The Abundance of Water in Primitive Ordinary Chondrite Meteorites (OC): Implication for the Delivery of Water in Terrestrial Planets

Lionel G. Vacher[1], Lydie Bonal[1], Jolantha Eschrig[1], Laurène Flandinet[1], Thomas Rigaudier[1,2] & Pierre Beck[1]

[1]Univ. Grenoble Alpes, CNRS, IPAG, 38000 Grenoble, France (lionel.vacher@univ-grenoble-alpes.fr)
[2] Univ. de Lorraine, CNRS, CRPG, 54501 Vandœuvre-lès-Nancy, France

JC² October 12, 13 and 14, 2022

Introduction

The origin of water in terrestrial planets remains unknown. The inner Solar System was probably too warm to have retained water ice, so Earth's water is believed to have been delivered by volatile-rich materials that originally formed in the outer Solar System before migrating inward. However, recent studies of **Non-Carbonaceous materials** (enstatite chondrites [ECs] and Itokawa particles) suggest that these inner Solar System materials may be more water-rich than previously thought and contain sufficient water to have delivered to Earth all its water budget [1, 2].

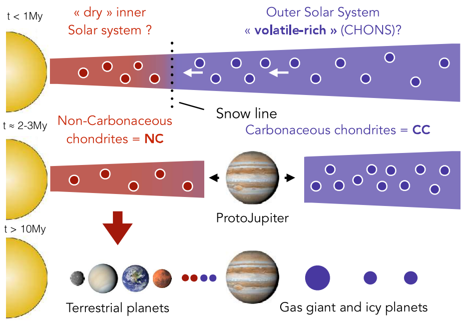


Fig.1 – The formation of the early of the Solar System.

Geochemical data from terrestrial and martian rocks suggests that the overall composition of Mars is unlike that of the Earth. Compared to various meteorite groups, isotopic data for Mars meteorites match the **ordinary chondrite (OC)** group, while Earth composition matches the enstatite chondrites (EC) group [3].

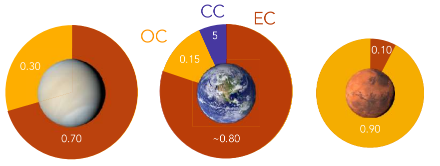


Fig.2 – Pie charts of the composition of terrestrial planets based on numerical simulations. Adapted from [4].

Ordinary chondrites are more oxidized and contain a higher proportion of water and volatile elements compared to ECs [4]. This suggest that Mars may have been initially more enriched in water after its main accretion phase compared to Earth.

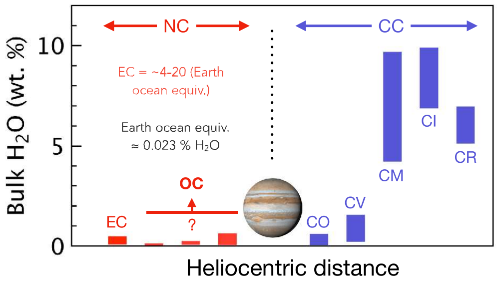


Fig.3 – Water abundance in primitive meteorites as function of their expected heliocentric distance in the protoplanetary disk.

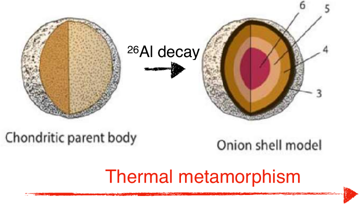
However, reconstructing the initial amount of water in OCs is not straightforward because most of these meteorites have been affected by **intense thermal metamorphism** on the ir parent body(-ies) (up to 900 °C) that strongly modified their initial volatile abundance and isotopic composition.

This work was funded by **Centre National d'Etudes Spatiales** (CNES) and **LabEx OSUG 2022** (project ELVISS).

(1) Piani L. et al. (2020) Science, 369:1110–1113. (2) Jin Z. & Bose M. (2019) Sci. Adv., 5:eaav8106. (3) McCubbin FM, Barnes JJ (2019) Earth Planet. Sci. Lett. 526:115771. (4) Brasser R. et al. (2017) Earth Planet. Sci. Lett., 468:85–93. (5) Norton RO & Chitwood LA (2008) Field guide to meteors and meteorites (p52). (6) Doyle P. et al. (2015) Nat. Com., 6:7444. (7) Kurokawa P. et al. (2014) Earth Planet. Sci. Lett., 394:179-185. (8) Tian Z. et al. (2021) PNAS, 118:e2101155118. (9) Piani L. et al. (2021) EPSL, 567:117008. (10) Alexander CMOD. et al. (2010) GCA, 74:4417-4437. (11) Eschrig J. et al. (2022) GCA, under review. (12) Vacher LG. et al. (2020) GCA, 281:53-66.

Results

Figure adapted from [5].



Type 3 (T$_{max}$ < 600°C) → Type 4 (~650°C) → Type 5 (~800°C) → Type 6 (~900°C)

Unequilibrated (UOC) Petrographic type (PT): 3.0 to 3.9

Equilibrated (EOC)

Primitive ordinary chondrites (PT < 3.1) contain up to ~1.2 wt. % of H_2O and show the highest bulk δD values (up to ~ +2,700‰). In contrary, the highest metamorphosed (PT = 6) OCs display the lowest amount of water (< 0.1 wt. %) and show δD values consistent with terrestrial weathering products (~ –100‰).

