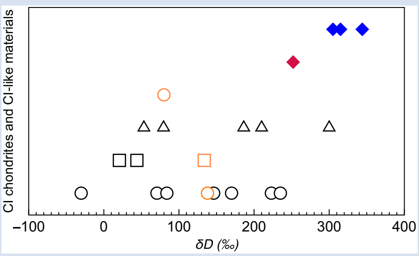
Geochemical Perspectives Letters

H-N budgets and isotopic signatures of Oued Chebeika 002 and CI reservoir heterogeneity

Y. Marrocchi[1*], E. Füri[1], L. Zimmermann[1], L. Piani[1]

OPEN ACCESS
https://doi.org/10.7185/geochemlet.2605

Abstract



We report the hydrogen (H) and nitrogen (N) elemental and isotopic compositions of the recently recovered CI chondrite Oued Chebeika 002 (OC 002) and compare them with published data for other CI meteorites and CI-like samples returned from the asteroids Ryugu and Bennu. When measured using the same protocol (vacuum degassing at 120 °C for 48 hr), OC 002 exhibits similar H concentrations but lighter isotopic compositions than other CIs and Bennu samples. Nitrogen data likewise indicate that the parent body of OC 002 accreted isotopically lighter nitrogen. Compilation of available data reveals pronounced H-N isotopic heterogeneities among CI-like materials, even when analysed under comparable conditions. These observations suggest that CI chondrites are intrinsically heterogeneous and that a single representative CI isotopic composition cannot be defined. This variability likely reflects the late accretion history of CIs and the incorporation of organic grains and ammonia ice that experienced diverse thermal histories in the protosolar disk. Such intrinsic heterogeneity strongly affects mass balance estimates of CI contributions to Earth's surface volatiles, potentially varying by more than a factor of two depending on the CI reference used.

Received 3 November 2025 | Accepted 14 January 2026 | Published 10 February 2026

Introduction

Among the diverse types of meteorites, CI (Ivuna-type) carbonaceous chondrites (CCs) are unique objects with distinctive mineralogical, chemical, and isotopic characteristics (Morlok *et al.*, 2006; Russell *et al.*, 2022). The predominance of phyllosilicates, and to a lesser extent magnetite and carbonates, attests to the high degree of parent body aqueous alteration, which erased the initial CI components (Russell *et al.*, 2022). Nevertheless, CI chondrites have bulk chemical compositions similar to that of the solar photosphere, except for highly volatile elements such as H, N and noble gases (Lodders *et al.*, 2025). Compared to other CCs, CIs have distinct O, Fe, and Ni isotopic compositions (Clayton and Mayeda, 1984; Hopp *et al.*, 2022; Spitzer *et al.*, 2024). Based on these results, it has been proposed that CIs originate from a unique parent body (or bodies) that records an isotopically distinct third reservoir located beyond Saturn's orbit (Hopp *et al.*, 2022), in addition to the classical non-carbonaceous and carbonaceous reservoirs, which are thought to represent the inner and outer solar system, respectively (Tissot *et al.*, 2025). Alternatively, CI chondrites may reflect a specific accretion process triggered by photoevaporation during the final stages of the disk's lifetime (Spitzer *et al.*, 2024). Although rare in our collections, CIs were likely much more abundant in the early outer disk, as attested by the CI-like nature of the samples returned from the asteroids Ryugu and Bennu by JAXA's Hayabusa2 and NASA's OSIRIS-REx missions, respectively (Yokoyama *et al.*, 2023; Barnes *et al.*, 2025). In addition, it has recently been proposed that CI-like material could represent the matrix component of all CCs (Hellmann *et al.*, 2020). Altogether, these observations suggest that CI-like material constituted a major component of the outer solar system reservoir and may also have contributed to inner solar system planetesimals, as inferred from bulk chemical compositions of NC and CC meteorites (Braukmüller *et al.*, 2025).

CI chondrites are also of paramount importance, as they may represent a significant mass fraction of the building blocks of the terrestrial planets, with estimates ranging from 5 to 50 % (Tissot *et al.*, 2025). Thus, CIs could have provided an important source of volatile elements, including H and N, which played a fundamental role in shaping the habitability of Earth and Mars. However, estimating the initial H-N budget and isotopic composition of CIs is not straightforward, as their volatile signatures may have been (i) overprinted by terrestrial contamination (Vacher *et al.*, 2020; Greenwood *et al.*, 2023), and/or (ii) affected by nugget effects resulting from small sample sizes and their brecciated nature (Morlok *et al.*, 2006; Barrat *et al.*, 2012). Advances in analytical techniques, the increasing number of CI samples made available through space missions, and the recent discovery of Oued Chebeika 002 (hereafter OC 002; Gattacceca *et al.*, 2025) in the Sahara Desert, now offer a unique opportunity to address these issues. Here, we report the bulk H and N (as well as Ne and Ar) abundances and isotopic compositions of OC 002, and compare these data with previously published results to discuss the potential heterogeneity of the CI reservoir, the extent to which its H and N characteristics can be defined, and the implications for the volatile budget of the terrestrial planets.

