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# Oued Chebeika 002: A new CI1 meteorite linked to outer solar system bodies

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Abstract-CI1 chondrites are rare meteorites with high scientific value. In fact, they are the most chemically primitive meteorites and show evidence of intense parent-body aqueous alteration. They also share strong similarities with samples from Ryugu and Bennu asteroids returned by the JAXA Hayabusa2 and NASA's OSIRIS-REx missions. In this work, we present a detailed study of the Oued Chebeika 002 meteorite, a ~420 g CI1 chondrite found in Morocco in 2024. We describe its petrography, texture, and mineralogy, with a focus on clay mineralogy. We provide the bulk and mineral chemical composition, as well as the bulk oxygen, iron, and chromium isotopic compositions. Spectroscopic properties were studied by means of infrared and Raman spectroscopies. We also measured the density, grain density and magnetic properties. Our results confirm that Oued Chebeika 002 is a CI1 chondrite, with close similarities to the other five know CI1 chondrites, and samples from Ryugu and Bennu asteroids. Several lines of evidence indicate that Oued Chebeika 002 has suffered no significant terrestrial alteration. It is more pristine in that regard than Alais, Orgueil and Ivuna CI1 chondrites, and more similar to samples from asteroids Ryugu and Bennu. Subtle differences exist between Oued Chebeika 002 and other CI1 chondrites that

cannot be accounted for by terrestrial alteration of the latter. For instance, olivine and calcite were not observed. It is also noteworthy that the magnetic mineral assemblage of Oued Chebeika 002 is significantly different from that of Alais, Ivuna and Orgueil, but undiscernible from that of Ryugu samples. Chromium and iron isotopic composition of Oued Chebeika 002 confirms that CI1 chondrites, like Ryugu samples, are distinct from meteorites belonging to the non-carbonaceous and carbonaceous isotopic groups and may have originated from the same region where ice giant planets and Oort Cloud comets were formed.

#### **INTRODUCTION**

CI chondrite meteorites are important materials in cosmochemistry. Their chemical composition matches that of the solar photosphere within 10% for about 30 elements (e.g., Asplund et al., 2009). All other chondritic groups are significantly fractionated relative to CI chondrites and the solar photosphere (Braukmüller et al., 2018). The CI chemical composition is thus considered the best proxy for the early solar system composition (Lodders, 2003). The CI chemical composition is even considered a reference chemical composition in extra-solar astrophysics (e.g., Trierweiler et al., 2023).

CI chondrites are usually made mostly of phyllosilicates and are therefore classified as petrologic type 1 chondrites. Type 1 chondritic materials are typically found in the form of fine-grained micrometeorites, interplanetary dust particles (IDPs), a few members of the CM and CR chondrite groups (Russell et al., 2021), and rare ungrouped chondrites such as Flensburg (Bischoff et al., 2021). Type 1 chondritic materials are rich in light elements such as hydrogen, nitrogen, or carbon (e.g., Alexander et al., 2012; Hashizume et al., 2024), which are prone to form volatile components in many geochemical environments. This enhancement in light elements compared to other chondrites has been especially scrutinized as their compounds (H<sub>2</sub>O, CO<sub>2</sub> or N<sub>2</sub>) represent (or represented) a significant fraction of planetary atmospheres. Several modeling studies consider type 1 chondritic material as a possible contributor to the planetary budget of light elements and water (e.g., Nimmo et al., 2024). In addition, the nature of important organics such as amino acids in CI1 chondrites is distinct from that in other carbonaceous (CC) chondrites (e.g., Ehrenfreund et al., 2001).

CI1 meteorites are exceedingly rare. Besides Oued Chebeika 002, only nine are listed in the Meteoritical Bulletin Database, but this includes four meteorites collected in the Yamato Mountains in Antarctica (Y-86029, Y-86737, Y-980115, and Y-980134) now identified as metamorphosed and, at least for some of them, unrelated to CI chondrites (King et al., 2019; Schrader et al., 2025; Tonui et al., 2014; Zuh et al., 2025). The five classic CI1 chondrites (Alais, Orgueil, Tonk, Ivuna, Revelstoke) are all falls from

1806, 1864, 1911, 1938, and 1965, respectively. The available material varies from a few grams (Revelstoke and Tonk) to about 13 kg (Orgueil, out of an initial total known weight of 14 kg). From Alais and Ivuna remain only about 600 and 200 g out of an initial total known weight of 6 kg and 705 g. respectively (Grady, 2000). Because most available CI1 material may be sourced from Orgueil, many of the observations on CI1 chondrites originate from that meteorite, limiting potential investigations of CI1 diversity. In addition to these five meteorites, CI1-like material has also been identified as xenoliths in a variety of meteorites such as ureilites (Brearley & Prinz, 1992), howardite, eucrite, and diogenite (HED) achondrites (Zolensky et al., 1996), CR and CH chondrites (e.g., Bischoff et al., 1993), or the Kaidun polymict breccia (Zolensky & Ivanov, 2003). CI1-like materials have also been found among micrometeorites (Genge et al., 2008). However, for these xenoliths and micrometeorites, it is often not possible to classify this material exactly as CI1 because their small size prevents detailed and representative petrographic description. In fact, it has been shown that some CI1-like clasts are not related to CI1 chondrites and should rather be called C1 clasts (Patzek et al., 2020). Moreover, CI1-like micrometeorites may have been modified during atmospheric entry.

CI1 chondrites are dark, and though compact after their fall, tend to crumble with time (e.g., Gounelle & Zolensky, 2014). Unlike any other chondritic group, CI1 chondrites contain very little olivine or pyroxene and lack chondrules (Krot et al., 2014; Rubin, 1997). They are mainly made of phyllosilicates (saponite and serpentine), abundant magnetite, minor carbonates (dolomite, calciumcarbonates, and breunnerite), sulfides (pyrrhotite, pentlandite, cubanite), and phosphates (Alfing et al., 2019).

The distinct mineralogical assemblage of CI1 chondrites is usually interpreted as resulting from aqueous alteration on their parent body (Zolensky & McSween Jr., 1988), though alternative views postulate it can also be accounted for by nebular processes (Ciesla et al., 2003; Thi et al., 2020). The parent-body alteration hypothesis is compatible with the observation that CI1 chondrites have among the heaviest oxygen isotopic compositions (Clayton & Mayeda, 1999; Young et al., 1999). Regardless of the setting, the fact that CI1 chondrites experienced extensive alteration makes them paradoxical rocks: they are the most chemically primitive and the most petrographically modified (Brearley, 2014; Gounelle & Zolensky, 2014).

Similar to many other meteorites (Bischoff et al., 2006), CI1 chondrites are typically brecciated (Morlok et al., 2006). Brecciation can be seen in hand samples through a diversity of black shades and the existence of centimeter-size clasts. In addition, some CI1 chondrites such as Orgueil tend to crumble, producing coherent centimeter-size fragments. As a consequence of that brecciated nature, there is intra-meteorite variability within CI1 chondrites that should be kept in mind when inter-meteorite comparisons are made.

Despite recovery soon after their fall, CI1 meteorites were significantly altered during their terrestrial stay. They contain an unusually high abundance of sulfates (Richardson, 1978) and ferrihydrite (Tomeoka & Buseck, 1988) that probably formed in the terrestrial environment. The growth of sulfate minerals, for example, is now well documented in terrestrial laboratories (Gounelle & Zolensky, 2001; Imae et al., 2024; King et al., 2020). Abundant ferrihvdrite is also considered to have formed in a terrestrial environment (Imae et al., 2024; Leroux et al., 2024; Nakamura et al., 2022; Roskosz et al., 2023). Terrestrial water replaces some indigenous organic compounds in the phyllosilicate interlayers (Viennet et al., 2023). Finally, CI1 chondrites tend to disaggregate with time. The realization that CI1 chondrites have strongly interacted with the terrestrial atmosphere has important consequences for models of planetary atmospheres as well as for the assessment of their oxidation state (Leroux et al., 2024; Roskosz et al., 2023; Thompson et al., 2021).

vIn 2021, about 5 g of the C-type asteroid (162173) Ryugu were returned to Earth by the JAXA Hayabusa2 mission. The chemical, isotopic, and mineralogical properties of Ryugu samples share many common characteristics with CI1 meteorites, providing so far the best available match to the bulk Solar System composition (Ito et al., 2022; Nakamura et al., 2022; Yokoyama, Nagashima, et al., 2023). Though not yet as finely characterized as Ryugu's, the initial analyses of samples from the carbon-rich asteroid (101955) Bennu returned by the NASA's OSIRIS-REx mission in September 2023 also indicate close similarity with CI1 chondrites (Lauretta and Connolly et al., 2024). Therefore, although rare in meteorite collections, CI1 material is probably widespread in the solar system.

Overall, CI1-like materials represent a key component of solar system material, because of their abundance and their primitive chemical composition. Their scarcity in the form of actual meteorites is likely due to a combination of orbital dynamics and poor survivability during atmospheric entry because of the friable nature of the material (Russell et al., 2021). They are also very susceptible to terrestrial weathering due to their friable and porous nature, and their high reactivity with water. This makes them unlikely to survive at the terrestrial surface for extended periods of time. In that context, the addition of significant masses of CI1 meteorites is of the utmost importance.

Here we present a detailed description of Oued Chebeika 002, a new CI1 meteorite found in Morocco in 2024, and compare it with other CI1 meteorites and Ryugu and Bennu samples.

# MATERIAL AND METHODS

As of January 2025, the total recovered weight of Oued Chebeika 002 is 418 g, likely originating from a single broken stone. The five largest fragments weighed 136.4, 33.9, 12.44, 10.64, and 8.0 g (Figure 1). About 173 g of material was collected in the form of millimeter-sized fragments.

The samples studied in this work come from the 33.9 g stone found by Bobaker Bakarrat on June 20, 2024, in Morocco on a sandy surface at location 28°5'34.45" N and 11°32'10.34" W. The recovery area is characterized by an arid climate with about  $100 \text{ mm year}^{-1}$  rainfall (mostly during winter months), in a favorable area for meteorite collection (e.g., Aboulahris et al., 2019). The 33.9 g stone was later bought by Jean Redelsperger. We also obtained material from a collection of millimeter-sized fragments later bought by Mark Lyon. The former material reached the Centre Européen de recherche et d'enseignement des géosciences de l'environnement (CEREGE) on September 1, 2024. The latter material reached CEREGE in November 2024. Since then, these samples have been curated in a desiccator cabinet with a monitored 10% relative humidity.

X-ray microcomputed tomography (micro-XCT) of a 10.407 g stone of Oued Chebeika 002 was performed using the micro-XCT-400 X-ray microscope (Zeiss) of the MATRIX platform at CEREGE. Data were acquired with a tungsten X-ray source at an accelerating voltage of 80 kV and a power of 10 W. The scan consists of 1201 projections at an exposure time of 2 s per projection collected over a 360° rotation of the sample. The sample was placed in a polypropylene sample holder and blocked with polystyrene spacer. The 3-D volume а reconstruction using back-projection filtering (by XMReconstructor, Xradia software) achieved an isotropic voxel size of 28.8 µm and a field of view of  $28.8 \times 28.8 \times 28.8$  mm<sup>3</sup>. Avizo 2020 software (Thermo Scientific, Hillsboro, OR, USA) was used for the visualization, processing, and analysis of the 3-D images.

Additional, higher resolution microcomputed tomography (CT) imaging of three smaller fragments



FIGURE 1. Optical images of fragments of Oued Chebeika 002 with the largest stone of 136.4 g (a, credit Luc Labenne), a 3.96 g stone (b), and a 3.93 g partially crusted stone (c, with a close-up view of the fusion crust on figure d). Scale bar is 1 cm for (a), (b), and (c), and 1 mm for (d).

(~18, ~18, and ~19 mg) was conducted using a Zeiss Xradia Versa 520 CT system at the Natural History Museum (NHM), London. X-rays were generated from a tungsten source (140 kV, ~70  $\mu$ A), and for each fragment, ~2400 projections (exposure time of 10 s/projection) were acquired while it was rotated by 360°. Each projection was magnified by a 4× objective lens, resulting in a spatial resolution (in voxels) of ~2  $\mu$ m.

Thick polished sections were prepared from centimeter-sized fragments following the technique described in Wilson et al. (2024). Sections were first dry polished using silicon carbide sandpaper down to 4000 grit. Sections were then polished with diamond using mineral oil as a lubricant and hexane to clean the sections in-between polishing steps. At the Muséum national d'histoire naturelle (MNHN), Paris, one polished section was examined with a TESCAN CLARA scanning electron microscope (SEM) equipped with dual energy-dispersive X-ray spectroscopy (EDS). It was operated at an acceleration of 15 kV and a working distance varying between 9 and 16 mm. Qualitative mineral chemistry analysis was performed using EDS. Two additional polished sections were imaged with the SEM at CEREGE with a Hitachi S3000N SEM fitted with a Bruker X-Flash/Esprit EDS, at Centre Pluridisciplinaire de Microscopie de Marseille with a Zeiss Gemini 500 FEG-SEM fitted with an EDAX EDS and at Centre Interdisciplinaire de Nanoscience de Marseille (CINaM) with a JEOL JSM-7900F FEG-SEM equipped with a Bruker X-Flash/ESPRIT EDS. Most

images were recorded in a backscattered electron (BSE) mode with an accelerating voltage of 15 kV. Some high-resolution images were recorded with lower accelerating voltages of 10 or 5 kV. Some SEM images were also recorded on broken chips, a few hundred micrometer large, deposited on a carbon tape, to better observe the morphologies of magnetite crystals.

Quantitative mineral elemental compositions were obtained with an SX-Five electron microprobe at the Camparis facility (Sorbonne Université, Paris). Additional analyses were obtained on an SX-Five electron microprobe at Laboratoire Magmas et Volcans, Clermont-Ferrand, France. The operating conditions were 15 keV accelerating voltage and a current of 15 nA. The beam size varied according to the nature of the mineral between 1 and  $20 \,\mu$ m. Synthetic and natural standards were used.

Quantitative EDS of sulfide grains in Oued Chebeika 002 was conducted at the NHM using a ZEISS EVO 15LS SEM equipped with an Oxford Instruments AZtec EDS system and an Ultim Max 100 silicon drift detector (SDD). Analyses were performed at an accelerating voltage of 20 kV, with a probe current of 1.5 nA and a working distance of 8.5 mm. This resulted in an input count rate of approximately 150,000 counts per second (cps) and a dead time of around 24% for sulfide minerals. Spectra were acquired with a total count statistic of 2,000,000 counts, corresponding to a  $\sim$ 13 s acquisition time. Elemental quantification was performed using the XPP matrix correction procedure (Pouchou and Pichoir, 1991), calibrated against a set of reference materials (S-chalcopyrite, Fe-Fe metal, Ni-Ni metal and Cu-Cu metal) supplied by Micro-Analysis Consultants Ltd. Cobalt was quantified using the internal Co metal reference provided by the AZtec software. To ensure analytical accuracy and precision, concentrations were regularly cross-checked against a set of sulfide and reference samples (pentlandite, pyrrhotite. chalcopyrite) both prior to and during data acquisition.

Analytical transmission electron microscopy (TEM) was performed on a Jeol JEM2010 operated at 200 kV at CINaM. Sawing residues and one chip (13 mg) of Oued Chekeiba 002 were crushed, and the clay fraction was put in suspension in water or ethanol. Droplets of the solutions were deposited on TEM Cu grids covered with a carbon film. TEM-EDS microanalyses were conducted on individual particles or aggregates using an X-Flash Silicon Drift EDS Detector 5030 and the Esprit software (Bruker). Data collection parameters were set as follows: magnification of 50,000×, 4 L spot size, angular tilt of 20° toward the detector, time constant of 60 kcp.s<sup>-1</sup>, energy range of 40 keV, and corrected counting time of 30 s. The beam diameter was set to  $\sim 20$  nm (200 Å) in order to image the smallest particles. The constant beam density was  $\sim 63.5$  pA.cm<sup>-2</sup>. Oxygen, Na, Mg, Al, Si, K, Ca, and Fe were quantified by applying the Bruker AXS MET line mark data quantification procedure, which is close to the original Cliff and Lorimer method (Cliff & Lorimer, 1975). In this procedure, the acquired EDS spectra are corrected by background subtraction (Bremsstrahlung calculation), Gaussian deconvolution, and *k* factor corrections using values previously calculated on layer silicate standards with known homogeneous compositions (Berthonneau et al., 2014).