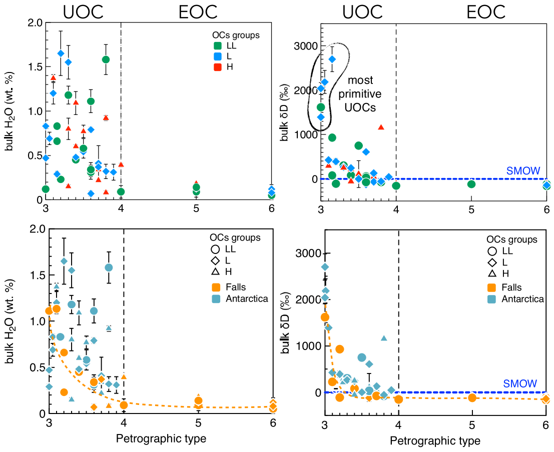


Fig.4 – (left) Bulk H_2O abundances and (right) hydrogen isotopic compositions (δD) of ordinary chondrites (OCs) as function fo their metamorphic degree (PT). SMOW: Standard Mean Ocean Water.

Discussion

1. Water in the inner Solar System

The total amount of water measured in primitive OCs is almost twice higher than the highest water concentration measured in enstatite chondrite (i.e. ~0.6 wt.%) [1]. Ordinary chondrites accreted very early (~2My after the formation of the Solar System [6]) and probably close to the snow line. This implies that water ice grains were present in the inner region of the Solar System very early, before the accretion of terrestrial planets. In addition, this also suggests that Mars could have initially retained a higher fraction of its volatile inventory than Earth [7] (before its loss of volatiles triggered by its small mass [8] and/or the loss of its protective magnetic field).

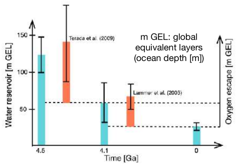


Fig.5 – Evolution of the Martin water reservoir estimated from water present in polar layered deposits (blue) and oxygen escape calculation models (orange). Figure from [7].

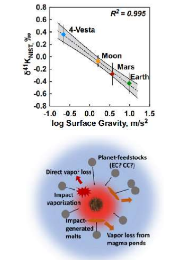


Fig.6 – (up) Potassium isotope data of various planetary bodies versus their corresponding gravity. (down) Schematic diagram of mechanics of volatile loss during accretionary growth. Figures from [8].

2. Origin of water in ordinary chondrites

Primitive OCs host D-rich water (up to 1,500‰ in the most primitive LL3.0 Semarkona). The presence of hydrous phases (presence of the 2.8 µm band related to phyllosilicates in some primitive samples [11]) further supports a possible cometary/interstellar origin of H_2O given that it is more difficult to produce D-rich water than D-rich organics through disk processes.

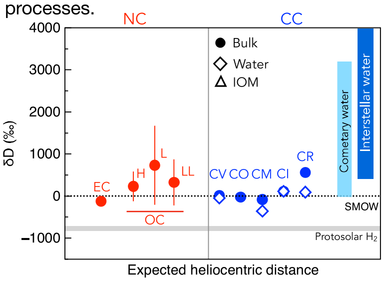


Fig.7 – Bulk hydrogen isotope data of non-carbonaceous (NC) and carbonaceous (CC) chondrites, cometary and interstellar water. Adapted from [9].

bulk H ≈ hydrated minerals (water) + organic matter

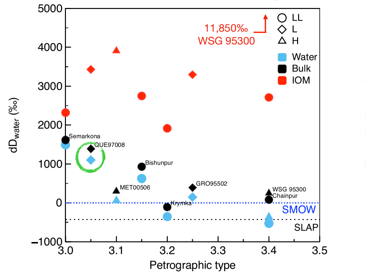


Fig.8 – Bulk hydrogen isotope data of water in ordinary chondrites determined by mass balance equation between the bulk and the insoluble organic matter (IOM). Data of IOM from [10].

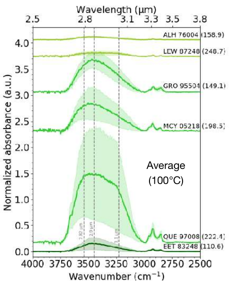


Fig.9 – IR spectra of UOCs in the 4000 – 2500 cm-1 region at 100°C. Shown is the 3-micron region. Figure from [11].

Methods

Typically ~6-10mg of OCs were crushed into powder, weighted in tin capsules and degassed under vacuum at 120°C for 48h in a degassing canister to remove absorbed atmospheric water following [12]. After dehydration, the degassing canister was opened in a N2-flushed glove box and samples were transferred into a custom sealed, auto-sampler pre-flushed with He. Samples experienced pyrolysis at 1450°C on a EA glassy carbon reaction tube using the Thermo Scientific EA IsoLink deltaV IRMS System at CRPG laboratory (Nancy, France). After chromatographic separation, the extracted H_2 was introduced into the mass spectrometer and its H abundance and δD value were characterized.

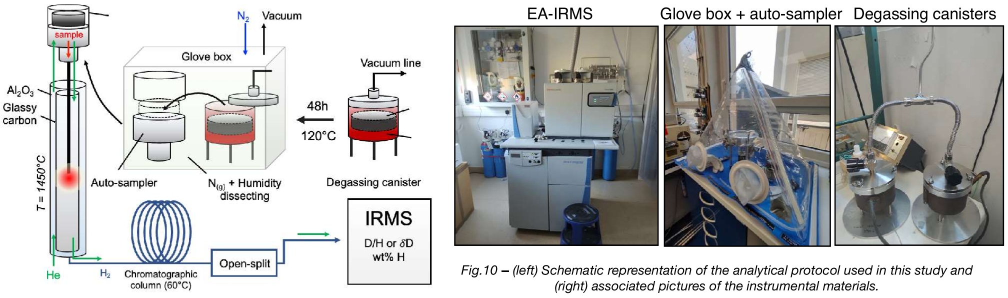


Fig.10 – (left) Schematic representation of the analytical protocol used in this study and (right) associated pictures of the instrumental materials.