1. Université de Lorraine, CNRS, CRPG, F-54000 Nancy, France
* Corresponding author: (email: yves.marrocchi@univ-lorraine.fr)

Methods and Results

The sample analysed here was recovered during the initial collection of OC 002 fragments and has been stored at CEREGE in Aix-en-Provence under conditions minimising terrestrial weathering (Lee and Glazer, 2026). The H concentration and isotopic composition of one OC 002 aliquot (1.21 mg) was determined using a Thermo Scientific EA IsoLink-DeltaV IRMS (isotope ratio mass spectrometer) system at the stable isotope mass spectrometry facility of the Centre de Recherches Pétrographiques et Géochimiques (CRPG, Nancy, France). The 1.21 mg aliquot was taken from a ~5 mg fragment that was crushed and homogenised. The procedure was similar to that detailed in Vacher *et al.* (2020) and included a pre-degassing step to remove adsorbed atmospheric water. Details on the analytical procedure are provided in the Supplementary Information. The analysed aliquot of OC 002 contains 0.82 wt. % H, equivalent to 7.36 wt. % H_2O, and has an H isotopic value of δD = 81.6 ± 2 ‰ (Fig. 1). The H content is consistent, within uncertainty, with that previously determined for OC 002 by Gattacceca *et al.* (2025) (*i.e.* 0.97 ± 0.2 wt. %; determined by elemental analysis of two ~1.5 mg powdered aliquots, without pre-degassing).

Nitrogen and noble gas (Ne, Ar) concentrations and isotopic compositions of six OC 002 fragments (0.048 to 0.417 mg) were determined by CO_2 laser heating using a Noblesse-HR multicollector noble gas mass spectrometer at CRPG's noble gas facility (Fig. 2; Zimmermann *et al.*, 2025). Details of the analytical procedure for N-Ne-Ar measurements and for the noble gas (Ne, Ar) isotopic composition of OC 002 are provided in the SI. Nitrogen concentrations (determined in five of the six fragments) range from 1036 ± 48 to 2290 ± 105 ppm (by weight) and are significantly higher than those reported for OC 002 by Gattacceca *et al.* (2025) (*i.e.* 0.07 ± 0.02 wt. %). The corresponding $\delta^{15}N$ values vary from +0.7 ± 0.9 to +27.4 ± 1.4 ‰ (Fig. 2).

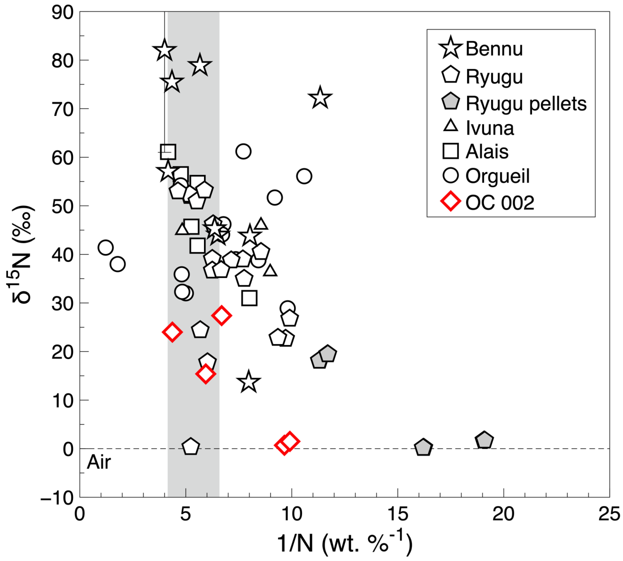


Figure 2 Nitrogen isotopic composition ($\delta^{15}N$) as a function of the inverse of the N concentration of five OC 002 fragments compared to other CI chondrite samples (Alais, Ivuna, Orgueil) and samples returned from the asteroids Ryugu and Bennu (compiled data provided at https://doi.org/10.24396/ORDAR-190, and additional results for Bennu by Marty *et al.*, 2026). 'Pellets' correspond to Ryugu samples placed into a Cu disk and pressed against a diamond disk; this pelletisation procedure was carried out within a N_2-filled glove box (Okazaki *et al.*, 2022). The average N content for CI chondrite (1965 ± 447 ppm N) proposed by Lodders *et al.* (2025) is indicated by the grey bar.