At MNHN, X-ray diffraction (XRD) measurements were performed on a 32-mg fragment of Oued Chebeika 002 mounted in a membrane box. Following the experimental protocol of Viennet et al. (2023), the XRD measurements were repeated after the grain was dried overnight and then sealed in a capillary within a glove box with a typical total pressure of 3 mbar of argon (Alphagaz1),  $H_2O < 0.5$  ppm, and  $O_2 < 1.5$  ppm. XRD measurements were obtained on a Rigaku MM007HF diffractometer operating at the XRD facility of the Institut de Minéralogie, de Physique des Matériaux et Cosmochimie (IMPMC), Sorbonne Université (Paris, France). The diffractometer is equipped with Varimax focusing optics, an RAXIS4++ image plate detector placed at a distance of 350 mm from the sample, and an Mo rotating anode  $(\lambda K\alpha_1 = 0.709319 \text{ \AA})$  and  $\lambda K\alpha_2 = 0.713609 \text{ Å}$ ) operated at 50 keV and 24 mA. The scan range was  $3-30^{\circ}2\theta$  and the acquisition time was 45 min. The FIT2D program (Hammersley, 2016) was used for the integration of 2-D images into 1-D patterns after a calibration using an LaB<sub>6</sub> standard. The XRD beam size was  $\sim 80 \,\mu\text{m}$  in diameter. XRD of oriented clay fractions was recorded at CINaM using a Panalytical X'Pert Pro MPD  $\theta$ - $\theta$  diffractometer using a Cu X-ray tube and an Xcelerator detector. Additionally, the modal mineralogy of  $a \sim 50$ -mg sample was determined using position-sensitive detector X-ray diffraction (PSD-XRD) at the NHM following the method described by King, Schofield, et al. (2015).

A representative bulk composition of a CI cannot be correctly determined using only a small sample (Morlok et al., 2006). Thus, a 1.06 g sample (representing 4% of the type specimen mass) was crushed using a boron carbide mortar and pestle into a homogenous fine-grained powder in clean room conditions at the Institut Universitaire Européen de la Mer (IUEM), Plouzané. A 111 mg aliquot was digested and analyzed for major and trace element concentrations by ICP-SFMS (inductively coupled plasma-sector field mass spectrometry) using a Thermo Scientific ELEMENT XR<sup>TM</sup> spectrometer at Pôle Spectrométrie Océan (Brest), according to our usual analytical protocol for chondrites (e.g., Barrat et al., 2012, 2016, 2023). The concentration reproducibility is generally much better than 5%. The precision for trace element ratios (e.g., Y/Ho, Zr/Hf, Nb/Ta, Eu/Eu\*) is better than 2.5%

 $(2 \times \text{relative standard deviation [SD]})$ . Notice that the procedures and calibrations are the same as Barrat et al. (2012), and consequently, the results are directly comparable (no bias) to those of this previous study on CIs.

The C, N, H, and S bulk contents of two aliquots (1.55 and 1.56 mg) of a 100 mg powdered sample were measured with a Thermo Finnigan EA 1112 analyzer at the Spectropole of the Fédération des Sciences Chimiques in Marseille, France. Samples were combusted at 970 °C under helium gas with a flow of 140 mL min<sup>-1</sup>. Gases released by combustion were separated by a chromatography column and analyzed using a thermal conductivity detector. Analytical errors on the measurement were  $\pm 0.2$  wt% for C,  $\pm 0.2$  wt% for H,  $\pm 0.02$  wt% for N, and  $\pm 0.02$  wt% for S, measured in referenced soil samples.

The triple oxygen isotope analysis was carried out at the Stable Isotopes Laboratory of CEREGE. We analyzed one raw chip of 3.40 mg of Oued Chebeika 002. Molecular O<sub>2</sub> was extracted using the infrared (IR) laser-heating fluorination technique (Alexandre et al., 2006; Crespin et al., 2008; Suavet et al., 2010). At the end of the procedure, the gas was passed through a  $-114^{\circ}$ C slush to refreeze any molecule interfering with the mass 33 (e.g., NF potentially remaining in the line). The gas was directly sent to the dual-inlet mass spectrometer (ThermoQuest Finnigan Delta V Plus). The measured isotope composition of the sample was corrected using a laboratory quartz standard itself calibrated against the international standard NBS28  $(\delta^{18}O = 9.57\%)$ ;  $\delta^{18}O = 4.99\%)$ . Isotope composition is expressed in standard  $\delta$  notation, relative to the Vienna Standard Mean Ocean Water (VSMOW) and using  $\Delta^{17}O = \delta^{17}O - 0.525 \times \delta^{18}O$ . One meteorite aliquot was analyzed. Reproducibility (1 SD) of analyses of the quartz laboratory standard during the analytical session was 0.10% for  $\delta^{18}$ O, 0.06% for  $\delta^{17}$ O, and 0.015% for  $\Delta^{17}$ O (n = 3).

An aliquot representing 85 mg of Oued Chebeika 002 digested at IUEM was provided to the Origins Laboratory of the University of Chicago for Fe isotopic analysis. Two aliquots containing 1 mg Fe were sampled for purification and isotopic analysis using established protocols (Hopp et al., 2022; Tang & Dauphas, 2012). Approximately 25 mg of CI chondrite Orgueil (from Museum National d'Histoire Naturelle, Paris) was digested in Chicago using HNO<sub>3</sub> and HF following the same protocol as that used for Oued Chebeika 002 (Barrat et al., 2012). One aliquot of that Orgueil digestion solution containing 1 mg Fe was sampled for further processing. Iron in the digestion solutions was purified at the University of Chicago following the methodology of Hopp et al. (2022). The aliquots containing 1 mg Fe (two aliquots for Oued Chebeika 002 and one aliquot for Orgueil) were loaded in 0.25 mL of 10 M HCl onto 10.5cm-long PFA Teflon columns (0.62 cm inner diameter) filled with 3 mL precleaned AG1-X8 (200–400 mesh) anion exchange resin. Matrix elements containing Ni were eluted using 5 mL of 10 M HCl and preserved. Other contaminants (Co, Cu) were eluted using 30 mL of 4 M HCl. Iron was eluted from the resin using 9 mL of 0.4 M HCl. The overall yield of Fe was over 99%.

Another aliquot of the sample solution. representing  $\sim 15 \text{ mg}$  of Oued Chebeika 002, was provided to the Institute of Science Tokyo, and approximately one-third of this solution (~5 mg of Oued Chebeika 002) was used for Cr isotopic analysis. Additionally, aliquots of meteorite sample solutions containing  $\sim 5 \text{ mg}$  of Kainsaz (CO3.1) and  $\sim 5 \text{ mg}$  of Forest City (H5), which were originally prepared from 30 mg of these meteorites by Yokoyama, Okhuma, et al. (2023), were treated in the same manner as Oued Chebeika 002 for reference. These sample solutions were dried and redissolved in 12 M HNO<sub>3</sub>. The sample solution was passed through 0.5 mL of DGA normal resin (50-100 µm) to retain Fe, Ti, high field strength elements (HFSEs), and rare earth elements (REEs) while eluting the other elements including Cr. The Cr cut was dissolved in 0.5 M HCl and loaded onto 1 mL of AG50W-X12 (200-400 mesh), followed by the elution of Cr with 1 M HCl while retaining the other major cations. The Cr cut was dried and dissolved in a mixture of 1 M HNO<sub>3</sub> and 10% H<sub>2</sub>O<sub>2</sub>, and then it was loaded onto a tandem column assembly placing the 0.5 mL DGA resin above 0.3 mL of AG50W-X8 (200-400 mesh). After eluting 1 M HNO<sub>3</sub> and 0.5 M HF for removing remaining major cations, Cr was collected with 6 M HCl. The overall Cr yields were over 90%-95% for the three samples examined in this study.

Iron isotopic compositions were measured in a medium-resolution mode on the Thermo Fischer Scientific Neptune multi-collector inductively coupled plasma-mass spectrometer (MC-ICP-MS) using established protocols at the Origins Laboratory (Hopp et al., 2022). Ion beams of <sup>54</sup>Fe<sup>+</sup>, <sup>56</sup>Fe<sup>+</sup>, <sup>57</sup>Fe<sup>+</sup>, and <sup>58</sup>Fe<sup>+</sup> were measured using Faraday cups and  $10^{11} \Omega$ amplifiers, except <sup>56</sup>Fe<sup>+</sup>, which was measured using a  $10^{10} \Omega$  amplifier. Ion beams of  ${}^{53}Cr^+$  and  ${}^{60}Ni^+$  were measured using faraday cups and  $10^{12} \Omega$  amplifiers to correct for <sup>54</sup>Cr<sup>+</sup> and <sup>58</sup>Ni<sup>+</sup> isobaric interferences on <sup>54</sup>Fe<sup>+</sup> and <sup>58</sup>Fe<sup>+</sup>, respectively. An electrospray ionization (ESI) nebulizer with an uptake rate of  $100 \,\mu L \,min^{-1}$ combined with a cyclonic glass spray chamber was used to introduce purified Fe solutions (10 ppm in 0.3 M HNO<sub>3</sub>) into the MC-ICP-MS. A blank solution made of the same acid and water as the ones used to analyze iron was measured at the beginning and end of each session to define blank intensities, and the average of those two

measurements was subtracted from all analyses (On Peak Zero procedure). A sample uptake rate of 90 s and washout time of 210 s were used between each analysis. Each measurement consisted of 50 cycles of 8.369 s each. Each sample measurement was bracketed by measurements of IRMM-524a in a standard-samplestandard-bracketing scheme. The Fe concentrations of the samples and bracketing standards were matched to within 2%, which is required for accurate and precise Fe isotopic analysis. The Fe isotopic analyses are reported in the following notations:

$$\delta^{56} Fe(\%) = \left[ \left( {}^{56} Fe / {}^{54} Fe \right)_{smp} / \left( {}^{56} Fe / {}^{54} Fe \right)_{std} - 1 \right] \times 10^3$$

$$\mu^{54} \mathrm{Fe} = \left[ \left( {^{54} \mathrm{Fe}} / {^{56} \mathrm{Fe}} \right)_{\mathrm{smp}} / \left( {^{54} \mathrm{Fe}} / {^{56} \mathrm{Fe}} \right)_{(57/56),\mathrm{std}} - 1 \right] \times 10^{6}$$

$$\mu^{58} \text{Fe} = \left[ \left( {}^{58} \text{Fe} / {}^{56} \text{Fe} \right)_{\text{smp}} / \left( {}^{58} \text{Fe} / {}^{56} \text{Fe} \right)_{(57/56), \text{std}} - 1 \right] \times 10^6$$

where  ${}^{57}\text{Fe}/{}^{56}\text{Fe}$  is used to correct for mass fractionation by internal normalization using the exponential law to a fixed  ${}^{57}\text{Fe}/{}^{56}\text{Fe}$  ratio of 0.023095. The reported values are the averages of all standardbracket measurements, and the uncertainties are the 95% confidence intervals of the mean. For  $\delta^{56}$ Fe, a constant error is added quadratically that captures the fact that precision cannot be arbitrarily decreased by repeating analyses of the same solution as the data show more dispersion when the full procedure is applied, starting from different sample aliquots (longterm reproducibility) (Dauphas et al., 2009).

Chromium isotopic compositions of the purified samples were measured by thermal ionization mass spectrometry (TIMS) using TRITON Plus (Thermo Fisher Scientific) installed at Institute of Science Tokyo. The instrument was equipped with eight movable Faraday cups and one center Faraday cup (amplifiers with  $10^{11} \Omega$  registers). The purified Cr was loaded onto an outgassed W ribbon (99.95%, Nilaco) together with a Si-Al-B activator. We employed the three-line multidynamic method established by Yokoyama, Ohkuma, et al. (2023). The spectral interferences on Cr isotopes (<sup>50</sup>Ti<sup>+</sup>, <sup>50</sup>V<sup>+</sup>, and <sup>54</sup>Fe<sup>+</sup>) were corrected by monitoring m/z = 49, 51, and 56, all of which did not affect the Cr isotopic measurement results significantly. Data for Cr isotope ratios were reduced by averaging 210 ratios (2 s rejection level = 4.55%), acquired 14 blocks of 15 cycles/block, 3 lines/cycle, and 16.667 s integration/line. Peak centering and lens focusing were performed at every two and three blocks of the entire run, respectively. A single isotopic measurement required  ${\sim}5\,h$  including the filament heating time. The Cr isotope ratios are reported in the  $\mu$  notation defined as follows:

$$\mu^{53} Cr = \left[ \left( {}^{53} Cr / {}^{52} Cr \right)_{smp} / \left( {}^{53} Cr / {}^{52} Cr \right)_{std} - 1 \right] \times 10^{6}$$
$$\mu^{54} Cr = \left[ \left( {}^{54} Cr / {}^{52} Cr \right)_{smp} / \left( {}^{53} Cr / {}^{52} Cr \right)_{std} - 1 \right] \times 10^{6}$$

where std refers to NIST SRM 979 standard. Tthe mass bias correction was performed using the exponential law by assuming that  ${}^{50}$ Cr/ ${}^{52}$ Cr = 0.051859.

Raman measurements were performed at the Ecole Normale Supérieure de Lyon (Laboratoire de Géologie de Lyon-Terre, Planètes, Environnement) using a LabRAM HR800 Evolution Raman spectrometer (Horiba) equipped with a  $600 \text{ g mm}^{-1}$  grating centered at 1400 cm,<sup>-1</sup> giving access to the spectral region  $500-2200 \text{ cm}^{-1}$ . The laser was focused through a  $100 \times$ objective to obtain a  $< 2 \,\mu m$  spot size. The power on the sample was 0.3 mW. Each acquisition comprised six integrations of 15 s that were averaged to make the final spectrum. A total of 40 spectra were acquired on  $\sim 20$ matrix fragments with 50-70 µm of typical size, with a maximum of three spectra per fragment. Prior to measurements, the matrix fragments had been selected manually according to color and texture under a binocular microscope. The selected matrix fragments were pressed between two glass slides that were also used as a substrate for the Raman analysis.

As some Raman bands related to CC matter are dispersive, data for Oued Chebeika 002 and samples of comparison (meteorites and Hayabusa2 particles) were acquired and analyzed along a strictly given set of parameters (power, acquisition time, data processing, etc.). The Raman spectra acquired on Oued Chebeika 002 systematically exhibit the so-called D- and G-bands related to the presence of polyaromatic CC matter (Ferrari & Robertson, 2000; Quirico et al., 2014). The individual spectra were adjusted similarly to comparison samples (meteorites and Hayabusa2 samples). A linear baseline correction of the spectra between 1000 and  $1700 \text{ cm}^{-1}$  was systematically subtracted. The G- and D-bands were fitted with a and Breit-Wigner-Fano a Lorentzian profile, respectively. The position  $(\omega)$ , peak intensity (I), and full width at half maximum (FWHM) of the D- and Gbands were determined for each spectrum. For every sample, the mean value and  $1\sigma$ -SD of each of these parameters were calculated.

Transmission IR spectra were obtained with a Bruker Hyperion 3000 IR microscope at Institut de Planétologie et d'Astrophysique (IPAG), Grenoble. The IR beam was focused through a 15× objective, and the typical size of the spot on the sample was  $80 \times 80 \,\mu\text{m}^2$ . Spectra were measured at 4 cm<sup>-1</sup> spectral resolution over the spectral range 4000–650 cm<sup>-1</sup>, using a mercury cadmium telluride (MCT) detector cooled with liquid nitrogen.

