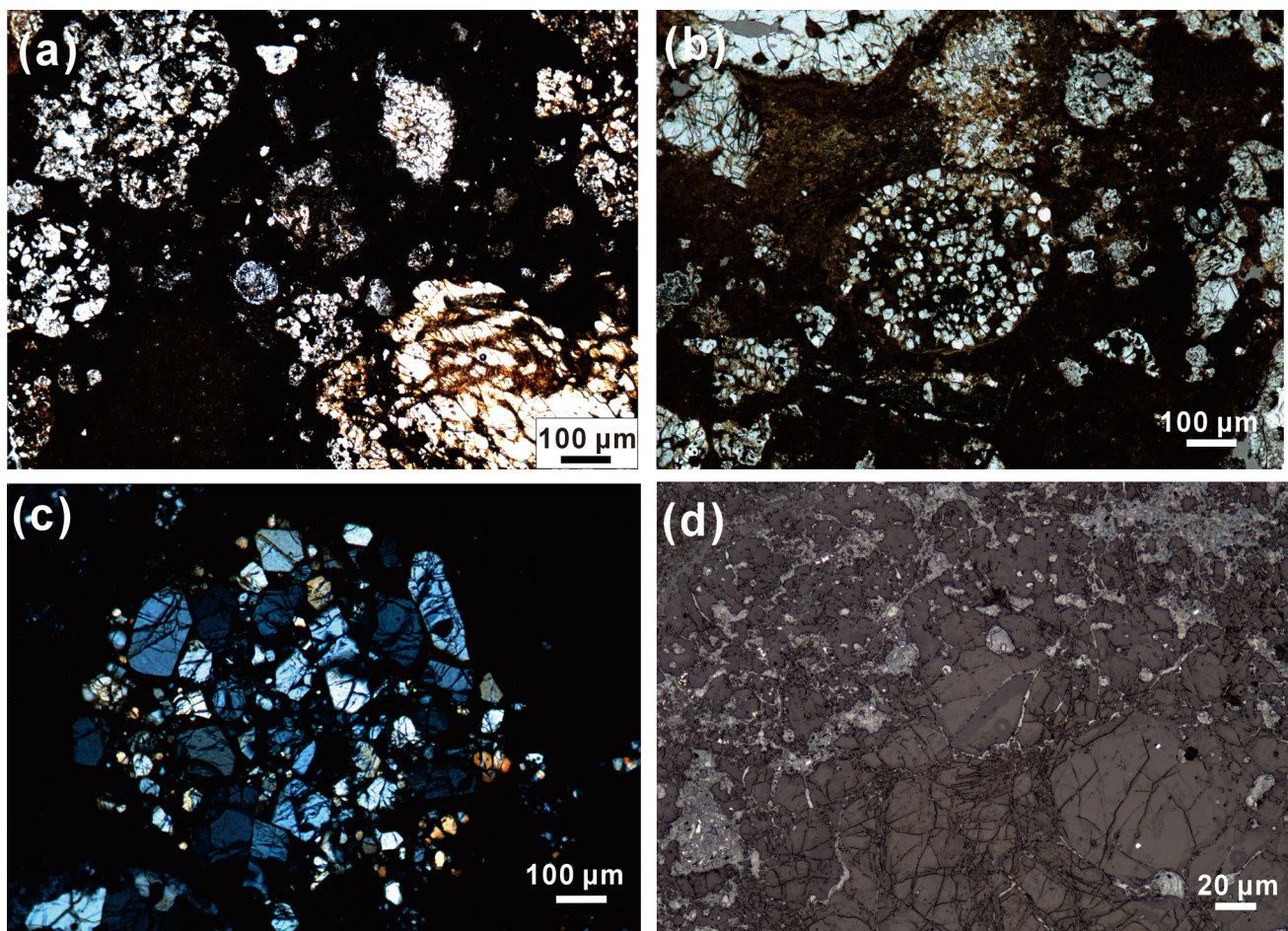


Fig. 9 Optical microscopoe images of the NWA 16080. **a** Plane-polarized light image, chondrule boundaries are well defined, cracks are fine and clear, matrix is not strong recrystallized. **b** Plane-polarized light image, the chondrule and matrix structures are distinct, with a uniform matrix. **c** Cross-polarized light image, the pyroxene and olivine crystals within the chondrule are clearly visible, with no signs of wavy extinction or plastic deformation. **d** Reflected light image, the metallic grains exhibit clear reflectivity, but some grains show slight darkening, indicating partial oxidation