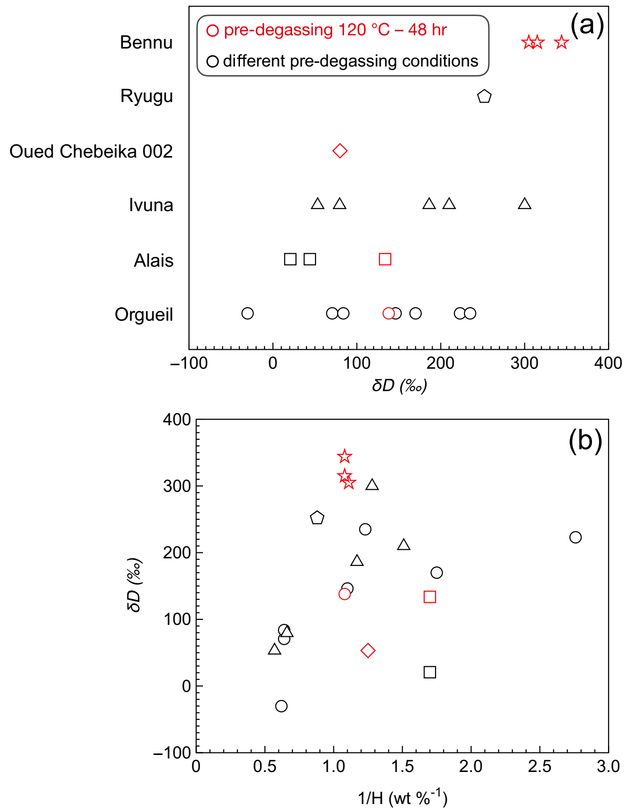


Figure 1 Comparison of **(a)** the bulk H isotopic composition (δD) and **(b)** the inverse of the H concentration of OC 002 with other CI chondrites (Alais, Ivuna, Orgueil) and with samples returned from the asteroids Ryugu and Bennu (compiled data provided at https://doi.org/10.24396/ORDAR-201). Red symbols indicate samples pre-degassed under identical conditions (120 °C for 48 hr), while black symbols correspond to those treated under different protocols. Data and associated references are reported in SI.

Discussion

Compared to other CIs (Alais, Ivuna, and Orgueil) as well as Ryugu and Bennu samples (see compiled data https://doi.org/10.24396/ORDAR-225), OC 002 shows similar H concentrations and light isotopic compositions (Fig. 1). To a first approximation, the compiled data set attests to the pronounced heterogeneity among CI samples, particularly in their H isotopic compositions, which range from −30.2 to +344 ‰ (Fig. 1). However, it should be noted that these data were obtained using markedly different analytical protocols: some samples were measured without prior degassing, whereas others underwent pre-degassing at temperatures ranging from 120 to 350 °C for varying durations. Interestingly, samples prepared following the same procedure (*i.e.* pre-degassing at 120 °C for 48 hr) show similar H concentrations (0.82–0.93 wt. %) but large H isotopic variations, with δD values ranging from +81.6 to +344 ‰ (Fig. 1). This includes Bennu samples returned by the OSIRIS-REx mission (Lauretta *et al.*, 2024), the fresh CI OC 002 (Gattacceca *et al.*, 2025), and the historical CIs Alais and Orgueil, which have been preserved in collections since 1806 and 1864, respectively. Although Bennu samples may appear as outliers relative to other CI chondrites, they nonetheless attest to the isotopic variability recorded within the CI group. Moreover, despite being obtained using a different analytical approach, data from Ryugu samples also support the existence of H isotopic heterogeneity. Accounting for potential atmospheric contamination would further shift the inferred H isotopic compositions of the Ryugu samples toward more deuterium-rich values.