Sample preparation is a critical issue in transmission IR microspectroscopy, as samples must be thin  $(<100 \,\mu\text{m})$  and their surfaces flat enough to minimize absorption band saturation and scattering artifacts. Small matrix fragments (50-80 µm) were therefore selected under a binocular microscope and pressed between two diamond windows  $(3 \text{ mm} \times 0.5 \text{ mm}, \text{ synthetic type IIa})$ diamond) (e.g., Battandier et al., 2018). The individual diamond windows were loaded into an environmental cell, designed and built at IPAG, enabling measurements under vacuum (typically  $\sim 2.5 \times 10^{-5}$  mbar for the measurements in this work) to remove adsorbed atmospheric molecular water. Optical access is permitted from both sides of the cell through ZnS windows, thus enabling measurements in transmission. Spectra were processed with the Igor Pro software (Wavemetrics): baseline corrections of an individual spectrum were first processed with spline functions. All spectra were then normalized by setting the absorbance of the peak of the  $1000 \text{ cm}^{-1}$  silicate Si-O stretching band to 1, which does not evolve in the pressure range of the measurements.

Reflectance spectra in the 500-4000 nm range were measured using the homemade reflectance spectrometers SHADOWS (Potin et al., 2018) and SHINE (Brissaud et al., 2004) at IPAG. Spectra of Oued Chebeika 002 were obtained for an assortment of raw chips (total mass m = 235 mg), as well as for a powder obtained after gently grinding a 100-mg sample in an agate mortar. Spectra were obtained under an illumination angle of 0° and an emergence angle of 30°, at a spectral sampling of 10 nm and a spectral resolution of 4.8 nm ( $0.55-0.67 \mu m$ ), 9.5 nm (0.68–1.59 um), 19 nm (1.60–2.83 um), and 39 nm (2.84-4.0 µm). Spectra were calibrated using reference surfaces (Spectralon and Infragold purchased from Labsphere). A spectrum of the Oued Chebeika 002 powder was also obtained using a homemade vacuum chamber (MIRAGE) at a pressure below  $10^{-4}$  mbar. The impact of the sapphire window on the reflectance level during measurements under vacuum was corrected using the same approach as Potin et al. (2019). Spectra were compared to those obtained for an Orgueil powder at IPAG with the same setup, and to reflectance spectra measured for Alais and Ivuna powders at RELAB (spectra c1mt264 and c1mb60).

Reflectance spectra in the 1.3–16 µm range were also obtained on the raw Oued Chebeika 002 sample using a Fourier-transform infrared (FT-IR) spectrometer (Brüker Vertex 70) equipped with a biconical reflectance apparatus (see Sultana et al., 2023). Spectra were measured under a dry-air purge and calibrated using two reference surfaces: a reflective diffuser made of a 120-grit-protected gold coating surface purchased from Edmund Optics (ref1) and a 1500grit-uncoated gold reflective ground glass diffuser purchased from Thorlabs (ref2). The former reference surface possesses some absorption features due to the protective coating, but it is spectrally flat over the studied wavelength range, whereas the latter reference surface is featureless but is less reflective as the wavelength increases. We measured a "[ref2]/[ref1]" spectrum and then computed a "[ref2]/[coating-free ref1]" spectrum by replacing the spectral ranges affected by ref1 absorption bands by a polynomial interpolation. Then, we multiplied the Chebeika of "[Oued spectrum 002]/[ref2]" by "[ref2]/[coating-free ref1]" to obtain the spectrum "[Oued Chebeika 002]/[coating-free ref1]," free of spectral artifact.

All spectral data acquired on Oued Chebeika 002 are available on the SSHADE database of Solid Spectroscopy at https://www.sshade.eu/ (Bonal, Beck, & Poch, 2024).

Mössbauer spectroscopy was applied to the same 32mg sample that was used for XRD measurements. Typically, Mössbauer spectroscopy of large particles would result in artificially broad lines. Therefore, the sample was gently crushed to a grain size of  $\sim 100 \,\mu\text{m}$ . This powder was compacted between two Kapton foils in a pierced (2 mm in diameter) lead foil. The measurements were performed at room temperature in transmission geometry, using a <sup>57</sup>Co-in-Rh matrix source of approximately 200 MBq in a constant acceleration mode. Isomer shifts are given relative to α-Fe at 300 K, a foil of which was used to calibrate the spectrometer's driving unit. Data were analyzed using the SYNCmoss software package (Yaroslavtsev, 2023; https://gitlab.esrf. fr/yaroslav/syncmoss). The instrumental function was determined from the spectrum collected on the iron foil. The line widths used to fit the spectra were reasonably wide to get a good fit, without invoking a Gaussian distribution of hyperfine field, quadrupole splitting, and isomer shift values. As described below, chondritic materials exhibit complex polyphasic Mössbauer spectra. For this reason, we established a systematic fitting procedure used for all the samples similar to the one established in Roskosz et al. (2023). First, site ratios of all phases were refined and then we proceeded to adjust magnetite hyperfine parameters, as outermost magnetite lines did not overlap with any other phase lines. Area ratios between A and B sites in magnetite were allowed to change arbitrarily. Pyrrhotite sites were then slightly adjusted from the starting model, and finally, silicate parameters were released. Instead of carrying out fitting procedures without any a priori trial parameters, we used the mineralogical model determined by XRD analysis to

TABLE 1. Mössbauer parameters derived from the spectrum.

Site#	Surface area fraction (%)	Error (±%)	$\frac{\text{IS}}{(\text{mm s}^{-1})}$	Error (±%)	$QS \ (mm \ s^{-1})$	Error (±%)	HT (T)	Error (±%)	Site assignment
1	22.7	0.9	0.62	0.00	0.02	0.01	45.97	0.04	Magnetite (site B)
2	13.2	0.6	0.22	0.01	0.00	0.01	48.68	0.05	Magnetite (site A)
3	18.4	2.1	0.33	0.01	0.81	0.04	0.00		Clay minerals (Fe <sup>3+</sup> )
4	12.8	0.5	1.08	0.01	2.63	0.01	0.00		Clay minerals (Fe <sup>2+</sup> )
5	7.9	0.8	0.62	0.01	0.13	0.02	22.39	0.10	Pyrrhotite (site 1)
6	12.1	0.9	0.64	0.01	0.06	0.02	25.67	0.13	Pyrrhotite (site 2)
7	9.8	0.5	0.62	0.01	0.04	0.01	30.23	0.04	Pyrrhotite (site 3)
8	0.4	0.3	0.57	0.01	0	0.006	0		Pentlandite (site 1)
9	2.7	2.1	0.26	0.02	0.37	0.01	0.00		Pentlandite (site 2)

*Note:* No correction for the Lamb-Mössbauer factors of ferrous and ferric iron silicates was applied here (see the Methods section). Abhavirting (T), IS is small big (nor  $s^{-1}$ ), OS and  $marks a plitting (run <math>s^{-1}$ ).

Abbreviations: HT, magnetic hyperfine splitting (T); IS, isomer shift (mm  $s^{-1}$ ); QS, quadrupole splitting (mm. $s^{-1}$ ).

adjust the best fit to the spectra. Additional tests, including free variations of other parameters, were carried out in order to confirm the robustness of the model obtained following this methodology.

The Lamb-Mössbauer factors were not taken into account. In fact, the true  $Fe^{3+}/Fe_{tot}$  of clays may not be strictly proportional to the areas of the quadrupole doublets as tabulated in Table 1. Although generally neglected in the literature, the recoil-free fraction of iron atoms is slightly different for Fe<sup>2+</sup> and Fe<sup>3+</sup> in silicates at any temperature. Despite the fact that the correction can vary from one mineral to another, a typical, reasonable correction can be assumed: the ratio of doublet areas for  $Fe^{3+}$  and  $Fe^{2+}$  can overestimate the true  $Fe^{3+}/Fe_{tot}$  by a factor of up to 1.2 (De Grave & Van Alboom, 1991; Dyar et al., 2009; Roskosz et al., 2022). The need for such correction on these samples is uncertain, and for this reason, we do not provide the corrected ratios in Table 1. The difference is still within the typical error associated with redox determination based on Mössbauer spectra, typically estimated to be 3%-5%.

For thermogravimetric analyses (TGA), a 12-mg chip of Oued Chebeika 002 was powdered using an agate mortar and pestle, loaded into an alumina crucible, and then characterized using a TA Instruments Simultaneous Thermal Analysis SDT Q600 thermogravimetric analyzer at the NHM. Mass loss was recorded as the sample was heated in a sealed furnace from ~20 to 1000°C at a rate of 10°C min<sup>-1</sup> under an N<sub>2</sub> flow of 100 mL min<sup>-1</sup>.

The grain density was measured at CEREGE with a Quantachrome helium stereopycnometer on four assortments of fragments with masses 14.84 g (many fragments, including millimeter-sized ones), 12.49 g (2 fragments), 11.88 g (3 fragments), and 7.02 g (5 fragments).

Magnetic measurements were conducted at CEREGE. The natural remanent magnetization (NRM) of Oued Chebeika 002 samples was measured on a SQUID magnetometer (2G Enterprises, model 755R,

with a sensitivity of  $5 \times 10^{-12}$  A m<sup>-2</sup>) on 7 samples in the  $\sim$ 10-mg range and with a Minispin spinner magnetometer from Molspin for 11 larger samples with masses above 800 mg. Stepwise alternating field (AF) demagnetization was conducted using the three-axis AF demagnetizer attached to the SQUID magnetometer. All three-axis demagnetization step was repeated three times, each time finishing on a different axis to prevent the acquisition of a gyroremanent magnetization. An AGICO LDA5 AF demagnetizer and anhysteretic magnetizer was used to impart anhysteretic remanent magnetizations to the sample. The low-field magnetic susceptibility  $(\chi_{LF})$  was measured with an Agico MFK1 (sensitivity of  $5 \times 10^{-13}$  m<sup>3</sup>, operating at 200 A m<sup>-1</sup> and 976 Hz). For some samples, the susceptibility was also measured at 15616 Hz to estimate the frequency dependence (FD) of magnetic susceptibility (computed as  $FD = (\chi_{976Hz} - \chi_{15616Hz})/\chi_{976Hz}$  expressed in %), a proxy to the amount of superparamagnetic grains. A few large samples of CI1 falls were measured with a KLY2 susceptibility-meter equipped with a 65-cm<sup>3</sup> coil (see method in Rochette et al., 2008). Hysteresis parameters. coercivity spectrum, and first-order reversal curves (FORCs) were obtained using a LakeShore 8600 series vibrating sample magnetometer. To impart a saturation isothermal remanent magnetization (SIRM; i.e., the maximum remanent magnetization acquired by a sample after being subjected to a saturating magnetic field), we used а 3-T pulse magnetizer from magnetic measurements.

#### RESULTS

#### **Mineralogy and Petrography**

The macroscopic samples are black and reveal that the meteorite is brecciated (Figure 1). The fusion crust is visible on some fragments, including the largest one. It is



FIGURE 2. Computed tomography (CT)-scan views of Oued Chebeika 002. (a, b) 2-D cross sections on two orthogonal planes from a 10.4 g stone. Scale bars are 5 mm (a), and 6 mm (b). (c, d) Slices into a 18-mg sample.

remarkably well preserved with no sign of abrasion by wind, dust, and sand (Figure 1d). The XCT scan of the 10.4 g stone shows that the brecciation scale is of a few millimeter and that the clasts are subangular (Figure 2a,b).

SEM-BSE imaging of the polished sections and EDS microanalyses reveal abundant grains and aggregates of magnetite and sulfides, as well as carbonates and phosphates, embedded in a fine-grained matrix of phyllosilicates (Figure 3). Magnetite displays a wide range of morphologies: framboids, platelets organized as "honeycomb" aggregates, spherulites, subhedral grains made of nanometer-sized needles or isolated grains with various shapes, from rounded to euhedral, and rarely cube-shaped grains (Figure 4).

Pyrrhotite (Fe<sub>1-x</sub>S), with nickel contents up to 1.1 wt% and x varying between 0.11 and 0.13 (average 0.12), is by far the most abundant sulfide (Table S1). In some rare

occasions, pyrrhotite contains inclusions of pentlandite. Pentlandite also occurs as individual grains up to 10 µm, with an average structural formula  $(Fe_{3,9}Ni_{4,9}Co_{0,3})_{\Sigma=9,0}S_8$ . Rare grains of Cu-rich iron sulfide have been observed: four grains of cubanite, and one  $\sim 100 \,\mu\text{m}$ -sized grain of chalcopyrite (Figure S1, Table S1). One cubanite grain contains inclusions of pentlandite (Figure 3f). Their composition is given in Table S1. Carbonates occur either as large grains, up to 400 µm, with morphologies ranging from anhedral to angular or euhedral, as aggregates, or as smaller rounded grains of  $\sim 10 \,\mu m$  heterogeneously dispersed in the finegrained matrix. The main carbonate is dolomite. The (Fe, Mn)-rich variety of magnesite (variety "breunnerite") also occurs as grains up to 400 µm (Figure 3). Phosphates are dominated by apatite, though we observed a few Mg-, Narich phosphates and one hydrated phosphate. Carbonates, apatite and coarse-grained phyllosilicates, or a mixture of



FIGURE 3. Backscattered electron (BSE)-scanning electron microscopic (SEM) images of Oued-Chebeika 002. (a) Low magnification image showing an Fe-rich clast (center) and carbonate grains in a fine-grained matrix of phyllosilicates containing numerous grains of magnetite and Fe-sulfides (white). (b) Energy-dispersive X-ray spectroscopy (EDS) chemical maps superimposed on a BSE image, showing large euhedral pyrrhotite grains (green), magnetites with various morphologies (red), carbonates (blue), and one pentlandite crystal (arrowed). Clasts of larger phyllosilicates, nearly devoid of magnetite or sulfide inclusions, are outlined by dashed lines. (c) Apatite (bottom) and dolomite (top) inclusions. (d) A large breunnerite grain. (e) A dolomite grain with included magnetites. (f) A large cubanite grain with pentlandite inclusions.

two or three of those, sometimes form aggregates hosting abundant magnetite crystals with varied morphologies (Figure 3e). Clasts up to  $200 \,\mu\text{m}$  made of "pure" phyllosilicates were observed in all three studied polished sections. These clasts of phyllosilicates are poor in magnetite or iron sulfide inclusions compared to the "normal" matrix and coarser grained, with grain sizes ranging from a few micrometer to approximately  $20 \,\mu\text{m}$  (Figures 3b and Figure 5c,d). The chemical compositions of these clasts of phyllosilicates, measured by electron probe microanalyses (EPMAs) with a defocused beam of  $20 \,\mu\text{m}$ , are reported in Table S1 and Figure 6. They can be interpreted as a mixture between saponite and serpentine, with a remarkably constant Fe/(Fe + Mg) ratios of  $0.15\pm0.01.$ 

Micro-XCT imaging of three small (<20 mg) fragments (Figure 2c,d) shows that they are broadly "bright" abundant similar, with (i.e., denser) micrometer-sized individual grains and aggregates set finer-grained matrix, within а consistent with identification of sulfides. magnetite, the and phyllosilicates in polished sections. Larger ( $\sim 10$ 's µm) euhedral grains are likely pyrrhotite (bright in the images), dolomite (dark gray), and breunnerite (light gray). Brecciation is not clear at this scale, and the

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FIGURE 4. Backscattered electron (BSE)-scanning electron microscopic (SEM) images of magnetite grains with various morphologies. (a) Framboidal aggregates and spherulites made of radial crystals. (b) Framboidal aggregate of dodecahedral crystals, along a euhedral hexagonal crystal of pyrrhotite (right). (c) A cube-shaped magnetite crystal. (d) "Honeycomb" aggregate of platelets. (e) A subhedral grain made of nanometer-sized needles of magnetite (inset). (f) An exceptional framboid made of isometric dodecahedra of magnetite grains, closely packed to form a colloidal crystal.

fragments show no obvious petrofabrics. However, one fragment contains a vein of a dark gray phase, most likely carbonate, infilling a fracture (Figure 2c), while a second fragment has a region where bright material forms finer veins (Figure 2d), similar to the magnetite-rich veins seen in Ryugu particles (e.g., Bazi et al., 2022).

