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## Carbon-rich interiors of Ganymede and Titan: application of a kinetic model of carbonaceous organic matter transformation

Camille Delarue<sup>1</sup>, Bruno Reynard<sup>1</sup>, Christophe Sotin<sup>2</sup>, Fella Clémentine<sup>1</sup>, Cardon Hervé<sup>1</sup>, Montagnac Gilles<sup>1</sup>, Confortini Giorgia<sup>1</sup>, and Rafael Ferreiro Mählmann<sup>3</sup>

<sup>1</sup>ENS de Lyon, LGL TPE, Geology, Lyon, France (camille.delarue@ens-lyon.fr)

<sup>2</sup>Nantes Université, Univ Angers, Le Mans Université, CNRS, Laboratoire de Planétologie et Géosciences, LPG UMR 6112, 44000 Nantes, Nantes, France

<sup>3</sup>Technische-u. Niedrigtemperatur Petrologie, Technische Universität Darmstadt, Schnittspahnstrasse 9, 64287 Darmstadt, Germany

Composition models of icy bodies require the incorporation of important volume of carbonaceous organic matter (COM) in their rocky cores to account for their density and moment of inertia<sup>[1]</sup>, as measured by the *Cassini* and *Galileo* missions. In these models, the effects of temperature and pressure on COM were either simplified or neglected due to the lack of experimental data. To address this, we conducted experiments to constrain the evolution of COM composition and density at elevated temperatures and pressures within the range of icy moons core conditions (up to ~7 GPa and 1300 K in Ganymede's core). Type III kerogens were used as analogs for COM to quantify this transformation.

The ambient-temperature compressibility of kerogens was measured using diamond anvil cell experiments while the evolution of COM chemistry and density with temperature and time was described by adapting a kinetic model previously developed for coals<sup>[2]</sup>. Kinetic model parameters<sup>[3]</sup> were adjusted to account for the chemical composition and physical properties (density, vitrinite reflectance) of experimental samples heated between 473 and 723 K for durations ranging from seconds to hundreds of days under various pressures (0.2–2.5 GPa). The density of COM as a function of time, temperature, and pressure was determined by combining compressibility data with the kinetic model.

The kinetic model adjusted to experimental data on coals provides a good fit to experimentally determined chemical variations of IOM and IOM analogs (Miller). This suggests that type III kerogens are indeed valid analogs to describe the density and composition of meteoritic IOM submitted to metamorphism in icy bodies. The kinetic model was implemented in thermo-chemical evolution models to describe the composition and density evolution of COM in the refractory cores of icy bodies.

At astronomical timescales (>100 Myrs), COM density undergoes a rapid variation from ~1350 kg/m<sup>3</sup> 300 K to values close to that of graphite (~2250 kg/m<sup>3</sup>) at 600 K according to the present kinetic model. Additionally, the kinetic model predicts the nature and proportions of released volatiles (H<sub>2</sub>O, CO<sub>2</sub>, and CH<sub>4</sub>). Reactions between core material and volatiles produced during COM transformation have been investigated, and are taken into account in the thermal evolution model. Applications to Titan and Ganymede suggest that the amount of COM required to match gravitational constraints is higher than previously estimated, potentially reaching 40 wt% for Titan and 25% for Ganymede, based on the newly determined density values. Future gravity measurements by the JUICE and Europa Clipper missions will allow testing and refining the present reference composition models.

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[1] Reynard, B., & Sotin, C. (2023). Carbon-rich icy moons and dwarf planets. *Earth and Planetary Science Letters*, 612, 118172.

[2] Burnham, A. K. Kinetic models of vitrinite, kerogen, and bitumen reflectance. *Organic Geochemistry* **131**, 50-59 (2019).  
<https://doi.org/https://doi.org/10.1016/j.orggeochem.2019.03.007>

[3] Braun, R. L., & Burnham, A. K. (1987). Analysis of chemical reaction kinetics using a distribution of activation energies and simpler models. *Energy & Fuels*, 1(2), 153-161.