At first order, the lighter H isotopic compositions of Alais and Orgueil compared to Bennu samples could be attributed to terrestrial contamination; however, several lines of evidence argue against this interpretation. First, pre-degassing at 120 °C for 48 hours has been shown to remove most terrestrial contamination (Vacher *et al.*, 2020), a protocol now routinely adopted by other research groups (*e.g.*, Lauretta *et al.*, 2024). Second, the most pristine CI, OC 002, displays H isotopic compositions within the same range as those of the historical CIs Alais and Orgueil (Fig. 1). Although terrestrial contamination can rapidly result in contamination by adsorbed water (Lee *et al.*, 2023), OC 002 does not show the sulfate veins that developed extremely rapidly in Orgueil (Gounelle and Zolensky, 2014; Lee and Glazer, 2026). Finally, the H isotopic compositions of Alais, Orgueil, OC 002, and the Bennu and Ryugu samples correlate positively with their C contents (Fig. S-3a). These samples were selected because they were degassed at 120 °C for 48 hr, and the Ryugu data are affected by minimal contamination. The δD-C correlation is unlikely to result from terrestrial contamination, as such contamination would affect only the H isotopic compositions of Orgueil, Alais, and OC 002, without modifying their carbon contents. This is supported by the fact that no δD-C correlation is observed when including CI chondrites whose H isotopic compositions were determined without degassing or at different degassing temperatures (Fig. S-4). Instead, we argue that the δD-C correlation reflects H isotopic variations arising from the heterogeneous distribution of deuterium-rich organic matter (OM) at both (i) the macroscale, as illustrated by the large variability in the C contents of different Ryugu grains (Nakamura *et al.*, 2022), and (ii) the micron scale, as shown by the D/H heterogeneity observed in CI chondrites from *in situ* measurements (Remusat *et al.*, 2010). We note that the δD *vs.* C correlation yields an intercept of −183 ± 91 ‰, a value consistent with that previously inferred from *in situ* δD *vs.* C/H mixing lines in CI chondrites (−100 ± 100 ‰; Piani *et al.*, 2021). Similarly, the δD *vs.* 1/C correlation (Fig. S-5) suggests an H isotopic composition of the CI insoluble organic matter of around 1000 ‰, which is fully consistent with values reported for the insoluble OM of Orgueil and Ivuna (Alexander *et al.*, 2007).

We also note that CIs display distinct features compared to CM chondrites, the other main group of hydrated chondrites. Whereas CIs show a strong δD-C correlation (Fig. S-3a) and a weaker δD-C/H relationship (Fig. S-3b), CMs display the opposite behaviour (Fig. S-3c,d). It is important to note that δD-C/H relationships have been observed in CM chondrites, both without and with degassing prior to analysis (Alexander *et al.*, 2012; Marrocchi *et al.*, 2023). This suggests that the H isotopic variations among CIs and CMs are controlled by different H-bearing carriers. The fact that δD of CIs preferentially correlates with their C contents (and not their C/H ratios) suggests that they accreted similar abundances of water-ice grains with homogeneous D/H ratios but variable amounts of D-rich OM. Conversely, the co-variation observed in CMs between H isotopic compositions and their C/H ratios (and not their C contents, Fig. S-3c,d; Alexander *et al.*, 2012) indicates that their isotopic compositions are controlled by the abundances of three H-bearing carriers: water-ice grains, OM and amorphous silicates (Marrocchi *et al.*, 2023).

Nitrogen abundances and isotopic compositions in CI chondrites (Alais, Ivuna, and Orgueil) and CI-like material returned from the asteroids Ryugu and Bennu are also highly heterogeneous (Fig. 2). Overall, N concentrations range from 524 to 2500 ppm, excluding two exceptionally high values of 0.56 and 0.82 wt. % reported for Orgueil by Pearson *et al.* (2006) (see compiled data at https://doi.org/10.24396/ORDAR-190, and additional results for Bennu by Marty *et al.*, 2026). Deriving an average N abundance for CI chondrites (*e.g.*, Lodders *et al.*, 2025) is therefore challenging and potentially misleading. The $\delta^{15}N$ values of CI-type samples vary between −2.8 and +82 ± 21 ‰ (Fig. 2). Notably, the $\delta^{15}N$ values of OC 002 are lower than those of other CIs and most Bennu samples (Fig. 2), and the ^{15}N-rich component ($\delta^{15}N > 80$ ‰, up to 160 ‰) observed during step heating analyses of individual Bennu particles (Marty *et al.*, 2026) is not detected here (SI). The N isotopic composition of OC 002 is, however, comparable to that of several Ryugu particles and pellets. The observed N abundance and isotopic variations likely reflect, in part (i) the heterogeneous distribution of various N carrier phases in CIs, including (insoluble and soluble) OM and ammonia, at both micro- and macro-scales (see Gamblin *et al.*, 2024 and references therein; Glavin *et al.*, 2025; Sandford *et al.*, 2025), and/or (ii) nugget effects resulting from the small mass of analysed material, particularly in studies conducted using static noble gas mass spectrometry (≪1 mg; Broadley *et al.*, 2023; Gamblin *et al.*, 2024; Marty *et al.*, 2026). Nonetheless, the results obtained here suggest that the parent body of OC 002 accreted isotopically lighter N than the parent body or bodies of other CIs and Bennu.