The XRD patterns of Oued Chebeika 002 are shown in Figure 7. The PSD-XRD pattern is shown in Figure S2. Oued Chebeika 002 is primarily composed of two phyllosilicates forming the fine-grained matrix: a smectiterich one (001 reflection at 12.6 Å) and a serpentine-rich one (001 reflection at 7.3 Å). The clay mineralogy is detailed in the Matrix mineralogy section. Other minerals visible in the XRD patterns are magnetite (with peaks at 5.25, 2.96, 2.54, 2.11, 1.72, 1.62 Å), dolomite (peaks at 2.89, 2.20 Å), pyrrhotite 4C (peaks at 5.8, 5.3, 3.6, 2.64, 2.06, 1.44, 1.43, 1.42 Å), and pentlandite (peaks at 2.89, 1.93, 1.78, 1.49 Å), in agreement with the main minerals visible in the thin section by SEM-EDS and EPMAs. Olivine and calcite are not visible in the XRD patterns. The bulk modal mineralogy of Oued Chebeika 002 based on the PSD-XRD analysis is ~88 vol% phyllosilicates, ~7 vol% Fe-sulfides, ~4 vol% magnetite and ~1 vol% carbonate.

In Figure 7a, we also show the XRD patterns of Orgueil and of Ryugu grain C-0061 that were measured previously (Viennet et al., 2023) and of a  $\sim$ 500-µm-sized



FIGURE 5. Backscattered electron (BSE)-scanning electron microscopic (SEM) images of clasts in Oued Chebeika 002. (a) Abundant grains of magnetite, most with a platelet morphology, in a clast of dolomite, apatite, and phyllosilicates. (b) Grains of magnetite, most with a platelet morphology, in a grain of apatite. (c, d) Large clasts of coarse-grained phyllosilicates, nearly devoid of magnetite or sulfide inclusions. A smaller clast made of finer-grained phyllosilicates is visible in (c, top-right).



FIGURE 6. Chemical analyses of phyllosilicates in Oued Chebeika 002, plotted in a (Si + Al)-Mg-Fe ternary diagram. Transmission electron microscopy (TEM)-energy-dispersive X-ray spectroscopy (EDS) analyses are in blue (spot size approximately 200 nm); EPMAs of large clasts of phyllosilicates such as those depicted in Figure 5c,d are in red (defocused beam  $20 \,\mu$ m); EPMAs of matrix are in brown (defocused beam  $5-20 \,\mu$ m, avoiding larger magnetite and sulfides grains).

fragment of Alais measured as part of this study. The XRD patterns of Oued Chebeika 002 are similar to those measured for Ryugu grain C-0061, Alais, and Orgueil, demonstrating that the same minerals are present in these materials. Note that there are slight differences in the shape of the background at low angles that are mainly due to the sample preparation and XRD instrument configurations.

#### Matrix Mineralogy

The fine-grained matrix was studied by defocusedbeam EPMAs, XRD, and analytical TEM.

EPMAs, with beams defocused between 5 and 20  $\mu$ m in regions of matrix avoiding large (>1  $\mu$ m) grains of magnetite or sulfides, are reported in Table S1. They show a dominant (Mg, Fe) silicate composition, with minor Al<sub>2</sub>O<sub>3</sub> (2–4 wt%), a variable Na<sub>2</sub>O content (1–6 wt %), and traces of Cr, K, Ca, and Mn. Variable Fe, S, and Ni contents can be attributed to contamination of phyllosilicates by sub-micrometer sulfides and magnetite grains. All matrix analyses are characterized by low analytical totals, in the range of 81–93 wt% (Table S1).



FIGURE 7. (a) X-ray diffraction (XRD) patterns obtained on grains of Oued Chebeika 002 at ambient condition (in red), grain C0061 of Ryugu at curation conditions (in blue— Viennet et al., 2023), Orgueil at ambient condition (in orange–Viennet et al., 2023) and Alais at ambient condition (in gray this study). The mineral assignation, thanks to the peak position labeled in Å, is detailed in the text. (b) XRD patterns of the same grain of Oued Chebeika 002 obtained under 40% of relative humidity in orange and 0% of relative humidity in blue. (c) XRD patterns of oriented preparations of the clay fraction of Oued Chebeika 002, recorded after drying in air (in black), treated with ethylene glycol (in blue) and after heating at 500°C for 2 h (in red).

The range of the total can be accounted for by the variable proportion of phyllosilicates, sulfides, and magnetite.

The XRD patterns (Figure 7) indicate that Oued Chebeika 002 is primarily composed of trioctahedral Mgrich clay minerals based on their 02.11 and 06.33 reflections at 4.6 and 1.54 Å. Such clay minerals consist of a smectite-rich one with 001 reflection at 12.6 Å and a serpentine-rich one with 001 and 002 reflections at 7.3 and 3.6 Å, respectively. The slight irrationality between the 001 and 002 reflections of serpentine is either due to a low coherent scattering domain size (small particle size along the *c*-axis) or due to mixed layering of serpentinerich minerals with a layer of unknown nature. XRD of oriented clay fractions dried in air, glycolated, and heated (Figure 7c) confirms the identification of serpentine (unvarying 001 reflection at 7.3 Å) and Na-smectite (001 at 12.5 Å in air, swelling at 17.2 when glycolated and collapsing at 10 Å after heating) as the main phyllosilicates. Note that the 00 l (l > 1) reflections of the smectite-rich mineral are not visible, which prevents discussing the potential interstratification of such phase. The XRD patterns after drying the grains at 0% relative humidity are shown in Figure 7b and are described in the discussion.

Analytical TEM of the clay fraction shows finegrained clay particles from a few tens of nanometers to about 200 nm, along with rounded to euhedral particles of sulfides and magnetite 50–200 nm in size (Figure 8). In the TEM sample prepared from a fragment that was kept dry before preparation in ethanol, most of the magnetite and sulfide particles are crystalline; only a few show a small rim of amorphous material. On the other hand, in another sample for which the clay fraction was kept in suspension in water for several weeks, most grains are transformed into amorphous or extremely fine-grained material resembling what was described as ferrihydrite in Orgueil (Figure 8b; Tomeoka & Buseck, 1988).

High-resolution TEM lattice fringe imaging of the clay particles (Figure 8c,d) shows basal spacings of 0.7 nm, characteristic of serpentine minerals, as well as spacings approximately 1.0 nm, characteristic of smectite minerals collapsed under vacuum. The thickness of the particles along the *c* direction typically varies from a few layers to approximately 20 layers. Serpentine grains are usually separated from smectite grains, with only limited interstratification. TEM-EDS analyses were recorded on aggregates of clay particles approximately 250 nm, avoiding magnetite and sulfide particles. The results are reported in a (Si + Al)-Mg-Fe diagram in Figure 6. They show a mixture of Mg-rich serpentine and saponite clays, at this scale, with a trace of Cr, Fe/(Mg + Fe) atomic ratios varying from 0.15 to 0.20 and Al/Si atomic ratios around 0.1. As with the EPMAs, compositions with higher Fe content can be attributed to contamination by nanometer-sized sulfides or magnetite grains. Na  $(1.8 \pm 0.7 \text{ wt}\% \text{ element})$  and minor K  $(0.2 \pm 0.1 \text{ wt}\%)$ 



FIGURE 8. (a) Low magnification image of clay-sized particles from the matrix of Oued Chebeika 002 deposited on a transmission electron microscopy (TEM) grid covered by a carbon film. Clay particles with various morphologies range in size from a few tens to a few hundreds of nanometers. They are mixed with numerous sulfide and magnetite nanoparticles ranging from approximately 20–150 nm (dark gray on the picture). (b) An Fe-rich grain from a clay fraction of Oued Chebeika 002 that was kept in suspension in water for several weeks. Most Fe-rich grains in this sample appear with this mottled contrast revealing amorphous or extremely fine-grained material typical of the "ferrihydrite" particles described in the matrix of Orgueil (Tomeoka & Buseck, 1988), contrary to the sample in (a) that was prepared using ethanol. (c, d) High-resolution image of clay particles showing interlayer basal spacing of 7Å characteristic of serpentine and approximately 10Å ones typical of smectite collapsed under vacuum. A limited amount of interstratified layers (arrowed) are observed in serpentine.

element) can be attributed to the interlayer content of the smectite component. The combination of XRD analyses, EPMAs, and TEM-EDS analyses and TEM imaging unambiguously reveals that phyllosilicates in the matrix and clasts of Oued Chebeika 002 is a mixture of Mg-rich serpentine and Na-saponite, intermixed at a nanometric scale, with limited interstratifications.

#### **Bulk Chemical Composition**

The chemical bulk composition is given in Table 2. The bulk carbon, nitrogen, sulfur, and hydrogen contents are  $3.09 \pm 0.2$  wt%,  $0.07 \pm 0.02$  wt%,  $6.51 \pm 0.06$  wt%, and  $0.97 \pm 0.2$  wt%, respectively. The bulk oxygen isotopic

composition is  $\delta^{17}O = 8.81 \pm 0.06$ ,  $\delta^{18}O = 15.34 \pm 0.10$ , and  $\delta^{17}O = 0.76 \pm 0.015$  (slope 0.525, the uncertainties are 1SD, determined from the reproducibility of quartz standards analyzed during the same session).

#### Iron and Chromium Isotopic Compositions

Two aliquots from the same solution of Oued Chebeika 002 were processed through chemistry and analyzed separately. The measurements are consistent within errors ( $\mu^{54}$ Fe = +1 ± 5, N = 29 and +3 ± 11, N = 12, and  $\mu^{58}$ Fe = +9 ± 10, N = 29 and +10 ± 12, N = 12). We therefore combined the results using weighted means (Table 3). Oued Chebeika 002 and

	CI Barrat et al. (2012)	Oued Chebeika 002 This work		CI Barrat et al. (2012)	Oued Chebeika 002 This work
Li	1.44	1.74	Nb	0.289	0.352
Be	0.0226	0.0258	Cs	0.189	0.216
Na (wt%)	0.48	0.66	Ba	2.46	2.89
Mg (wt%)	9.42	10.45	La	0.235	0.278
Al (wt%)	0.79	1.09	Ce	0.6	0.696
Р	1010	1152	Pr	0.091	0.106
Κ	550	675	Nd	0.464	0.540
Ca (wt%)	0.84	1.12	Sm	0.153	0.174
Sc	5.85	7.20	Eu	0.0586	0.0666
Ti	449	505	Gd	0.206	0.231
V	52.4	59.3	Tb	0.0375	0.0431
Cr	2627	2560	Dy	0.254	0.289
Mn	1910	2269	Но	0.0566	0.0641
Fe (wt%)	19.52	20.28	Er	0.166	0.188
Co	519	634	Tm	0.0262	0.0298
Ni (wt%)	1.13	1.24	Yb	0.168	0.190
Cu	127	99.93	Lu	0.0246	0.0280
Zn	303	389	Hf	0.107	0.126
Ga	9.48	10.74	Та	0.0148	0.0171
Rb	2.33	2.82	Pb	2.69	2.14
Sr	7.73	9.18	Th	0.0283	0.0336
Y	1.56	1.81	U	0.0077	0.0089
Zr	3.52	4.15			

TABLE 2. Element abundances in CI (Barrat et al., 2012) and in Oued Chebeika 002 (in wt% for Na, Mg, Al, Ca, Fe, and Ni, and in  $\mu$ g/g for the other elements).

TABLE 3. Iron and chromium isotopic anomalies and fractionation in Oued Chebeika 002 relative to terrestrial standard IRMM-524a for Fe and NIST SRM-979 for Cr.

Sample	Measured at	N	µ <sup>54</sup> Fe	μ <sup>58</sup> Fe	δ <sup>56</sup> Fe (‰)
OC002 Orgueil (CI)	UofC UofC	41 24	$+1 \pm 5 +2 \pm 7$	$+9 \pm 11 + 13 \pm 11$	$-0.01 \pm 0.02$ +0.005 ± 0.02
Sample	Measured at	N	μ <sup>53</sup> Cr	μ <sup>54</sup> C	r
OC002 Kainsaz (CO3.1) Forest City (H5)	Science Tokyo Science Tokyo Science Tokyo	4 2 2	$+24 \pm 3$ +4 ± 6 +15 ± 3	5 +103 +71 = 5 -35	$3 \pm 13 \pm 13 \pm 13 \pm 13$

*Note:* N is the number of repeat analyses of standard-sample-standard solution for Fe isotopic analysis and the number of repeat analyses of the sample for Cr isotopic analysis using TIMS.

Abbreviations: OC002, Oued Chebeika 002; TIMS, thermal ionization mass spectrometry.

Orgueil display limited mass-dependent Fe isotopic variation relative to terrestrial standard IRMM-524a (Table 3). This means that all isotopic anomalies reported here are real and not artifacts from the internal normalization scheme used to correct for natural and instrumental mass fractionation using exponential law. Iron isotopic anomaly measurements reveal that Oued Chebeika 002 displays an average  $\mu^{54}Fe = +9 \pm 11$ , while Orgueil displays an average  $\mu^{54}Fe = +2 \pm 7$  and  $\mu^{58}Fe = +13 \pm 11$ . The reported data for Orgueil are consistent with previous measurements done by Hopp et al. (2022).

Oued Chebeika 002 has  $\mu^{53}Cr = +24 \pm 5$  and  $\mu^{54}Cr = +103 \pm 13$ . For comparison, Kainsaz (CO3.1) and Forrest City (H5) were also measured at the same time. Kainsaz has  $\mu^{53}Cr = +4 \pm 6$  and  $\mu^{54}Cr = +71 \pm 13$ , and Forrest City has  $\mu^{54}Cr = +15 \pm 5$  and  $\mu^{54}Cr = -35 \pm 13$  (Table 3). These are identical to previously measured values for Kainsaz of  $\mu^{54}Cr = +87 \pm 18$  (Qin et al., 2011) and for Forrest City of  $\mu^{54}Cr = -36 \pm 3$  (Pedersen et al., 2019). For Oued Chebeika 002,  $\mu^{53}Cr$  was found to be identical to other CI1 chondrites; however,  $\mu^{54}Cr$  is slightly lower (+103 ± 13 vs +151 ± 5) than CI samples measured in

Zhu et al. (2021). The Cr recovery yields during chemical separation were >90%-95% for these samples, so we do not think that mass-fractionation departing from the exponential law can explain the low  $\mu^{54}$ Cr value in Oued Chebeika 002. The values measured in Kainsaz and Forrest City are consistent with previous data, so it is also unlikely that the data would be affected by unresolved isobaric interferences. Yokovama, Wadhwa, et al. (2023) reported such low  $\mu^{54}$ Cr values in the CI1s Alais ( $\mu^{54}Cr = +90 \pm 10$ ) and Orgueil ( $\mu^{54}Cr = +84 \pm 14$ ), but these are outliers, as the vast majority of  $\mu^{54}$ Cr measurements in CI1s give values around 1.5 (22 out of 24; Dauphas et al., 2024). We have no reason to doubt the accuracy of our analysis at the present time. The two possible explanations then are that (i) the sample digested is not representative of the bulk, which could have been the case for the previously analyzed CI with low  $\mu^{54}$ Cr as only  $\sim 20 \text{ mg}$  of Orgueil and Alais had been digested (Yokoyama, Wadhwa, et al., 2023) or (ii) the digestion was incomplete, as the main scope was to analyze the trace, major, and minor compositions of Oued Chebeika 002, and some carriers of isotopic anomalies are highly chemically resistant. The  $\mu^{53}$ Cr value that we measure agrees with previous CI measurements, indicating that the issue lies primarily with  $\mu^{54}$ Cr. Most likely, the digestion was not thorough enough to completely destroy the carrier of <sup>54</sup>Cr anomalies. Presolar nanospinel (Cr oxide) is a known carrier of <sup>54</sup>Cr anomalies in meteorites (Dauphas et al., 2010; Nittler et al., 2018; Oin et al., 2011) and there may be more carriers of <sup>54</sup>Cr anomalies. The main carrier of <sup>54</sup>Cr anomalies can be digested in hot HCl (Dauphas et al., 2010; Nittler et al., 2018; Qin et al., 2011; Rotaru et al., 1992). The samples of Oued Chebeika 002 and Orgueil were digested with a mixture of HF-HNO<sub>3</sub> (at 130°C) and HNO<sub>3</sub>, and then dissolved in HCl (Barrat et al., 2012). Such a protocol should have digested most nanospinels, but it is conceivable that part of those grains or another presolar carrier survived this procedure, which could explain the low  $\mu^{54}$ Cr value measured. More measurements are needed to answer this question, but, in all likelihood, this would shift the true  $\mu^{54}$ Cr value toward higher  $\mu^{54}$ Cr closer to the value measured in other CI1s. Unlike Cr, there is to this day no evidence that the isotopic composition of Fe could be affected by such incomplete digestion.

