氏　　名	RAHUL KUMAR
授与した学位	博　士
専攻分野の名称	理　学
学位授与番号	博甲第　　７３８９　　号
学位授与の日付	２０２５年　９月　２５日
学位授与の要件	自然科学研究科　　地球惑星物質科学専攻 （学位規則第４条第１項該当）
学位論文の題目	Development of a micro-organic matter identifier and its application to characterise insoluble organic matter in carbonaceous chondrite and Ryugu samples （小惑星物質からミクロンサイズの有機物質を検出する手法の開発とその応用）
論文審査委員	准教授　Potiszil Christian　教授　田中　亮吏　准教授　国広　卓也 教授　亀田　純　教授　Mark A. Sephton

学位論文内容の要旨

Asteroidal materials contain various types of micrometer-sized insoluble organic matter (μ-OM), including concentrated (COM) and diffuse OM (DOM). COM appears dark in SEM-BSE images and shows high carbon signals, while DOM blends with the matrix visually but still shows abundant carbon in X-ray element maps. Traditional scanning electron microscope with energy dispersive spectrometer (SEM-EDS) analyses are limited by manual detection and bias toward larger particles.

To overcome this, a new workflow combining image processing and machine learning was developed. After testing various clustering and classification algorithms, the random forest method was chosen for its superior accuracy in identifying μ-OM (>1 μm) across entire 1 mm² areas. The workflow efficiently produces OM phase maps from elemental data, reducing analysis time by ~4 hours per region.

This approach allows for accurate selection of regions for advanced analyses (TEM, SIMS, Raman, FTIR) and identifies 50–100 μ-OM occurrences per section, with results consistent with manual methods. COM size distributions follow power-law trends, differing between Ryugu-A and Ryugu-C, suggesting varying alteration conditions. Morphology and mineral associations of COM indicate that oxidizing aqueous processes influenced OM transformation, with irregular and larger COM more frequently associated with carbonates, especially in Ryugu-C.

論文審査結果の要旨

Carbonaceous chondrite meteorites and C-type asteroid return samples represent primitive materials that preserve organic matter. Extraterrestrial organic matter, not only includes biologically important molecules, but also the processes that formed and shaped our solar system. However, deciphering the processes that are recorded my asteroidal organic matter is very challenging, due to the vast number of environment that organic matter has been exposed to, from the interstellar medium to current day asteroid surfaces. To try and elucidate that various process that have affected asteroidal organic matter Rahul developed an analytical, image processing and machine learning protocol to allow the identification, elemental and isotopic characterization and classification of micrometer-sized organic matter on mm-sized meteorite and Ryugu samples. Using the large data set generated, Rahul then discussed and evaluated the different processes capable of giving rise to the observed attributes of the targeted extraterrestrial organic matter. Rahul's doctoral thesis was structured into 6 chapters: (1) an introduction reviewing previous studies that had investigated extraterrestrial organic matter, carbonaceous chondrites, Ryugu and image processing and machine learning, and which also outlined the aim and objectives of Rahul's PhD research, (2) a section describing the development of an image processing protocol for generating maps of micrometer-sized organic matter, (3) a section detailing the development of a machine learning protocol to identify and characterize micrometer-sized organic matter, (4) a section demonstrating the application of the image processing and machine learning protocol to identify, characterize and classify organic matter in carbonaceous chondrite and Ryugu samples and also highlight organic-mineral associations, (5) a section showcasing the in-situ determination of the isotopic characteristics of organic matter investigated by chapter (4), and (6) a conclusions section. At the thesis defense, Rahul presented parts of all chapters, with a focus on the results and interpretation from chapters 4 and 5. The presentation was evaluated well in terms of outlining the major data trend of Rahul's work and for highlighting several plausible interpretations for the trends. However, the presentation was criticized for not including more discussion of the spatial distribution of the organic matter or how this might relate to aqueous alteration. The thesis was evaluated positively in terms of the protocol development and for showcasing the huge data set and trend in the data. However, the thesis was criticized for having insufficient discussion of the potential interpretations of the trends observed in chapters 4 and 5. Overall, Rahul was evaluated to have passed the examination based on his development and application of a novel image processing and machine learning protocol to meteorite and return samples, the generation of a large and unique data set, and the publishing of parts of their thesis in a peer reviewed paper. Furthermore, Rahul's doctoral thesis was considered to represent an important contribution to the field of planetary science.