Altogether, these observations attest to the intrinsically heterogeneous nature of CI samples. They also illustrate that defining a single, representative CI value for H and N is likely illusory. This is particularly true for isotopic compositions, as evidenced by the large H and N isotopic variations observed among CI-type materials (Figs. 1, 2), even when analysed using the same technique in the same laboratory. It is, however, noteworthy that these results were obtained from small aliquots, whereas data derived from much larger, homogenised samples, might show less variable isotopic compositions (Barrat *et al.*, 2012). That said, the isotopic heterogeneities may also reflect specific conditions and timing of CI parent body accretion. Although Bennu, Ryugu and CI chondrites represent an end member of the carbonaceous meteorites in the ^{50}Ti-^{54}Cr-O isotope space, they nonetheless plot along the extension of the trend defined by other CCs (Barnes *et al.*, 2025; Tissot *et al.*, 2025). In contrast, the Fe and Ni isotopic anomalies of Ryugu and CIs are indistinguishable from each other but significantly different from those of other CCs (Hopp *et al.*, 2022; Spitzer *et al.*, 2024). This has been interpreted as reflecting the late accretion of the CI parent bodies (*i.e.* ~4–5 Myr after Ca-Al-rich inclusions), when planetesimal growth was driven by photoevaporation rather than by streaming instability (Spitzer *et al.*, 2024). This scenario implies that CIs accreted small, icy pebbles carrying ammonia ice (Glavin *et al.*, 2025) and small OM grains: (i) more efficiently than other CCs, because the streaming instability process favours the incorporation of large grains compared to photoevaporation, and (ii) that these grains did not undergo isotopic exchange with the disk gas as it cooled below the organic sublimation temperature (*i.e.* 350–450 K; Piani *et al.*, 2021). A natural consequence is that CIs accreted D- and ^{15}N-rich, isotopically heterogeneous ices and OM, consistent with the H and N isotopic heterogeneities observed in CI insoluble organic matter (Nittler *et al.*, 2024). Therefore, random sampling of small CI fragments for analysis is bound to yield variable H and N isotopic compositions, as illustrated in this study (Figs. 1, 2).

The H-N isotopic heterogeneities observed among CI chondrites have fundamental implications for Earth's volatile budget. Early interpretations of the H and N isotopic compositions of the bulk silicate Earth (BSE) suggested a CI/CM-like source (Alexander *et al.*, 2012; Marty, 2012) More recent studies, however, indicate that the H and N isotopic compositions of Earth's mantle are indistinguishable from those of enstatite chondrites (ECs; Piani *et al.*, 2020), whereas Earth's surface reservoirs (oceans and atmosphere) have signatures that differ from ECs and instead require an additional CI-like contribution (Piani *et al.*, 2020). Assuming a fixed, average H-N isotopic composition for ECs (*i.e.* $\delta D = -104.4$ ‰ and $\delta^{15}N = -23$ ‰; Piani *et al.*, 2020), the mass fraction of H and N brought by CI chondrites can be estimated as follows:

$$f_{CI}(H)_{surface} = \frac{\delta D_{surface} - \delta D_{EC}}{\delta D_{CI} - \delta D_{EC}}$$

and

$$f_{CI}(N)_{surface} = \frac{\delta^{15}N_{surface} - \delta^{15}N_{EC}}{\delta^{15}N_{CI} - \delta^{15}N_{EC}}$$

It is evident that estimates of the CI contribution to Earth's surface volatiles are strongly influenced by their heterogeneous H-N isotopic compositions among CI samples. For example, calculations based on OC 002, which exhibits the lightest average H and N isotopic signatures, yield CI-derived H and N mass fractions that are 0.57 ± 0.05 and 0.67 ± 0.04 (2 s.d.), respectively (Fig. 3). In contrast, calculations using Bennu samples, which display the heaviest average values, produce much lower mass fractions of 0.23 ± 0.09 and 0.33 ± 0.06 (Fig. 3). These differences underscore the difficulty of accurately constraining this critical parameter, as it is highly sensitive to the specific CI reference adopted for mass balance calculations. They also reveal that, under extreme scenarios, CIs could dominate Earth's surficial H and N budget. Future high precision isotopic analyses of diverse solar system materials — including samples from both primitive (undifferentiated) and differentiated planetary bodies — as well as direct comparisons with returned samples from primitive asteroids, will be essential to refine these mass balance estimates and better quantify the nature and timing of volatile delivery to Earth.