### Mössbauer Spectroscopy

Based on XRD patterns, and SEM and TEM observations, the major Fe-bearing phases present in the sample are magnetite, pyrrhotite, pentlandite, and clay minerals. The Mössbauer spectrum is dominated by magnetite and pyrrhotite sextets (Figure 9a). The magnetically split components assigned to iron in

the tetrahedral (A) and octahedral (B) sites of magnetite present area ratios close to the nominal stoichiometry of magnetite of 1:2 (Table 1). This value is close to the quasi-stoichiometric magnetite crystals measured in Ryugu (Roskosz et al., 2023), unlike magnetite crystals in Orgueil that are significantly oxidized (Madsen et al., 1986). Two paramagnetic  $Fe^{2+}$  and  $Fe^{3+}$  doublets are observed in the central part of the spectra. They are typical of iron accommodated in silicates (Figure 9a). The Mössbauer parameters of each identified phase are very similar to those measured in Ryugu samples (Table 1; Roskosz et al., 2023). The fraction of iron present in each of these sites was derived from the fits to the experimental data and can be used as a first approximation to derive phase proportions. Magnetite concentrates about 36 atom% of the total iron, pyrrhotite concentrates  $\sim 30$ atom%, phyllosilicates contain  $\sim$ 31 atom% of iron, and pentlandite amounts to  $\sim 3$  atom% of the total iron (Table 1). From this fit to the data, the redox ratio  $(Fe^{3+}/Fe_{tot})$  of phyllosilicates is found to be 59% and the average bulk redox ratio of the meteorite is  $\sim$ 42%. These ratios are significantly lower than those measured in Orgueil. Alais (typically  $\sim 80\% - 90\%$ ) and Murchison (typically 70%), and very comparable to the redox ratio determined for Ryugu particles (Nakamura et al., 2022; Roskosz et al., 2023). The amount of iron accommodated in phyllosilicates is also very similar to Ryugu particles  $(\sim 30 \text{ atom}\%)$ . The attribution of the observed doublets to specific silicates is not straightforward. The  $Fe^{2+}$  is attributed to phyllosilicates (ferrous iron in octahedral position) and the Fe<sup>3+</sup> doublet could be attributed either to octahedral or tetrahedral sites within clay mineral structures. Our preliminary cryo-Mössbauer measurements rule out the possibility that ferrihydrite represents a significant fraction of iron in Oued Chebeika 002.

#### **IR Spectroscopy**

The IR transmission spectra were acquired both (i) under ambient conditions of temperature and pressure and (ii) under vacuum and ambient temperature (Figure 10a). Each Oued Chebeika 002 spectrum acquired under ambient conditions is characterized by the presence of a broad absorption between 3700 and 3000 cm<sup>-1</sup>. Typically, this broad "3- $\mu$ m" feature may be due to (i) interlayer water and -OH groups in phyllosilicates and/or (ii) physically adsorbed water. In a manner similar to reflectance measurements (Figure 11), this broad feature largely disappears in spectra acquired from Oued Chebeika 002 samples placed under vacuum. This illustrates the major contribution of adsorbed water in this spectral region. For this reason, we will consider spectra acquired under vacuum in the following (Figure 10b).



FIGURE 9. (a) Conventional Mössbauer spectrum of the bulk El Oued 002 sample. The fit to the data is the sum of nine different lines shown individually as solid lines. (b) Comparison of conventional Mössbauer spectra of El Oued 002, Ryugu (grain C0061), and the CI1 chondrites Orgueil and Alais. Data from Roskosz et al. (2023) and Madsen et al. (1986).

The 3- $\mu$ m band of any type 1 and 2 chondritic matrices is controlled by the hydrous mineralogy of the samples. In Orgueil, for example, the spectral features at 3  $\mu$ m are interpreted as resulting from a mixture of serpentine and saponite in association with ferrihydrite. The average IR spectra of Oued Chebeika 002 is characterized by a sharp asymmetric feature with a welldefined peak at 3685 cm<sup>-1</sup> (i.e., 2.71  $\mu$ m). The spectral feature at  $\sim 1000 \text{ cm}^{-1}$  is related to Si-O stretching. It is controlled by both chemistry and the crystallographic structure of the phyllosilicates. The profile of the so-called 10-µm band is often modified in chondrites by the presence of additional bands of lower intensity such as sulfates ( $\sim 1100 \text{ cm}^{-1}$ ) and carbonates ( $\sim 900 \text{ cm}^{-1}$ ). These bands are mostly absent in the spectra of Oued Chebeika 002.

Oued Chebeika 002 also displays spectral bands related to the presence of CC matter: aliphatic C-H bands at 2960 cm<sup>-1</sup> (CH<sub>3</sub> asymmetric stretching), 2930–2925 cm<sup>-1</sup> (CH<sub>2</sub> asymmetric stretching), and 2855–2850 cm<sup>-1</sup> (CH<sub>3</sub> and CH<sub>2</sub> symmetric stretching), and spectral bands at 1460 cm<sup>-1</sup> (scissoring for CH<sub>2</sub>) and 1380 cm<sup>-1</sup> (antisymmetric bending for CH<sub>3</sub>). Features at 1705–1690 cm<sup>-1</sup> and ~1600 cm<sup>-1</sup> are attributed to C=O and aromatic C=C stretching (with some water bending mode contribution), respectively.

The IR reflectance of the raw sample and powder is low (about 2.5% at  $0.55 \,\mu$ m) and lower than the typical values measured for CI1 chondrites (Figure 11, left). Compared with the raw sample, the reflectance spectrum of the Oued Chebeika 002 powder shows a steeper spectral slope and deeper 3-µm absorption. Exposing this powder to vacuum resulted in a major change in the shape of the 3-µm band (Figure 11, right), as was also observed in the transmission spectra (Figure 10a). Under vacuum, the reflectance at 2.9 µm increases, likely due to the elimination of weakly bonded water molecules, and the sharp absorption at 2.72 µm becomes more visible, as do the CH modes related to organic compounds at 3.4-3.5 µm. Upon exposure to vacuum, a weak but detectable absorption at 3.05-3.06 µm becomes visible (Figure 11, right, arrow) that we attribute to the presence of NH-bearing compounds such as ammoniated phyllosilicates or NH-bearing organic molecules (De Sanctis et al., 2015; King et al., 1992; Pilorget et al., 2022; Viennet et al., 2023). This is also consistent with observations in Bennu samples (Glavin and Dworkin et al., 2025). It is noteworthy that these compounds are not detectable in the transmission spectra of the matrix, where they would appear as a  $\sim 3.06 \,\mu\text{m}$  spectra feature. It could be partly masked by the contribution of remaining adsorbed water or be absent from the matrix fragments selected for transmission IR spectroscopy.

Small absorptions at 3.8 and  $3.95\,\mu\text{m}$  are also observed in the spectrum obtained on the raw sample that we interpret as the presence of carbonates. Reflectance spectra obtained up to 16  $\mu$ m confirm the spectral similarities of Oued Chebeika 002 with CI1-like material and in particular Ryugu samples, in terms of absolute reflectance, spectral slope, presence, and amplitude of spectral features (Figure 12). Because the Si-O and carbonate modes are particularly strong in this range, reflectance is in an interplay of the real and



FIGURE 10. (a) Representative transmission spectra of three distinct matrix fragments of Oued Chebeika 002 obtained under ambient conditions of temperature and pressure (in black) and under vacuum and ambient temperature (in blue). The disappearance of the 3- and 6- $\mu$ m features is indicative of H<sub>2</sub>O loss. (b) Transmission spectra of Oued Chebeika 002 in comparison to Orgueil, and Hayabusa2 particles A0108-10 and C0109-12 (Yabuta et al., 2023). Spectra were baseline corrected and normalized to the 10- $\mu$ m band. An arbitrary offset was applied on the vertical axis for the sake of clarity.

imaginary part of the optical constants, and comparison to transmission spectra (Figure 10) is not direct. The difference in silicate mineralogy between Oued Chebeika 002 and a CM2 chondrite (Murchison) can be seen by looking at the position of the peak reflectance in the 10-µm region. The presence of anhydrous silicate in CM2 chondrites and the distinct nature of the phyllosilicate between CM2 and CI1 chondrites explain this difference.

#### Raman Spectroscopy

All Raman spectra obtained on matrix fragments of Oued Chebeika 002 exhibit the D- and G-bands, indicating



FIGURE 11. (Left) Reflectance spectra obtained on Oued Chebeika 002 (powdered raw sample in red and raw sample in burgundy) compared to measurements on powders of other CI chondrites. The spectrum of Orgueil was obtained at Institut de Planétologie et d'Astrophysique (IPAG), Grenoble, and the spectra of Alais and Ivuna are from the RELAB database (c1mt264 and c1mb60). (Right) Reflectance obtained on Oued Chebeika 002 in the 3-µm region, on raw sample (burgundy color), powder (red), and powder exposed to vacuum (light red). The spectra are compared to a spectrum obtained on Orgueil powder under vacuum (black) and to a spectrum obtained on raw aggregated Ryugu grains (in blue, from Amano et al., 2023). The salmon arrow is the absorption feature at 3.05–3.06 µm, attributed to NH-bearing organic molecules.



FIGURE 12. Mid-infrared (IR) reflectance spectra obtained on Oued Chebeika 002 (raw sample) compared to measurement on raw samples (chips) of Ryugu, Orgueil, and Murchison (from Amano et al., 2023).

the presence of polyaromatic CC matter. The spectral features are broad and are superimposed on a fluorescence background, as typically observed for Orgueil, Hayabusa2 samples (Bonal, Quirico, et al., 2024; Yabuta et al., 2023) and unshocked CM chondrites (Quirico et al., 2018) (Figure 13).

The numerical values of the derived spectral parameters of the D- and G-bands are as follows: FWHM<sub>D</sub> (cm<sup>-1</sup>) = 167.1  $\pm$  5.7, FWHM<sub>G</sub> (cm<sup>-1</sup>) = 69.1  $\pm$  5.7,  $I_D/I_G$  =  $0.73 \pm 0.04$ ,  $\omega_D$  (cm<sup>-1</sup>) = 1349.7 ± 3.08, and  $\omega_G$  (cm<sup>-1</sup>) = 1598.0 ± 1.80.

#### Thermogravimetric Analyses

The total mass loss (20–1000°C) for Oued Chebeika 002 was 18.7 wt%, with the differential thermogravimetry (DTG) curve highlighting several mass loss events related to the different minerals and



FIGURE 13. Comparison of Raman data of Oued Chebeika 002 and other primitive extraterrestrial materials: average Raman spectra (a) and average spectral parameters (b–d). Average Raman spectra of Oued Chebeika 002 (in red) are compared with individual intact Ryugu particles (in black and gray) and with matrix fragments of type 1 (in yellow) and type 2 chondrites (unheated and heated in dotted black lines) and type 3 chondrites (in gray diamonds). Spectral parameters of Raman bands of carbonaceous materials (b, c, d) of Oued Chebeika 002 (in red) are compared to reference chondrites (Orgueil in yellow, CM2 chondrites in green, with some Hayabusa2 samples in black and crossed circles a,d with same type 3 chondrites in gray diamonds) in full width at half maximum (FWHM)<sub>D</sub> versus  $I_D/I_G$  (b),  $\omega_G$  versus  $\omega_D$  (c), and FWHM<sub>G</sub> versus  $\omega_G$ . (d) Averages (symbols) and standard deviations (bars) are plotted for each sample.

species present within the sample (Figure 14). A significant peak in the DTG curve at  $\sim$ 50°C is attributed to the removal of adsorbed terrestrial water and dehydration of interlayer water from smectites, while a relatively minor mass loss event at  $\sim$ 115°C may likely result from the breakdown of sulfates (e.g., Garenne et al., 2014; King, Solomon, et al., 2015).

However, the main mass loss for Oued Chebeika 002 occurred between  $\sim$ 400 and 700°C, consistent with the dehydration and dehydroxylation of structural OH from serpentine and smectite, followed by a sharp peak in the DTG curve at  $\sim$ 700–800°C due to the decomposition of carbonates (King, Solomon, et al., 2015; Yokoyama, Nagashima, et al., 2023).



FIGURE 14. Intrinsic magnetic properties of Oued Chebeika 002 (OC002) compared to other CI1 chondrites and Ryugu. (a) Saturation magnetization ( $M_s$ ) as a function of sample mass. (b) Low-field susceptibility ( $\chi_{LF}$ ) as a function of sample mass. For (a) and (b), the horizontal dashed lines are the mass-weighted average values. Data in (a) and (b) can be found in Table S2. (c) Low-field susceptibility as a function of temperature. (d)  $M_{RS}$ -normalized coercivity spectra plotted using the MAX Unmix software (Maxbauer & Feinberg, 2016). A single 21-mg sample of Ryugu (Maurel et al., 2024), a single 49-mg sample of Oued Chebeika 002, and a single 47-mg Orgueil sample are shown, but spectra acquired on multiple samples are shown in Figure S3. (e) First-order reversal curve (FORC) diagrams obtained with a 9-mg powdered sample of Oued Chebeika 002 and a 28.8-mg sample of Alais. (f) Orthogonal projection of the natural remanent magnetization (NRM) of a 34-mg of Oued Chebeika 002 during stepwise alternating field (AF) demagnetization. Open and closed symbols show the projection onto the (y, z) and the (y, x) planes, respectively. The color scale indicates the AF intensity. The NRM projected onto the (y, z) is shown.

If we assume that all mass loss between 200 and  $800^{\circ}$ C is due to the dehydration and dehydroxylation of phyllosilicates, then the water abundance for Oued Chebeika 002 is ~11 wt% (Garenne et al., 2014; King, Solomon, et al., 2015). However, we note that this approach is known to slightly overestimate the water content, with the breakdown of both smectites and carbonates contributing to the mass loss above 700°C, and the decomposition of sulfides and organic matter occurring above 400°C (King, Solomon, et al., 2015; Yokoyama, Nagashima, et al., 2023).

# **Bulk Density and Porosity**

Grain density is  $2.67 \pm 0.11 \text{ g cm}^{-3}$  (mass-weighted average of four measurements  $\pm 1 \text{ SD}$ , total measured mass 46.22 g). The XCT scan of a 10.407 g stone indicated a bulk volume of 5.105 cm<sup>3</sup>, resulting in a bulk

density of  $2.04 \text{ g cm}^{-3}$ . Combining grain and bulk density gives an estimated porosity of 24%.

#### **Magnetic Properties**

All magnetic data presented here can be found in Table S2. For comparison with other CI1 chondrites, we also measured samples from Alais, Orgueil, Ivuna, and Tonk CI1 chondrites. Hysteresis properties and low-field magnetic susceptibility ( $\chi_{\rm LF}$ ) were measured on 14 and 13 independent samples of Oued Chebeika 002, respectively, with mass ranging between 3.3 mg and 52.0 g. We measured a mass-weighted average  $\chi_{\rm LF}$  of  $6.52 \times 10^{-5} \, {\rm m}^3 \, {\rm kg}^{-1}$  for a total mass of 90.72 g and a mass-weighted average saturation magnetization ( $M_{\rm s}$ ) of 10.54 A m<sup>-2</sup> kg<sup>-1</sup> for a total mass of 0.275 g.