of CV3 chondrites are currently inconsistent. According to McSween (1977), CV chondrites exhibit relatively low levels of thermal metamorphism, categorizing their petrologic types within the range of 3.1 to 3.3. Guimon et al. (1995) proposed a metamorphic sequence for CV3 chondrites based on TL data; however, this approach was at odds with the Raman-based studies of OM conducted by Bonal et al. (2006). This research categorizes the NWA 16080 meteorite through the application of mineral chemistry, textural characteristics, and OM maturity parameters (Grossman and Brearley 2010; Bonal et al. 2006, 2016; Kimura et al. 2024). In the following section, we consolidate multiple lines of evidence to assess the petrologic classification of NWA 16080.

Grossman and Brearley (2010) as well as Kimura et al. (2024) have indicated that carbonaceous chondrites with petrologic types exceeding 3.1 generally show olivine Cr_2O_3 concentrations below 0.25 wt%. In NWA 16080, the measured Cr_2O_3 in olivine cores is significantly below 0.25 wt%, indicating a petrologic type distinctly above 3.1.

Bonal et al. (2006) noted the absence of significant olivine zoning in CV chondrites classified as types 3.0 to 3.2, while more metamorphosed CV chondrites, such as Mokoia (type ~3.6), exhibit distinct compositional zoning. In NWA 16080, chondrule olivine exhibits distinct zoning with notable Fe enrichment, indicating a metamorphic degree exceeding 3.2–3.3 yet remaining below 3.6, as its OM maturity is still less than that of Mokoia (Fig. 10a). Sears et al. (1980) indicates that sulfide Ni contents less than 0.5 wt% frequently suggest types greater than 3.2. The characteristics

of NWA 16080, including low nickel content in sulfides and the occurrence of fine-grained silicates within the matrix—lacking significant recrystallization or coarse plagioclase—indicate a state of moderate metamorphism.

In comparison to CV_{red} chondrites, Efremovka and Vigarano are typically classified as lightly to moderately metamorphosed (types ~3.1 to 3.4; Bonal et al. 2006). Minor iron enrichment is noted along grain boundaries or fractures, although olivine zoning is less distinct. NWA 16080 shows a greater degree of Fe enrichment and marginally elevated OM maturity values, positioning it at or slightly above the metamorphic level of Efremovka (~3.4). Righter et al. (2023) performed a systematic analysis of 119 CV chondrites, incorporating the OM Raman maturity parameters from Bonal et al. (2016) to develop a 3.x classification framework. The Raman parameters of NWA 16080 primarily align with petrologic types 3.4 to 3.6.

As a result, by incorporating mineralogical, textural, and organic matter-related parameters, it can be concluded that NWA 16080 is most accurately characterized as situated between type 3.4 and 3.5.

The Raman parameters of the carbonaceous material in NWA 16080 exhibit a broad spectrum of absolute variations (Fig. 10a), with the average I_D/I_G ratio being around 0.99. This ratio suggests that OM exhibits a relatively immature state overall, indicating a balance between disordered and ordered carbon, and reflecting a slightly ordered condition. Furthermore, certain OM exhibit I_D/I_G ratios exceeding 1, signifying a higher maturity level of these materials. The Γ_D values with the full width at half maximum (FWHM) are

