

## When crystallography meets planetary science: insights into large icy moons of Jupiter and Saturn

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Search for potential habitable environments beyond the Earth is a major challenge in modern planetary science and astrobiology. Until now, icy moons of Jupiter and Saturn are the only extra-terrestrial planetary bodies where the presence of liquid water has been discovered in the form of subsurface oceans [1,2]. Subsurface oceans are nowadays the most appealing astrobiological targets and have become the focus of diverse interdisciplinary research, as well as ongoing and upcoming space missions. A unique and intriguing aspect of extra-terrestrial ocean worlds is the influence of high pressure on their physical state and thermochemical evolution [2,3]. On the large ocean worlds like Ganymede, Titan, and Callisto, pressures at the bottom of the hydrosphere can achieve up to 1.7 GPa – far exceeding the conditions found at the Earth’s deepest oceans. While a variety of salts and volatiles are expected to be dissolved in the interior of large icy moons [4,5], some of these compounds can be stable in the form of salt hydrates or gas clathrate hydrates at relevant high-pressure and low/temperature conditions. Formation and destabilization of these hydrates govern the chemical exchange in the interior and control the amount of volatile dissolved in the ocean, with a major impact on the chemical evolution and astrobiological potential of subsurface oceans. The current contribution overviews the collaborative work of crystallographers and planetary scientists of the last years dedicated to 1) *in situ* X-Ray diffraction studies of high-pressure polymorphism and structural properties of potential extra-terrestrial minerals, and 2) implications of the experimental results to the evolution of the large ocean worlds. Methodological approach and the advantages of using of *in situ* single-crystal X-ray diffraction will be discussed. Several case studies on salt hydrates and clathrate hydrates will be presented, including studies on NaCl hydrates [6], gas clathrates of CH<sub>4</sub> and CO<sub>2</sub>, and methanol-bearing clathrates [7]. At the end of the contribution, the open questions and current research activities will be discussed.

[1] Nimmo, F. & Pappalardo, R. T. Ocean worlds in the outer solar system. *JGR: Planets* 121, 1378–1399 (2016).

[2] Journaux, B. et al. Large Ocean Worlds with High-Pressure Ices. *Space Sci. Rev.* 216, 7 (2020).

[3] Sotin, C., Kalousová, K. & Tobie, G. Titan’s Interior Structure and Dynamics After the Cassini-Huygens Mission. *Annu. Rev. Earth Planet Sci.* 49, 579–607 (2021).

[4] Tobie, G., Gautier, D. & Hersant, F. Titan’s bulk composition constrained by Cassini-Huygens: Implication for internal outgassing. *ApJ.* 752, 125 (2012).

[5] Choukroun, M., Kieffer, S. W., Lu, X. & Tobie, G. Clathrate Hydrates: Implications for Exchange Processes in the Outer Solar System. In *The Science of Solar System Ices* (eds. Gudipati, M. S. & Castillo-Rogez, J.) 409–454 (Springer, 2013). doi:10.1007/978-1-4614-3076-6\_12.

[6] Journaux, B., Pakhomova, A., Collings, I. E., Petitgirard, S., Boffa Ballaran, T., Brown, J. M., Vance, S. D., Chariton, S., Prakapenka, V. B., Huang, D., Ott, J., Glazyrin, K., Garbarino, G., Comboni, D., Hanfland, M. On the Identification of Hyperhydrated Sodium Chloride Hydrates, Stable at Icy Moon Conditions. *PNAS.* 2023, 120 (9), e2217125120.

[7] Pakhomova, A., Journaux, B., Kurnosov A., Boffa Ballaran, T., Tobie, G., Hanfland, M. Methanol Storage in High-Pressure Clathrate Hydrates as a Prolonged Source of Methane in Large Ocean Worlds. 2025. Under review in *EPSL*. DOI: <https://doi.org/10.21203/rs.3.rs-5600760/v1>

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