The  $M_s$  of Oued Chebeika 002 is relatively constant as sample mass decreases down to  ${\sim}20\,\text{mg},$  with a narrow

spread below 20 mg (Figure 14a). The  $\chi_{LF}$  is also relatively constant between 33.9 g and 7.0 mg (Figure 14b). This indicates that the magnetic mineralogy of Oued Chebeika 002 is homogenous down to the 10-mg scale or less. This is consistent with the relatively constant S<sub>-300</sub> ratio (i.e., the ratio between the SIRM and a backfield IRM acquired in a 300-mT field) of these samples. We find an average S<sub>-300</sub> ratio of -0.80, which indicates a significant amount of minerals with high magnetic coercivities (>300 mT). The mass-weighted average FD of magnetic susceptibility is FD = 1.6%, indicating the presence of a small amount of superparamagnetic minerals. These superparamagnetic grains are magnetite and/or pyrrhotite grains smaller than 20 nm (Clark, 1983; Worm, 1998).

At low temperature,  $\chi_{\rm LF}$  undergoes a characteristic sharp increase when heated above  $\sim 125 \text{ K}$ . corresponding to the Verwey transition of magnetite (Figure 14c). This is consistent with the presence of magnetite grains dominantly in the vortex magnetic state (grain size of  $\sim 0.1$  to  $\sim 5 \,\mu m$ ) and/or multidomain magnetic state ( $\gtrsim 5 \,\mu$ m). The coercivity spectrum (Figure 14d: Figure S3) provides estimated proportions of the different populations of grains contributing to the SIRM of a sample, that is, the maximum magnetic remanence recordable. Using the MAX Unmix software (Maxbauer & Feinberg, 2016), for a 49-mg sample, we find a dominant population with a median coercivity of 73 mT accounting for 55% of the SIRM, a second population with a median coercivity of 302 mT (20% of the SIRM), and a third population with a median coercivity of 31 mT (18% of the SIRM). Very similar distributions are found for two other samples with masses of 30 and 9 mg, respectively (Figure S4). Given its median value of  $\sim$ 300 mT, the high-coercivity population cannot correspond to magnetite, and we therefore identify it as micron/submicron pyrrhotite grains (Dekkers, 1988). The medium-coercivity peak likelv corresponds to the abundant magnetite found in the form of framboids, plaquettes, and spherulites, and the low-coercivity peak to larger grains of magnetite and/or pyrrhotite.

The FORC diagram (Figure 14e) exhibits a triangular pattern, observed in other CI1 chondrites (Sridhar et al., 2021; Figure S5). The broadened vertical signal, asymmetric with respect to the horizontal axis; the peak intensity around 30 mT; and the negative lower-right diagonal region are consistent with a dominant population of strongly interacting grains in the vortex magnetic state (Egli, 2021). This likely corresponds to magnetite grains. The weaker signal that extends along the horizontal axis at least up to 300 mT reflects the presence of minerals with a higher magnetic coercivity, like micrometer-sized pyrrhotite grains.

We measured the ratio of natural remanent magnetization over magnetic susceptibility (NRM/ $\gamma_{\rm LF}$ ) for 7 samples ranging between 20 and 52 mg, and 11 samples ranging between 0.88 and 10.41 g. All samples but one had an NRM/ $\chi_{LF}$  ratio >500 A m<sup>-1</sup>, indicating irreversible contamination by contact with a magnet (Maurel et al., 2024). A single, 34-mg sample had a low  $NRM/\chi_{LF}$  of 6.5 A m<sup>-1</sup>, indicating that it escaped magnetic contamination. This is confirmed by a low NRM/SIRM ratio of  $4.72 \times 10^{-4}$ . The stepwise AF demagnetization of this sample's NRM reveals a nonorigin trending, low-coercivity component of the magnetization between 0 and 9 mT (Figure 14f). This may correspond to a viscous remanent magnetization acquired during its short exposure to the geomagnetic field. For AF steps above 10 mT, the demagnetization of the NRM becomes chaotic, with no component identifiable.

#### DISCUSSION

# Comparison with Other CI1 Chondrites and Samples From Asteroids Ryugu and Bennu

The overall dark and brecciated aspect of Oued Chebeika 002 is similar to CI1 chondrites, with the notable difference that it does not carry sulfates, which in other CI1 chondrites are visible as white dots and veins in bulk samples (e.g., Gounelle & Zolensky, 2001). Sulfates are also absent in thick sections. The fusion crust is preserved and very pristine (Figure 1d), suggesting that the meteorite was collected soon after its fall. The excellent preservation state of the stones, despite the very high sensitivity of this type of material to exposure to water (e.g., Wilson et al., 2024), and the occurrence of about 100 mm rainfall on average in the area during the winter period (between October and March) suggest that the meteorite fell after March 2024 and in any case after the last significant rainfall.

The bulk chemical composition of Oued Chebeika 002, measured on an aliquot of a 1.06-g powdered sample, resembles the average composition of Orgueil measured on 5 samples for a total mass of nearly 4 g analyzed by Barrat et al. (2012). The trace element pattern unambiguously confirms that Oued Chebeika 002 is a CI chondrite (Figure 15a). However, Oued Chebeika 002 differs from Orgueil, Alais, and Ivuna in that it has slight (<20%) Cu and Pb deficits, and generally higher concentrations of the other trace elements. In Figure 15b, we compare the patterns obtained from Oued Chebeika 002 to those of relatively large samples of other CI1 chondrites: Alais, Ivuna, and Orgueil (Barrat et al., 2012). Apart from Alais, which shows a slightly convex pattern with a middle-RRE moderate enrichment, the other



FIGURE 15. Bulk composition of Oued Chebeika 002 in comparison to other CI chondrites and some other carbonaceous chondrites (Barrat et al., 2012; Hewins et al., 2014). (a) elements in the order of decreasing condensation temperatures. (b) Rare earth element patterns. For normalization, the CI values of Barrat et al. (2012) are used.

patterns are flat and without significant anomaly. Oued Chebeika 002, however, is  $\sim 15\%$  richer in REE than the Orgueil average. This REE enrichment does not reach the higher concentrations measured by Yokoyama, Nagashima, et al. (2023) in two Ryugu samples (24 and 22 mg), with the caveat that these concentrations were measured on much smaller, perhaps less representative samples. The REE enrichment is also lower than the enrichment found in other CC chondrites, as exemplified



FIGURE 16. (a) Oxygen isotopic composition of Oued Chebeika 002 compared to a selection of other carbonaceous groups. Data for CM and CO chondrites are from the compilation of Greenwood et al. (2020), except data for Sutter's Mill (Jenniskens et al., 2012). Data for CI1 chondrites and Ryugu samples are the mass-weighted average values from Greenwood et al. (2023). Data for Bennu samples are the massweighted average computed from Lauretta and Connolly et al. (2024). A selection of C2- and C3-ungrouped meteorites is also plotted. This data set is also from Greenwood et al. (2023), except data for Niger I and Bells (Clayton & Mayeda, 1999), WIS 91600 (Clayton & Mayeda, 2003), and Y-86029 (Tonui et al., 2014). The carbonaceous chondrite anhydrous mineral (CCAM) line is from Clayton and Mayeda (1999). (b) Oxygen isotopic composition of Oued Chebeika 002 compared to other CI1 chondrites, and Ryugu and Bennu materials. Data are individual analyses from Greenwood et al. (2023), except data for Bennu samples that are from Lauretta and Connolly et al. (2024). Error bars are  $\pm 2$  SD.

by the results for Paris CM2 and Allende CV3 in Figure 15b.

The oxygen isotopic composition of Oued Chebeika 002 is within the range of oxygen isotopic compositions measured in other CI1 chondrites and Ryugu samples measured using a similar technique (Greenwood et al., 2023). It is distinct from the oxygen isotopic composition of other CC chondrite groups (Figure 16a). Only two chondrites, Niger I (C2-ung) and Wisconsin

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FIGURE 17. Isothermal sections at (a) 25°C and (b) 100–135°C from Fe-Ni-S phase diagrams (atom%) (after Vaughan & Craig, 1997 and Naldrett, 1989, respectively) showing pyrrhotite (Po) and pentlandite (Pn) point analyses from Oued Chebeika 002. These are plotted alongside literature data for the CI1 chondrites Orgueil, Ivuna, and Alais (Bullock et al., 2005; Berger et al., 2016; Schrader et al., 2021; Harrison et al., 2025), and Ryugu (Harrison et al., 2025). Cobalt is combined with iron (after Berger et al., 2016 and Bullock et al., 2005) as both elements behave similarly in Fe-sulfides (Lauretta, 2005).

Range (WIS) 91600 (CM-an), have a similar yet distinct oxygen isotopic composition. The comparison of the oxygen isotopic composition of Oued Chebeika 002 with other CI1 chondrites and Ryugu material reveals subtle differences (Figure 16b). As observed in Greenwood et al. (2023), Orgueil, Alais, and especially Ivuna have slightly lower  $\Delta^{17}$ O values than Ryugu material. This was interpreted as possible contamination of the CI1 chondrites by terrestrial water. By contrast, the  $\Delta^{17}O$ value for Oued Chebeika 002 ( $\Delta^{17}O = 0.76 \pm 0.03\%$ ) is compatible within the 2SD level with the average  $\Delta^{17}$ O value for Ryugu samples ( $\Delta^{17}$ O = 0.66 ± 0.09‰, Greenwood et al., 2023) and Bennu samples ( $\Delta^{17}O =$  $0.62 \pm 0.15\%$ , computed from Lauretta and Connolly et al., 2024). This could indicate that Oued Chebeika 002 suffered less terrestrial alteration than the other three studied CI1 falls.

Petrographic observations and XRD measurements show that the mineralogy of Oued Chebeika 002 is similar to that of other CI1 chondrites, Ryugu and Bennu samples, with dominant serpentine and saponite clay minerals, magnetite, pyrrhotite, and lesser amounts of carbonates (dolomite and breunnerite), pentlandite, and accessory Cu-sulfides, apatite, and other Na,Mg phosphates. The high abundance of phyllosilicates (88 vol %) is comparable to the bulk mineralogy reported for other CI chondrites (King, Schofield, et al., 2015). The absence of anhydrous silicates is consistent with nearcomplete aqueous alteration.

The remarkable magnetite morphologies in Oued Chebeika 002 (Figure 4) are identical to the ones observed in other CI1 chondrites (Hua & Buseck, 1998; Jedwab, 1967), Ryugu samples (Dobrică et al., 2023) and

Bennu samples (Lauretta and Connolly et al., 2024). The sulfur content of Oued Chebeika 002 (6.5 wt%) is twice the amount found in Ryugu samples (3.3 wt%) and in other CI1 chondrites (3.0-4.4 wt%, Burgess et al., 1991), likely reflecting a higher abundance of sulfides in Oued Chebeika 002 than in other CI1 chondrites. Iron sulfides are predominantly pyrrhotite, with compositions most consistent with 4C-pyrrhotite (Fe<sub>7</sub>S<sub>8</sub>, or Fe<sub>0.875</sub>S) (Wang & Salveson, 2005) (Table S1), similar to other CI1 chondrites (Berger et al., 2016; Bullock et al., 2005), and Ryugu (Nakamura et al., 2022). The euhedral morphology of iron sulfides is also very similar to the other CI1 chondrites (Bullock et al., 2005), Ryugu samples (Harrison et al., 2025), and Bennu samples (Lauretta and Connolly et al., 2024). The average Fe/S atomic ratio of low-Ni (<1 atom% Ni) pyrrhotite, which decreases with increasing degrees of oxidation during aqueous alteration (Schrader et al., 2021), is 0.87 in Oued Chebeika 002. This is similar to the Fe/S ratio of low-Ni pyrrhotite in other CI1 chondrites (~0.86, Schrader et al., 2021), suggesting consistent degrees of oxidation between Oued Chebeika 002 and the other CI1 chondrites, while the Fe/S ratio is slightly lower in Ryugu samples ( $\sim 0.83$ , Harrison et al., 2025). Pentlandite compositions in Oued Chebeika 002 are more consistent with pyrrhotite-pentlandite phase relationships in the 25°C isothermal section from the Fe-Ni-S phase diagram compared to the 100–135°C isothermal section (Figure 17). This is similar to temperature estimates for the CI1 chondrites Orgueil and Ivuna (Berger et al., 2016; Harrison et al., 2025) and Ryugu samples (Harrison et al., 2025; Nakamura et al., 2022), while Fe-sulfides in Alais equilibrate at higher temperatures (~100-135°C)



FIGURE 18. Carbonate compositions in a ternary diagram Ca-Mg-Fe + Mn (mole%). Orange diamonds: Oued Chebeika 002, dark blue circles: Orgueil, red circles: Ivuna, green circles: Alais (data from Endreß and Bischoff (1996), Johnson and Prinz (1993), Lee and Nicholson (2009)), and light blue circles: Ryugu samples (average value from Nakamura et al., 2022).

(Berger et al., 2016). Cubanite, a rare mineral in meteorites, is present in Oued Chebeika 002 as well as in other CI1 chondrites (MacDougall & Kerridge, 1977) and in Ryugu samples (Yokoyama, Nagashima, et al., 2023). Cubanite was also described in samples of comet Wild 2 returned by the Stardust mission (Berger et al., 2011). One noticeable difference between Oued Chebeika 002 and other CI1 material is the presence of chalcopyrite. This Cu-rich iron sulfide has not been described in CI1 chondrites or in Ryugu samples, although rare nanoscale chalcopyrite grains have been identified in Bennu samples (Keller et al., 2024). Chalcopyrite has also been detected in thermally metamorphosed CK, CY, and R chondrites (Schrader et al., 2016; Harrison et al., 2025). The dolomite and breunnerite compositions (Figure 18) fall within the range carbonates chondrites of in CI1 (Endreß & Bischoff, 1996; Johnson & Prinz, 1993) and Ryugu samples (Nakamura et al., 2022). The range of compositions of apatites and Mg,Na-rich phosphates (Table S1) is compatible with those observed in CI1 chondrites, Ryugu samples (Mikouchi et al., 2024), and Bennu samples (McCoy et al., 2025).

The absence of calcite, Na-rich carbonates, or siderite in the  $\sim 3 \text{ cm}^2$  of sections of Oued Chebeika 002 that we studied and in the XRD patterns may be a significant mineralogical difference compared to other CI1 chondrites, Ryugu samples, and Bennu samples. However, these minerals are rare in other CI1 chondrites with highly heterogeneous abundances within a given CI1 (Johnson & Prinz, 1993; Lee & Nicholson, 2009). They are equally rare in Ryugu samples (Matsumoto et al., 2024; Yokoyama, Nagashima, et al., 2023) and Bennu samples (Connolly et al., 2025). The same holds true for olivine and pyroxene, which are rare in other CI1 chondrites (King, Schofield, et al., 2015; Leshin et al., 1997) and in Ryugu and Bennu (Connolly et al., 2025; Mikouchi et al., 2023). Like Ryugu samples, Oued Chebeika 002 lacks sulfates, confirming the fact that sulfates in Orgueil and other CI1 chondrites formed during the residence on Earth of meteorites (Airieau et al., 2005; Gounelle & Zolensky, 2001). The same observation probably holds for ferrihydrite (see below). We have not yet performed analytical chemistry to confirm the presence and measure the abundance of ammonium ions and other salts, which seem to be an important component at least of the Orgueil meteorite (Laize-Générat et al., 2024) and the Bennu samples (Glavin and Dworkin et al., 2025; McCoy et al., 2025).

The nature and composition of clay minerals is consistent with that reported from other CI1 chondrites, Ryugu and Bennu samples, with only minor differences. TEM-EDS analyses of phyllosilicates are similar to previous studies by the same technique on Orgueil (Leroux et al., 2024; Tomeoka & Buseck, 1988) and Ryugu (Leroux et al., 2024). Minor differences of average compositions, in terms of Fe/(Mg/Fe) or (Mg+Fe)/Si ratios or of Na content, should be considered with caution due to possible biases of representativity. Defocused-beam EPMAs of the Oued Chebeika 002 matrix give similar compositions to those of Orgueil reported by Zolensky et al. (1993). The matrix composition is, however, significantly different from that of Ivuna and Alais (Zolensky et al., 1993). However, these differences may not be significant, as matrix analyses consist of mixed signals influenced by infilling of the porosity by epoxy (Prêt et al., 2010), and by the presence or absence of  $<1 \,\mu m$  grains of magnetite, sulfides, or carbonates that may be included within the interaction volume of the electron microprobe beam. The only particularity of Oued Chebeika 002 in terms of phyllosilicates might be the occurrence of large clasts of nearly pure phyllosilicates, up to 200 µm large, that have been observed in all three polished sections we studied but, to our knowledge, have not been reported in other CI1 meteorites.