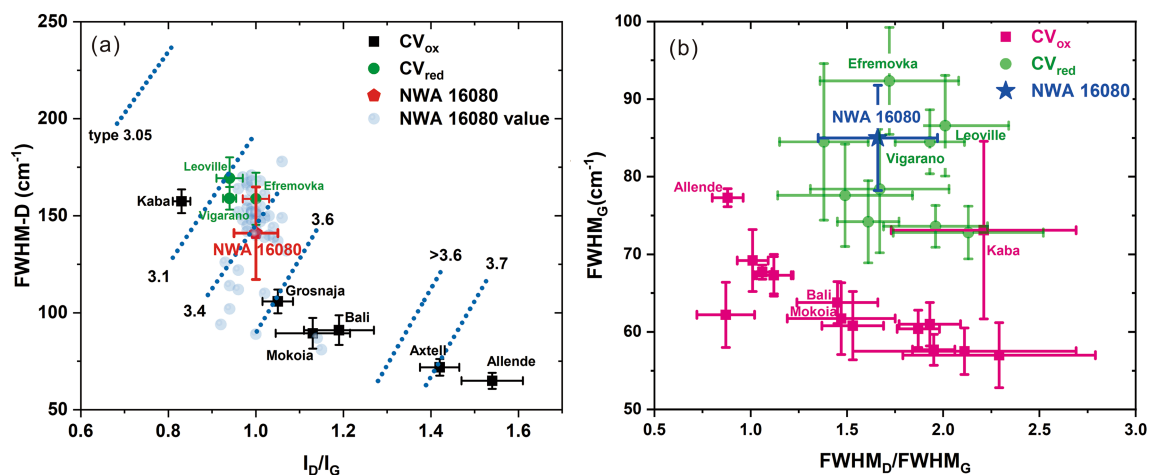


Fig. 10 Raman parameter diagram of OM in the NWA 16080 meteorite and other CV chondrites. **a** FWHM-D versus I_D/I_G ratio plot. The blue dashed line shows the petrological type range from previous studies, whereas the green pentagon represents the average Raman parameters of OM in NWA 16080, with significant variation in FWHM-D. **b** FWHM-G versus $\text{FWHM}_D/\text{FWHM}_G$ ratio plot. The blue star represents the Raman parameters of OM from NWA 16080, while the pink squares and green circles denote those of OM from CV_{ox} meteorites and CV_{red} chondrites respectively. The FWHM-G of OM from NWA 16080 is higher than that of CV_{ox} meteorites. CV_{red} chondrites include GRO 95652, MIL 07277, QUE 97186, RBT 04133, RBT 04143, RBT 04302. CV_{ox} chondrites include ALH 81003, ALH 85006, GRA 06101, LAP 02206, LAR 06317, MCY 05219, MET 00430, MET 00761, MET 01074, MIL 091010, QUE 94688. Source data: Bonal et al. (2006), Bonal et al. (2016), and Righter et al. (2023)

primarily centered around 150 cm^{-1} . However, the spectral parameters exhibit a broad distribution, with the minimum recorded at less than 100 cm^{-1} . This indicates that the maturity of organic materials in NWA 16080 is not consistent. With the progression of OM's maturity, there is a tendency for the Γ_D values to decline, while the I_D/I_G values generally increase. In two regions of this sample, the Γ_D values are negatively correlated with the corresponding I_D/I_G values (Bonal et al. 2006; Busemann et al. 2007). The Γ_D values of approximately 150 cm^{-1} in the OM's of NWA 16080 are close to and partially overlap with those of some CV_{red} chondrites, which exhibit lower I_D/I_G values. As the maturity of some OM's increases, the I_D/I_G values gradually increase, whereas the Γ_D values tend to decrease, partially overlapping with some CV_{ox} chondrites that contain more mature OM's. The results indicate that the area within the meteorite exhibiting high I_D/I_G values has experienced a significant level of metamorphism. The absolute values of the Raman parameters for NWA 16080 are distributed across three distinct regions (Fig. 10a), suggesting that the degree of metamorphism varies.

4.3 Conflict between the reducing formation environment and the onion-shell model

The metal phases present in the NWA 16080 chondrite consist mainly of taenite and kamacite, along with minor quantities of magnetite. In contrast, CV_{ox} typically contains abundant magnetite and reduced metal content (Mcsween 1977). The mineralogical differences suggest that the parent body region of NWA 16080 experienced a more reducing environment, as iron was not extensively oxidized into magnetite. Furthermore, the presence of Mg-rich silicate minerals and the extensive compositional variability noted in chondrule pyroxenes (Fig. 8) suggests a restricted supply of FeO, which contrasts with the FeO-rich silicates commonly found in CV_{ox} chondrites. Chondrites may undergo secondary modifications through processes such as thermal metamorphism, aqueous alteration, shock metamorphism, and terrestrial weathering (Botta and Bada 2002; Pizzarello 2006). In arid desert conditions, contamination or oxidative weathering can influence the native organic fractions (Busemann et al. 2007; Alexander et al. 2007), although contaminant organics generally exhibit unique Raman signatures. In contrast, NWA 16080 shows minimal shock effects (S1), lacking high-pressure phases or significant melting, indicating that shock likely did not have a major impact on its overall OM's maturity. Terrestrial weathering (W2) exhibits a moderate nature, characterized mainly by localized oxidation occurring on metal grains rather than extensive alteration. Although low-level shock and weathering may introduce slight variations, they do not significantly influence the thermal indicators. Furthermore, processes such as

fluid-rock interaction (Ganino and Libourel 2017) contributed to the resemblance of secondary minerals, reinforcing the perspective that the crust of the CV3 meteorite parent body was not stratified. According to Fu et al. (2021), the strong magnetization of Allende attributed to pyrrhotite may provide a more precise representation of the magnetic field conditions present in the early solar nebula, as opposed to the thermal differentiation of the parent body or the activity of the generator. Consequently, this conclusion somewhat diminishes the backing for the differentiation parent body model.