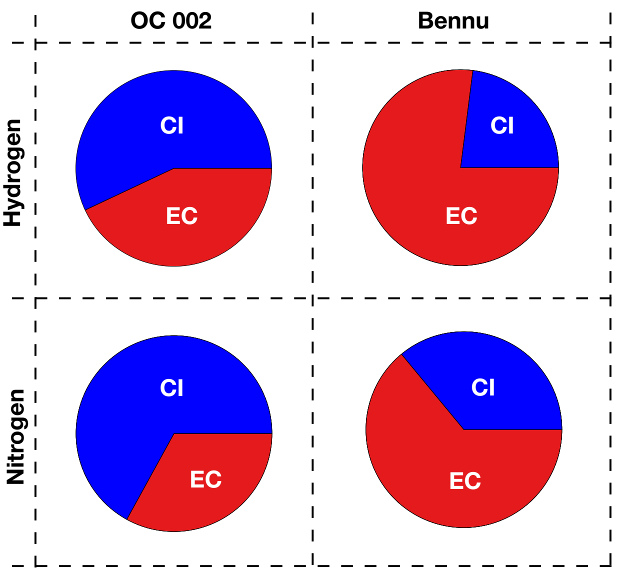


Figure 3 Pie charts showing the mass fraction of the Earth's surficial H and N budget derived from CI and enstatite chondrites (EC), depending on whether the average H-N isotopic composition of OC 002 or Bennu samples are considered.

Acknowledgements

We thank Jérôme Gattacceca for providing the sample of OC 002 used in this study and Thomas Rigaudier for performing H measurements. This work was co-funded by the European Union (ERC, IRONIS, 101087562, awarded to EF). Views and opinions expressed are however those of the author(s) only and do not necessarily reflect those of the European Union or the European Research Council. Neither the European Union nor the granting authority can be held responsible for them. We thank Jessica Barnes and Ashley King for their constructive reviews, and Romain Tartèse for efficient editorial handling. This is CRPG contribution #2879.

Editor: Romain Tartèse

Additional Information

Supplementary Information accompanies this letter at https://www.geochemicalperspectivesletters.org/article2605.

Cite this letter as: Marrocchi, Y., Füri, E., Zimmermann, L., Piani, L. (2026) H-N budgets and isotopic signatures of Oued Chebeika 002 and CI reservoir heterogeneity. *Geochem. Persp. Let.* 39, 7–11. https://doi.org/10.7185/geochemlet.2605

References

Alexander, C.M.O'D., Fogel, M., Yabuta, H., Cody, G.D. (2007) The origin and evolution of chondrites recorded in the elemental and isotopic compositions of their macromolecular organic matter. *Geochimica et Cosmochimica Acta* 71, 4380–4403. https://doi.org/10.1016/j.gca.2007.06.052

Alexander, C.M.O'D., Bowden, R., Fogel, M.L., Howard, K.T., Herd, C.D.K., Nittler, L.R. (2012) The Provenances of Asteroids, and Their Contributions to the Volatile Inventories of the Terrestrial Planets. *Science* 337, 721–723. https://doi.org/10.1126/science.1223474

Barnes, J.J., Nguyen, A.N, Abernethy, F.A.J., Bajo, K., Bekaert, D.V. *et al.* (2025) The variety and origin of materials accreted by Bennu's parent asteroid. *Nature Astronomy* 9, 1785–1802. https://doi.org/10.1038/s41550-025-02631-6

Barrat, J.A., Zanda, B., Moynier, F., Bollinger, C., Liorzou, C., Bayon, G. (2012) Geochemistry of CI chondrites: Major and trace elements, and Cu and Zn Isotopes. *Geochimica et Cosmochimica Acta* 83, 79–92. https://doi.org/10.1016/j.gca.2011.12.011

Braukmüller, N., Funk, C., Abouchami, W., Pickard, H., Rehkämper, M. *et al.* (2025) Moderately volatile elements in chondrites record chondrule formation, two-component mixing and redistribution on parent bodies. *Geochimica et Cosmochimica Acta* 393, 43–62. https://doi.org/10.1016/j.gca.2025.02.001

Broadley, M.W., Byrne, D.J., Füri, E., Zimmermann, L., Marty, B. *et al.* (2023) The noble gas and nitrogen relationship between Ryugu and carbonaceous chondrites. *Geochimica et Cosmochimica Acta* 345, 62–74. https://doi.org/10.1016/j.gca.2023.01.020