The bulk hydrogen content, which is a proxy for the abundance of hydrated mineral (Alexander et al., 2012, 2013), is similar in Oued Chebeika 002 ( $0.97 \pm 0.2$  wt% H), Ryugu (1.14 wt% H), and Bennu (0.90-0.93 wt% H), in agreement with the observed mineralogy between samples (Glavin and Dworkin et al., 2025; Lauretta and Connolly et al., 2024; Naraoka et al., 2023).

The ferromagnetic mineralogy of Oued Chebeika 002 is dominated by (i) magnetite grains in the 0.1–5- $\mu$ m size range, corresponding to assemblages of magnetite framboids, plaquettes, spherulites, and (ii) micron/ submicron-size pyrrhotite grains. Only a small fraction of the magnetite grains is superparamagnetic, that is, smaller than about 20 nm in size. Based on the measured M<sub>s</sub> values, the magnetic mineralogy is noticeably homogenous down to <10 mg, more than in other CI1 chondrites (Orgueil, Ivuna, Alais; Figure 14a). The coercivity spectrum and higher mass-weighted average M<sub>s</sub> indicate that Oued Chebeika 002 is slightly enriched in magnetite and/or pyrrhotite compared to other CI1 chondrites.

Despite overall mineralogical similarities with CI1 chondrites (e.g., Figure 14a; Figure S3), the grain size range and proportions of the ferromagnetic minerals in Oued Chebeika 002 differ significantly from those in Orgueil, Ivuna, and Alais, instead resembling those of Ryugu samples. This is apparent from the lower average  $S_{-300}$  of Oued Chebeika 002 and Ryugu (-0.80 and -0.85, respectively) compared to the other CI1 chondrites (-0.98,-0.94, and -0.95 for Orgueil, Ivuna, and Alais, respectively), indicating a larger relative abundance of minerals with coercivities above 300 mT. The coercivity spectra clearly separate into two groups, Oued Chebeika 002 and Ryugu on one hand and Orgueil, Ivuna, Tonk, and Alais on the other hand, which differ both in the mean coercivities and the proportions of the medium- and highcoercivity populations (Figure 14d; Figure S3; Table S2). This is all the more remarkable that this observation holds when measuring multiple samples of Ryugu (from both chambers A and C), Oued Chebeika 002, and Orgueil, with sample masses ranging from 1.6 to 44 mg (Figure S4). Terrestrial weathering can cause the alteration of certain magnetic minerals. For example, pyrrhotite can alter into sulfates in CI1 chondrites (Gounelle & Zolensky, 2001). The lower median value of the high-coercivity component (>300 mT) of Orgueil, Ivuna, and Alais may be explained by the transformation of the smallest-grained pyrrhotite grains. This would be consistent with a higher  $S_{-300}$  for these meteorites compared to Ryugu and Oued Chebeika 002. Although magnetite is usually stable in the terrestrial environment, small grains in an acidic environment (favored by the presence of organic matter) can oxidize into maghemite. In fact, about 12% of the magnetite in Orgueil has been replaced by maghemite (Madsen et al., 1986; Roskosz et al., 2023). Although maghemite has a lower M<sub>s</sub> than magnetite (75 and 92 A  $m^{-2} kg^{-1}$ , respectively), 12% of maghemitization is not enough to account for the lower M<sub>s</sub> value in CI1 falls compared to Oued Chebeika 002. Moreover, terrestrial alteration cannot explain the overall higher relative contribution to the saturation magnetization of pyrrhotite versus magnetite in Orgueil, Alais, Tonk, and Ivuna compared to Oued Chebeika 002 and Ryugu material (Figure 14d). Therefore, we interpret these data as an intrinsic difference in the original magnetic mineral assemblages between these two sets of samples.

The paleomagnetic behavior of the 34-mg magnetically uncontaminated sample of Oued Chebeika 002 is similar to that of Orgueil and Ryugu samples++ (Mansbach et al., 2024; Maurel et al., 2024): a chaotic AF demagnetization, and low NRM/ $\chi$  and NRM/SIRM ratios. For Orgueil and Ryugu, it was concluded that their magnetic remanence was acquired in a very weak to null magnetic field, indicating a late occurrence of aqueous alteration and/or distal formation of their parent body (Mansbach et al., 2024; Maurel et al., 2024). However, a detailed paleomagnetic study of Oued Chebeika 002 material is beyond the scope of this paper.

#### Absence of Terrestrial Weathering

Meteorite weathering is very fast in most hot desert settings, and the mineralogical and chemical changes these rocks undergo are well documented (e.g., Barrat et al., 1999; Bland et al., 2006; Stelzner et al., 1999). Oued Chebeika 002 does not show any evidence of the typical chemical fingerprints of Saharan weathering that are ubiquitous even in apparently very fresh finds, such as marked Ba, Sr, and sometimes U enrichments. Here, the concentrations for these elements are exactly as expected for a CI free of hot desert alteration, (Ba/La)n = 0.994, (Sr/La)n = 1.005, and Th/U = 3.78 compared to 3.68 for average Orgueil. This suggests that Oued Chebeika 002 was recovered very soon after its fall.

Compared to Oued Chebeika 002, it is noteworthy that the XRD spectra of Alais and Orgueil present additional peaks at 7.6, 4.3, 3.8, 3.06, and 2.75 Å corresponding to gypsum (Figure 7a).

Petrographic observations at all scales (macroscopic, SEM, TEM) do not reveal the presence of sulfates or ferrihydrite. The narrow 10-µm band in the IR reflectance spectra of Oued Chebeika 002 confirms the absence of sulfates. The steep 3-µm band and the easiness with which the water desorbed from the surface of Oued Chebeika 002 matrix fragments under pumping with no heating reflect the freshness of Oued Chebeika 002. This is also supported by the spectral similarity (3-µm band profile, absence of oxides) with Ryugu samples (Figure 11). The 10-µm bands in the IR spectra for Orgueil are significantly enlarged in comparison to those of Oued Chebeika 002. This can possibly be explained by the presence of sulfate grains, which produce a secondary peak around  $1100 \text{ cm}^{-1}$  (Salisbury et al., 1991) in Orgueil, but are mostly absent in the Oued Chebeika 002 spectra.



FIGURE 19. Mass loss and differential thermogravimetry (DTG) curves for Oued Chebeika 002 and Ivuna (from King, Solomon, et al., 2015). The main mass loss events are attributed to terrestrial and interlayer water ( $<300^{\circ}$ C), the release of  $-OH/H_2O$  from phyllosilicates ( $\sim400-800^{\circ}$ C), and the breakdown of carbonates ( $\sim700-800^{\circ}$ C).

The total mass loss (20-1000°C) of 18.7 wt% for Oued Chebeika 002 during TGA analyses, shown in Figure 19, is  $\sim 35\%$  lower than the values reported for samples of Ivuna ( $\sim 29 \text{ wt\%}$ ) and Orgueil ( $\sim 30 \text{ wt\%}$ ) analyzed using the same method (Table 4, King, Solomon, et al., 2015). Qualitatively, the DTG curve for Oued Chebeika 002 is similar to those for Ivuna and Orgueil, with most of the mass loss occurring from  $\sim 400$ to 800°C due to the dehydroxylation of phyllosilicates and decomposition of carbonates ( $\sim$ 700–800°C). Mass loss from 400 to 700°C and 700 to 800°C was 8.1 and 2.5 wt%, respectively, for Oued Chebeika 002, compared to  $\sim 10$  and  $\sim 3 \text{ wt}\%$  in the same temperature ranges for Ivuna and Orgueil. Therefore, the major difference is a mass loss event at  $\sim$ 220–250°C for Ivuna and Orgueil that was not observed for Oued Chebeika 002. Using TGA combined with mass spectrometry, Yokoyama, Nagashima, et al. (2023) showed that for Ivuna, mass loss at this temperature was associated with a release of H<sub>2</sub>O and SO<sub>2</sub> most likely from the breakdown of sulfates. Furthermore, such a mass loss event was not seen in analyses of pristine samples returned from asteroid Ryugu (Yokoyama, Nagashima, et al., 2023). Since most of the sulfates in the CI1 falls are thought to be terrestrial in origin (e.g., Gounelle & Zolensky, 2001), their apparent scarcity in Oued Chebeika 002 indicates that it is a fresh example of a CI1 chondrite despite being a desert find.

Mössbauer spectroscopy has shown that Orgueil contains up to 5 wt% of ferrihydrite (Bland et al., 2004; King, Schofield, et al., 2015; Madsen

et al., 1986; Roskosz et al., 2023; Tomeoka & Buseck, 1988). This distinctive Mössbauer signature of CI1 meteorites is not observed in Ryugu samples and in Oued Chebeika 002 (Figure 9b). The absence of ferrihydrite in Oued Chebeika 002 is also inferred from the narrower band at  $3685 \,\mathrm{cm}^{-1}$  in the IR spectra, a difference that we attribute to the absence of hydroxides. Furthermore, two Mössbauer spectroscopy measurements performed on the same sample, 1 month apart, did not show significant changes, suggesting that oxidation in an uncontrolled terrestrial environment (through the formation of ferrihydrite) does occur over a characteristic time longer than months. The Fe<sup>3+</sup>/Fe<sub>tot</sub> of magnetite indicates that Oued Chebeika 002 is significantly less oxidized than historical CI1 falls. Like in Ryugu samples, magnetite crystals are almost stoichiometric, in contrast with the 12% of maghemitization detected in Orgueil (Madsen et al., 1986; Roskosz et al., 2023). The redox state of hydrous silicates is also relatively low (59%) and the overall redox ratio of the meteorite (42%) is comparable to Ryugu samples and much lower than in other CI1 falls. If these signatures are primarily indicative of the formation conditions and of putative parent-body processes, they also clearly indicate that Oued Chebeika 002 did not suffer extensive oxidation on Earth compared to other fragile and porous CC chondrites. Furthermore, from the comparison with Orgueil and Alais Mössbauer spectra (Figure 9b), it is clear that Oued Chebeika 002 is more akin to Ryugu samples. For this reason, we propose that the redox ratios measured here are primarily the redox ratio of iron-bearing minerals present in the parent body of Oued Chebeika 002 at the time of its ejection.

In summary, several lines of evidence (trace elements, TGA, preservation of the fusion crust, absence of sulfates, ferrihydrite, maghemite, and possibly oxygen isotopic composition) indicate that Oued Chebeika 002 is a very pristine meteorite with little or no detectable terrestrial contamination. These results indicate that Oued Chebeika 002 is less affected by terrestrial alteration than the CI1 falls Orgueil, Alais, and Ivuna.

In fact, these falls have been in meteorite collection for durations in the 100–200 years range, without efficient atmospheric control for most of this time. Although the fall date of Oued Chebeika 002 is not known, it is certainly short in view of its excellent preservation state. Its extreme sensitivity to water suggests that it has never suffered rain at the find location and that the fall date was at most a few weeks before the collection date of June 6, 2024. The studied material has been preserved in a stable atmosphere with a controlled hygrometry of 10% since August 30, 2024, meaning it was in contact with the atmospheric water

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Samples	25–1000°C	<100°C	100–200°C	400–700°C	700–800°C	200-800°C		
Oued Chebeika 002	18.7	4.9	0.9	8.1	2.5	11.0		
Ivuna	29.2	5.0	3.8	10.6	3.0	18.6		
Orgueil	29.0	5.5	3.7	9.6	2.8	17.8		

TABLE 4. TGA mass loss (wt%) as a function of temperature for Oued Chebeika 002, Ivuna, and Orgueil. Data for Ivuna and Orgueil are from King, Schofield, et al. (2015) and King, Solomon, et al. (2015).

only during a few months. As such, it may represent the freshest available CI1 material besides Ryugu and Bennu samples.

# **Organic Content**

The carbon content of Oued Chebeika 002 (3.09 wt% C) is similar but slightly lower than that of other CI1 chondrites (3.5–3.9 wt% C), Ryugu samples A0106 (3.76 wt% C), and Bennu samples (4.5–4.7 wt% C) (Alexander al., 2012; Glavin and Dworkin et al., 2025; Lauretta and Connolly et al., 2024; Naraoka et al., 2023; Pearson et al., 2006). It will be interesting to investigate the diversity and molecular distribution of organic matter in Oued Chebeika 002 and compare it to that in Bennu and Ryugu samples (Glavin and Dworkin et al., 2025; Naraoka et al., 2023).

The Raman spectral parameters of Oued Chebeika 002 can be compared to those previously obtained under the same conditions from Orgueil and Ryugu particles (Bonal, Beck, & Poch, 2024; Bonal, Quirico, et al., 2024). The macromolecular structures of polyaromatic CC matter in extraterrestrial materials largely reflect the thermal histories of the meteorite parent bodies (Bonal et al., 2006, 2016; Bonal, Beck, & Poch, 2024; Bonal, Quirico, et al., 2024; Busemann et al., 2007; Quirico et al., 2003, 2018). The close matches to Oued Chebeika 002 are the type 1 and type 2 chondrites, and Hayabusa2 samples. Oued Chebeika 002 spectral parameters are distinct from those of type 3 CC chondrites and from those of the thermally metamorphosed subgroup of CM WIS 91600 and Pecora Escarpment 02012 meteorites (Figure 13). This indicates that Oued Chebeika 002 did experience long-duration radiogenic not thermal metamorphism on its parent body, as petrologic type 3 chondrites did, or impact-induced short-duration heating, as experienced by some petrologic type 2 chondrites (Quirico et al., 2018).

Spectral bands related to the presence of CC matter are present in the matrix spectra of Oued Chebeika 002, as in Orgueil and Ryugu particles (Yabuta et al., 2023). The spectra of Oued Chebeika 002 and Hayabusa2 samples display organic features at 1705–1690 cm<sup>-1</sup> (C=O) and ~1600 cm<sup>-1</sup> (aromatic C=C with some water bending mode contribution) that are not visible in the spectra of Orgueil in which they are most likely masked by the water bending feature. The XRD patterns of Oued Chebeika 002 grains under 0% relative humidity show a displacement of the XRD peaks related to molecular water within the interlayer space (Figure 7b). The interlayer space of smectite did not collapse at  $\sim 10$  Å as would be the case for a smectite free of organics (Viennet et al., 2023). The 001 reflection at 11.3 Å under 0% relative humidity could be due to the presence of organic matter and/or NH-bearing compounds within the interlayer space, as was proposed for Ryugu samples.

The weak absorption feature visible at  $3.05-3.06 \,\mu\text{m}$  in Oued Chebeika 002 samples measured under vacuum is similar to the faint ~3.06- $\mu$ m absorption feature observed at a large scale on the entire Ryugu grain collection (Figure 11, right; Yada et al., 2022; Pilorget et al., 2022). This absorption feature could be attributed to NH-bearing organic or inorganic compounds (NH<sub>4</sub><sup>+</sup>) within the interlayer space of phyllosilicates (Pilorget et al., 2022; Viennet et al., 2023), similar to what was observed in Ryugu.

In Orgueil and Alais, which have long terrestrial residence times, such organics may have been desorbed or modified, as shown by the differences of the 001 reflection of smectite for these two meteorites. This would mean that the original phyllosilicate structure of CI1 material is to be found in Oued Chebeika 002 and Ryugu rather than in other CI1 chondrites.