The present study follows the Raman spectroscopy procedures described by (Bonal et al. 2006; Busemann et al. 2007). The experimental error margins may exhibit slight variations across different meteorite samples; therefore, the deviations noted in the Raman parameters of NWA 16080 fall within the ranges recorded in these studies. We recognize that measurement uncertainties are present and may have a minor impact on the accurate distribution of OM's maturity data. The FWHM-G values in NWA 16080 are typically greater than those observed in the CV_{ox} chondrites, which exhibit a relatively narrow FWHM-G range (Fig. 10b). However, the comparatively high FWHM-G values observed in Kaba and Allende could result not only from variations in oxidation conditions but also the precursor nature of the OM (Bonal et al. 2016). NWA 16080 displays a range of maturity in OM, with certain areas demonstrating thermal levels similar to CV_{ox} chondrites. The peak temperatures range from 311 to 577 °C, overlapping with values reported for Allende (330–600 °C) and Kaba (300–420 °C) using comparable spectroscopic methods (Rietmeijer and Mackinnon 1985; Huss and Lewis 1994; Bonal et al. 2006, 2016). This presents a challenge to the OSM of chondrites, which suggests that chondrites come from varying depths within their parent body (Weiss and Elkins-Tanton 2013). This model suggests that a parent body featuring a layered thermal structure will display a consistent gradient in metamorphism as depth increases. It implies that regional differences in the degree of thermal metamorphism should be observed among the various layers of the CV parent body, rather than an overlap occurring. Samples obtained from deeper layers are anticipated to exhibit significantly higher maturity levels in contrast to those derived from the surface in OSM. However, the OM maturity parameters in NWA 16080 show significant overlap with CV_{ox} chondrites data, suggesting the absence of a distinct radial thermal gradient (Weiss and Elkins-Tanton 2013). Furthermore, the low shock stage (S1) of NWA 16080 precludes the possibility of mechanical mixing with deep-layered CV_{ox} chondrites' materials. Other CV chondrites, including Kaba, have been noted to exhibit non-stratified maturity distributions (Bonal et al. 2016), indicating that the absence of a layered thermal structure is not exclusive to NWA 16080.

The presence of localized thermal and redox heterogeneities in a single non-equilibrated chondrite is expected; however, the significant overlap of NWA 16080's OM maturity with CV_{ox} chondrites indicates that the variability observed is not merely incidental at the sample scale. Within a rigorous OSM framework, it is expected that chondrites from varying depths will group within a maturity range that is separate from those of other layers; however, this is not evident in the current observations. This discrepancy indicates that the simple depth-related thermal gradient anticipated by OSM is not evident in NWA 16080.

While a single sample cannot conclusively disprove the OSM, the features of NWA 16080 raise questions about the OSM of the CV parent body. This indicates that the parent body may not possess a straightforward depth-layered structure and that the thermal metamorphism process could be more intricate.

5 Conclusion

1. NWA 16080 is classified as a CV_{red} carbonaceous chondrite, distinguished by its primitive mineral compositions within the chondrules, the presence of magnesium-rich and iron-poor pyroxenes, and a comparatively low abundance of matrix material. The matrix olivine is present as anhedral grains, characterized by a significant presence of metal and sulfides, with the compositions of these phases aligning with the CV_{red} chondrite region. The impact and weathering classifications of NWA 16080 are S1 and W2, respectively.
2. Considering the mineralogical characteristics of NWA 16080, such as the Cr₂O₃ contents in olivine, compositional zone, and Ni content in sulfides, along with the OM's maturity indicated by Raman parameters, it is proposed that NWA 16080 be classified as 3.4 to 3.5. NWA 16080 is classified as a moderately metamorphosed CV_{red} chondrite, indicating a more intricate and varied thermal history associated with its parent body.
3. The composition of the chondrules, characterized by a high magnesium and low iron content, along with the higher metal content and broader FWHM-G values in the NWA 16080 chondrite, indicates that it originated in a more reduced environment within the CV parent body. Furthermore, the inconsistent development of the OM's and differences in peak temperatures indicate that the conventional onion-shell model is not suitable in this scenario.

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Declarations

Conflict of interest All coauthors claim no conflict of interest in publishing this manuscript.

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