Clayton, R.N., Mayeda, T.K. (1984) The oxygen isotope record in Murchison and other carbonaceous chondrites. *Earth and Planetary Science Letters* 67, 151–161. https://doi.org/10.1016/0012-821X(84)90110-9

Gamblin, J., Füri, E., Marty, B., Zimmermann, L., Bekaert, D.V. (2024) Dissecting the complex Ne-Ar-N signature of asteroid Ryugu by step-heating analysis. *Geochemical Perspectives Letters* 31, 44–48. https://doi.org/10.7185/geochemlet.2431

Gattacceca, J., Gounelle, M., Devouard, B., Barrat, J.-A., Bonal, L. *et al.* (2025) Oued Chebeika 002: A new CI1 meteorite linked to outer solar system bodies. *Meteoritics & Planetary Science* 60, 1441–1479. https://doi.org/10.1111/maps.14359

Glavin, D.P., Dworkin, J.P., Alexander, C.M.O'D., Aponte, J.C., Baczynski, A.A. *et al*. (2025) Abundant ammonia and nitrogen-rich soluble organic matter in samples from asteroid (101955) Bennu. *Nature Astronomy* 9, 199–210. https://doi.org/10.1038/s41550-024-02472-9

Gounelle, M., Zolensky, M.E. (2014) The Orgueil meteorite: 150 years of history. *Meteoritics & Planetary Science* 49, 1769–1794. https://doi.org/10.1111/maps.12351

Greenwood, R.C., Franchi, I.A., Findlay, R., Malley, J.A., Ito, M. *et al.* (2023) Oxygen isotope evidence from Ryugu samples for early water delivery to Earth by CI chondrites. *Nature Astronomy* 7, 29–38. https://doi.org/10.1038/s41550-022-01824-7

Hellmann, J.L., Hopp, T., Burkhardt, C., Kleine, T. (2020) Origin of volatile element depletion among carbonaceous chondrites. *Earth and Planetary Science Letters* 549, 116508. https://doi.org/10.1016/j.epsl.2020.116508

Hopp, T., Dauphas, N., Abe, Y., Aléon, J., Alexander, C.M.O'D. *et al*. (2022) Ryugu's nucleosynthetic heritage from the outskirts of the Solar System. *Science Advances* 8, eadd8141. https://doi.org/10.1126/sciadv.add8141

Lauretta, D.S., Connolly Jr., H.C., Aebersold, J.E., Alexander, C.M.O'D., Ballouz, R.-L. *et al*. (2024) Asteroid (101955) Bennu in the laboratory: Properties of the sample collected by OSIRIS-REx. *Meteoritics & Planetary Science* 59, 2453–2486. https://doi.org/10.1111/maps.14227

Lee, M.R., Glazer, J. (2026) Rapid terrestrial weathering of the CI1 carbonaceous chondrite find Oued Chebeika 002. *Meteoritics & Planetary Science* (in press). https://doi.org/10.1111/maps.70089

Lee, M.R., Hallis, L.J., Daly, L., Boyce, A.J. (2023) The water content of CM carbonaceous chondrite falls and finds, and their susceptibility to terrestrial contamination. *Meteoritics & Planetary Science* 58, 1760–1772. https://doi.org/10.1111/maps.14099

Lodders, K., Bergemann, M., Palme, H. (2025) Solar System Elemental Abundances from the Solar Photosphere and CI-Chondrites. *Space Science Reviews* 221, 23. https://doi.org/10.1007/s11214-025-01146-w

Marrocchi, Y., Rigaudier, T., Piralla, M., Piani, L. (2023) Hydrogen isotopic evidence for nebular pre-hydration and the limited role of parent-body processes in CM chondrites. *Earth and Planetary Science Letters* 611, 118151. https://doi.org/10.1016/j.epsl.2023.118151

Marty, B. (2012) The origins and concentrations of water, carbon, nitrogen and noble gases on Earth. *Earth and Planetary Science Letters* 313–314, 56–66. https://doi.org/10.1016/j.epsl.2011.10.040

Marty, B., Zimmermann, L., Füri, E., Bekaert, D.V., Barnes, J.J., Nguyen, A.N., Connolly, H.C., Lauretta, D.S. (2026) Noble gases and nitrogen in material from asteroid Bennu. *Meteoritics & Planetary Science* (in press). https://doi.org/10.1111/maps.70058

Morlok, A., Bischoff, A., Stephan, T., Floss, C., Zinner, E., Jessberger, E.K. (2006) Brecciation and chemical heterogeneities of CI chondrites. *Geochimica et Cosmochimica Acta* 70, 5371–5394. https://doi.org/10.1016/j.gca.2006.08.007