However, the nitrogen content of Oued Chebeika 002 (0.07 wt% N) is much lower than that measured in other CI1 chondrites  $(0.20 \pm 0.11 \text{ wt}\% \text{ N};)$ Hashizume et al., 2024 and references therein) and Bennu samples (0.24 wt% N; Glavin and Dworkin et al., 2025), but comparable with the range of values measured in Ryugu grains (from 0.05 wt% N to 0.16 wt% N; Broadley et al., 2023; Hashizume et al., 2024; Naraoka et al., 2023; Oba et al., 2023; Okazaki et al., 2022). In fact, the N/C atomic ratio of Oued Chebeika 002 is only  $\sim$ 0.02, which is closer to the insoluble organic material (Alexander et al., 2007) than to the bulk organic matter in CI1 chondrites (~0.04-0.05 atomic ratios) or in Ryugu samples (0.032 atomic ratio) (Alexander et al., 2012; Naraoka et al., 2023; Pearson et al., 2006). The low N/C atomic ratio and lower carbon abundance suggest a different molecular distribution of organic molecules in Oued Chebeika 002 than in Ryugu or Bennu samples. This and the study of inorganic nitrogen species require further investigation (Laize-Générat et al., 2024).

#### Revisiting the Macroporosity of Asteroid Ryugu

The  $2.67 \pm 0.11 \,\mathrm{g}\,\mathrm{cm}^{-3}$  grain density of Oued Chebeika 002, measured on a total mass of 46.22 g, is notably higher than the average values for Alais, Ivuna, Orgueil, and Tonk (ranging between 2.20 and 2.38 g cm<sup>-3</sup>; Britt & Consolmagno, 2003). The most reliable value of this data set may be the measurement on a 47.2-g mass of Orgueil that yielded a grain density of  $2.43 \pm 0.06 \text{ g cm}^{-3}$  (Consolmagno & Britt, 1998), still significantly lower than our estimate for Oued Chebeika 002. An average CI1 grain density of  $2.46 \pm 0.04$  g cm<sup>-3</sup> is given by Consolmagno et al. (2008), still lower than Oued Chebeika 002. A difference in grain density reflects a difference in modal mineralogy, independent of porosity. We think that the lower value for CI1 falls may be due to terrestrial alteration, in particular the formation of sulfate from iron sulfides (Gounelle & Zolensky, 2001), or the absorption of terrestrial water in phyllosilicates in lieu of NH4-rich organics as discussed above (see also Baker et al., 2010). It is also noteworthy that grain densities calculated from the modal mineralogy derived from XRD analyses (King, Schofield, et al., 2015) and using average mineral densities (2.3, 5.17, 4.61, 3.32, 2.71, and  $3.93 \,\mathrm{g \, cm^{-3}}$  for phyllosilicates, magnetite, pyrrhotite, olivine, calcium carbonate, and ferrihydrite, respectively) are  $2.65 \,\mathrm{g \, cm^{-3}}$ for Alais,  $2.69 \text{ g cm}^{-3}$  for Orgueil, and  $2.72 \text{ g cm}^{-3}$  for Ivuna, close to the measured value for Oued Chebeika 002 (2.67 g cm<sup>-3</sup>). We conclude that our estimate of the grain density is more accurate than previous measurements on CI1 falls.

The bulk density of Oued Chebeika 002 (2.04 g cm<sup>-3</sup>) is identical within uncertainties to the  $2.11 \pm 0.12$  g cm<sup>-3</sup> value for Orgueil (Britt & Consolmagno, 2003). The porosity of Oued Chebeika 002 (24%) is notably higher than the porosity measured for CI1 falls: 2.0%, 5.0%, and  $19.0 \pm 27.0\%$  in Alais. Ivuna. and Orgueil. respectively. We attribute this intersample variability to variable extent of terrestrial alteration that can either fill the pores with alteration products (leading to a decrease in porosity) and/or open cracks (leading to an increase in porosity) (Britt & Consolmagno, 2003). The estimated bulk density of Ryugu particles is  $1.79 \pm 0.31 \,\mathrm{g \, cm^{-3}}$ (1 SD for 637 grains measured, Miyazaki et al., 2006). The estimated bulk density of Bennu material is  $1.71\pm0.10\,{g\,\text{cm}^{-3}}$  (mass-weighted average for a total mass of 14.25 g and 12 stones measured, 1 mass-weighted s.d. variation, Lauretta and Connolly et al., 2024). These two estimates are similar but lower than the bulk density of Oued Chebeika 002 and the CI1 falls, possibly indicating that only tougher CI-like material survives atmospheric entry filtering. On the other hand, the bulk density of asteroid Ryugu is much lower, at  $1.19 \,\mathrm{g \, cm^{-3}}$ 

(Watanabe et al., 2019), indicating an elevated macroporosity. If we recalculate the bulk porosity of asteroid Ryugu and Ryugu samples using our grain density of  $2.67 \text{ g cm}^{-3}$ , we find 55% and 33%, respectively. This indicates a macroporosity (at a ~10-cm scale, larger than the CI1 meteorite samples) of 22% for asteroid Ryugu.

# Spectral Links to Ryugu and Other Asteroids and Parent Body

The near-IR reflectance of the Oued Chebeika 002 raw sample and powder is lower than the values measured for CI1 chondrites (Figure 11, left). The near and mid-IR reflectance spectrum obtained on the raw sample (Figures 11 and 12) is remarkably similar to measurements obtained on an assembly of Ryugu particles (Amano et al., 2023), in terms of absolute reflectance, spectral slope, and band depth at 2.72 µm. In the near-IR, the main difference is a sharper band depth at 3 µm for the Ryugu sample, and conversely, a stronger absorption at 2.9 µm for Oued Chebeika 002 (Figure 11, right). In the mid-IR, the main difference is an absorption band around 6.1 µm in the spectrum of Oued Chebeika 002 (not obtained under vacuum), absent in the Ryugu sample, which can be attributed to the bending mode of water molecules (Figure 11, left). These differences around 3 µm and 6 µm are likely due to the presence of a small but detectable amount of weakly bonded terrestrial H<sub>2</sub>O in Oued Chebeika 002, which is absent in the Ryugu sample.

Brož et al. (2024) studied 38 individual asteroid families, including young and old ones, and identified their most likely meteorite analog. Within this large sample, 18 families appear to be related to CI1 chondrites and/or extraterrestrial materials that are poor in chondrules, such as IDPs and ungrouped CC chondrites such as Tagish Lake. In a second step, Brož et al. (2024) determined the contribution of these asteroid families to the near-Earth object (NEO) populations at meter and kilometer sizes using collisional and orbital models. It appears that six families are the source of more than 95% of meter-sized CI1-like NEOs, with each family contributing to at least 7% of the incoming flux of CI chondrites (Polana 38%, Clarissa 15%, Misa 13%, Hoffmeister 12.5%, Euphrosyne 10%, Themis 7.5%, by order of decreasing contribution). The Polana family, the most likely source of asteroids Ryugu and Bennu (Brož et al., 2024), is also likely the main source of CI1 chondrites. However, it is unlikely from a statistical point of view to be the only source for all CI falls. Hence, our currently limited collection of CI1 chondrites (6 falls) may well originate from more than one parent body.



FIGURE 20. Plots of Oued Chebeika 002 (OC002) on (a)  $\mu^{54}$ Fe- $\mu^{54}$ Cr and (b)  $\mu^{54}$ Fe- $\Delta^{17}$ O. For comparison, average composition of Ryugu and meteorite groups from CC, NC, and CI clan is also plot. It shows an isotopic trichotomy of CC-NC-CI clan of meteorites. OC002 plots within the CI field. CI meteorites (including OC002) and Ryugu represent another end member of solar system distinct from other meteorites and planetary materials. Average composition of each meteorite group is plot using compilation from Dauphas et al. (2024). The arrow in (a) is the expected shift attributable to the possible incomplete digestion of the sample of OC002 (see text).

#### **Chromium and Iron Isotopes**

Measurement of precise isotopic anomalies in meteorites has revealed the existence of distinct isotopic reservoirs in the inner and outer solar system (Dauphas et al., 2024; Hopp et al., 2022; Kruijer et al., 2020; Trinquier et al., 2009; Warren, 2011). Studies of isotopic anomalies in meteorites and planetary materials initially revealed the existence of two reservoirs: noncarbonaceous (NC) in the inner solar system and CC in the outer solar system (Kruijer et al., 2020: Warren, 2011). More recently, iron isotopic analyses and a reevaluation of the whole suite of isotopic anomalies in meteorites have revealed the possible existence of a third isotopic reservoir defined by CI meteorites (Hopp et al., 2022; Dauphas et al., 2024; Nesvorný et al., 2024). These meteorites, as well as samples returned from the Ryugu asteroid by the Hayabusa2 mission, have Fe isotopic anomalies that are close to terrestrial composition and NCs, while other CC chondrites show positive  $\mu^{54}$ Fe values (Hopp et al., 2022). In crosscorrelation diagrams involving Fe isotopic anomalies, planetary materials are divided into three distinct clusters, defining a trichotomy. Iron isotopic anomalies are therefore a potent diagnostic tool to identify CI materials. As shown in Figure 20, in  $\mu^{54}$ Fe- $\mu^{54}$ Cr and  $\mu^{54}$ Fe- $\Delta^{17}$ O diagrams. Oued Chebeika 002 clearly plots in the CI-Ryugu cluster. CIs have distinctive petrographic characteristics such as the absence of chondrules and refractory inclusions, and the present analyses show that these features are only found among meteorites that plot in the CI cluster. Previous studies (Dauphas et al., 2024; Hopp et al., 2022; Nesvorný et al., 2024) have argued that the CI-forming reservoir may have lied in the same region where ice giant planets and Oort Cloud comets formed, in agreement with the suggested cometary origin of Orgueil (Gounelle et al., 2006, 2008). The reason why meteorites formed in such a distant reservoir have distinct petrographic characteristics remains to be elucidated.

#### CONCLUSION

Oued Chebeika 002 is a CI1 chondrite whose texture, mineralogy (with, however, the noticeable absence of olivine and calcite, and presence of chalcopyrite), major and trace element content, oxygen isotopic composition, IR and Raman spectral properties, and magnetic properties are similar to those of the only five known CI1 meteorites (excluding the Yamato meteorites listed as CI1 in the Meteoritical Bulletin Database) and samples from Ryugu and Bennu asteroids. With a total known weight of 418 g and at least 35 g already in academic collections, Oued Chebeika 002 is a very significant addition to the CI1 sample suite whose overall study tends to be biased toward Orgueil.

Several lines of evidence (preservation of the fusion crust and the absence of sulfates, ferrihydrite, maghemite) indicate that Oued Chebeika 002 has suffered little or no terrestrial alteration. In that regard, it is more pristine than the 100-year-old CI1 falls Orgueil, Alais, and Ivuna that have interacted with the terrestrial atmosphere for decades and similar to samples from asteroids Ryugu and Bennu. We expect samples of Oued Chebeika 002 curated in the terrestrial atmosphere to develop sulfates, as observed in other CI1 falls. Incipient terrestrial contamination in Oued Chebeika 002 is revealed by IR spectra (from  $0.6-16 \mu m$ ) that, although remarkably similar to those of Ryugu grains, differ by the presence of adsorbed terrestrial water. Similarly, TGAs reveal the presence, although limited, of adsorbed terrestrial water in Oued Chebeika 002.

To avoid terrestrial contamination, we recommend storing this precious meteorite in controlled-atmosphere cabinets with relative humidity <10%. To avoid contact with terrestrial O<sub>2</sub>, the sample should ideally be stored in an atmosphere of pure N<sub>2</sub> or Ar, or under vacuum (Imae et al., 2024), but at low temperature to avoid desorption of very volatile compounds (e.g., Herd et al., 2016). The former solution is being implemented at CEREGE for the preservation of the type specimen.

The absence of terrestrial weathering is crucial for many aspects of the study of CI1 material. For instance, we estimated a grain density of Oued Chebeika 002 at  $2.67 \text{ g cm}^{-3}$ , which is significantly higher than previous estimates on CI1 chondrites and a better match to their modal mineralogy. This allows us to reestimate the porosity of Ryugu samples and asteroid Ryugu to 33% and 55%, respectively, indicating a 22% macroporosity for asteroid Ryugu.

Despite overall similarity, Oued Chebeika 002 shows subtle differences with other CI1 falls, some of which cannot be accounted for by terrestrial alteration. In particular, the magnetic mineral assemblage of Oued Chebeika 002 is different from that observed in Alais, Ivuna, and Orgueil, which suggests a different aqueous alteration history. Conversely, the magnetic properties of Oued Chebeika 002 are undiscernible from those of Ryugu samples.

The detection of chalcopyrite may be a significant difference between Oued Chebeika 002 and other CI1 chondrites. It will deserve more careful examination, especially as this mineral might bridge the gap between CI1 chondrites and CY chondrites (Harrison et al., 2025). This being said, one must keep in mind that CI1 chondrites are brecciated at the centimeter scale and are composed of a wide diversity of lithologies. The addition of Oued Chebeika 002 to the CI1 sample suite and the fact that it is made of coherent stones with significant masses will help understand the relationship between these lithologies using techniques such as CT scan. One important question to be addressed is how the variability within one CI1 objects.

That assessment will also help solve the important question of the number of CI1 parent bodies as well as their (possible) genetic relationship and their formation location in the solar protoplanetary disk. Although most CI1 chondrites probably come from asteroids now present in the inner solar system (Brož et al., 2024), isotopic evidence as well as the water abundance point toward an outer solar system formation. This is in line with the well-accepted fact that what is now the asteroid belt has been contaminated with outer solar system objects (Levison et al., 2009) and with the suggested cometary origin of the Orgueil meteorite (Gounelle et al., 2006). In the  $\mu^{54}$ Fe- $\mu^{54}$ Cr and  $\mu^{54}$ Fe- $\Delta^{17}$ O diagrams, Oued Chebeika 002 is plotted in the CI1-Ryugu cluster, which can be distinguished from the clusters of CC and NC group meteorites. The observed isotopic similarity between Oued Chebeika 002 and other CI1 chondrites suggests that they share a common genetic heritage, which may have originated from the same region where ice giant planets and Oort Cloud comets were formed.

Finally, the finding of Oued Chebeika 002, as well as finding out that asteroids Bennu and Ryugu are made of CI1 material, sheds light on the abundance of CI1 material in the solar system. Its rarity among meteorites is certainly a bias due to a low strength and its difficulty to sustain the terrestrial environment without crumbling within a short time. In future years, further studies of CI1 material focusing on (i) the relationship with other CC chondrite groups, (ii) the nebular and parent-body processes it recorded, and (iii) the nature of the incorporated ice and volatile components will be major topics in the field of cosmochemistry.

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#### SUPPORTING INFORMATION

Additional supporting information may be found in the online version of this article.

**Table S1.** Representative mineral compositions of phosphates, carbonates, sulfides, and matrix.

**Table S2.** Magnetic properties of Oued Chebeika002, CI1 falls, and Ryugu samples.

**Figure S1.** Backscattered electron (BSE)-scanning electron microscopic (SEM) images of a chalcopyrite grain in Oued Chebeika 002.

**Figure S2.** Position-sensitive detector X-ray diffraction (PSD-XRD) pattern for Oued Chebeika 002.

**Figure S3.** Mass-normalized coercivity spectra of a 47-mg sample of Orgueil, a 73-mg sample of Ivuna, a 23-mg sample of Alais, a 21-mg sample of Ryugu (Maurel et al., 2024), 9-mg powdered sample, and a 49-mg sample

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of Oued Chebeika 002. The gray dots show the derivative of the masss-normalized magnetic moment with respect to the logarithm of the applied field. The pink, blue, and green distributions represent different populations of grains. The yellow line is the best fit to the data obtained by summing the three distributions. Shaded areas show the 95% confidence intervals of each distribution. This figure was generated using the MAX Unmix software (Maxbauer and Feinberg, 2016).

**Figure S4.**  $M_{RS}$ -normalized coercivity spectra of multiple samples of Orgueil and Oued Chebeika 002 (this study), and two samples of Ryugu: a 22-mg sample from chamber C (Maurel et al., 2024) and a 1.6-mg sample from chamber A (Sato et al., 2022).

**Figure S5.** First-order reversal curve (FORC) diagrams of a 47-mg sample of Orgueil and a 73-mg sample of Ivuna. The color scale applies to both panels.