Nakamura, E., Kobayashi, K., Tanaka, R., Kunihiro, T., Kitagawa, H. *et al.* (2022) On the origin and evolution of the asteroid Ryugu: A comprehensive geochemical perspective. *Proceedings of the Japan Academy, Series B* 98, 227–282. https://doi.org/10.2183/pjab.98.015

Nittler, L.R., Barosch, J., Burgess, K., Stroud, R.M., Wang, J. *et al.* (2024) Microscale hydrogen, carbon, and nitrogen isotopic diversity of organic matter in asteroid Ryugu. *Earth and Planetary Science Letters* 637, 118719. https://doi.org/10.1016/j.epsl.2024.118719

Okazaki, R., Yamanouchi, S., Shimada, K., Baba, A., Kitajima, F., Yada, T. (2022) Methods and tools for handling, transportation, weighing, and pelletization applied to the initial analysis of volatile components in the Hayabusa2 samples. *Earth, Planets and Space* 74, 190. https://doi.org/10.1186/s40623-022-01747-7

Pearson, V.K., Sephton, M.A., Franchi, I.A., Gibson, J.M., Gilmour, I. (2006) Carbon and nitrogen in carbonaceous chondrites: Elemental abundances and stable isotopic compositions. *Meteoritics & Planetary Science* 41, 1899–1918. https://doi.org/10.1111/j.1945-5100.2006.tb00459.x

Piani, L., Marrocchi, Y., Rigaudier, T., Vacher, L.G., Thomassin, D., Marty, B. (2020) Earth's water may have been inherited from material similar to enstatite chondrite meteorites. *Science* 369, 1110–1113. https://doi.org/10.1126/science.aba1948

Piani, L., Marrocchi, Y., Vacher, L.G., Yurimoto, H., Bizzarro, M. (2021) Origin of hydrogen isotopic variations in chondritic water and organics. *Earth and Planetary Science Letters* 567, 117008. https://doi.org/10.1016/j.epsl.2021.117008

Remusat, L., Guan, Y., Wang, Y., Eiler, J.M. (2010) Accretion and preservation of D-rich organic particles in carbonaceous chondrites: Evidence for important transport in the early solar system nebula. *The Astrophysical Journal* 713, 1048–1058. https://doi.org/10.1088/0004-637X/713/2/1048

Russell, S.S., Suttle, M.D., King, A.J. (2022) Abundance and importance of petrological type 1 chondritic material. *Meteoritics & Planetary Science* 57, 277–301. https://doi.org/10.1111/maps.13753

Sandford, S.A., Gainsforth, Z., Nuevo, M., Marcus, M.A., Bechtel, H.A. *et al.* (2025) Nitrogen- and oxygen-rich organic material indicative of polymerization in pre-aqueous cryochemistry on Bennu's parent body. *Nature Astronomy* 9, 1803–1811. https://doi.org/10.1038/s41550-025-02694-5

Spitzer, F., Kleine, T., Burkhardt, C., Hopp, T., Yokoyama, T. *et al.* (2024) The Ni isotopic composition of Ryugu reveals a common accretion region for carbonaceous chondrites. *Science Advances* 10, eadp2426. https://doi.org/10.1126/sciadv.adp2426

Tissot, F.L.H., Burkhardt, C., Kuznetsova, A., Pack, A., Schiller, M., Spitzer, F., Van Kooten, E.M.M.E., Yap, T.E. (2025) Infall and Disk Processes – the Message from Meteorites. *Space Science Reviews* 221, 85. https://doi.org/10.1007/s11214-025-01207-0

Vacher, L.G., Piani, L., Rigaudier, T., Thomassin, D., Florin, G., Piralla, M., Marrocchi, Y. (2020) Hydrogen in chondrites: Influence of parent body alteration and atmospheric contamination on primordial components. *Geochimica et Cosmochimica Acta* 281, 53–66. https://doi.org/10.1016/j.gca.2020.05.007

Yokoyama, T., Nagashima, K., Nakai, I., Young, E.D., Abe, Y. *et al.* (2023) Samples returned from the asteroid Ryugu are similar to Ivuna-type carbonaceous meteorites. *Science* 379, eabn7850. https://doi.org/10.1126/science.abn7850

Zimmermann, L., Füri, E., Boulliung, J., Saxton, J.M. (2025) Performance of the 3F4M Noblesse–HR Noble Gas Mass Spectrometer for Multicollection Ne-Ar-N_2 Analyses. *Geochemistry, Geophysics, Geosystems* 26, e2025GC012247. https://doi.org/10.1029/2025GC012247