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Rapid colonization of a space-returned Ryugu sample by terrestrial microorganisms

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Abstract–The presence of microorganisms within meteorites has been used as evidence for extraterrestrial life, however, the potential for terrestrial contamination makes their interpretation highly controversial. Here, we report the discovery of rods and filaments of organic matter, which are interpreted as filamentous microorganisms, on a space-returned sample from 162173 Ryugu recovered by the Hayabusa 2 mission. The observed carbonaceous filaments have sizes and morphologies consistent with microorganisms and are spatially associated with indigenous organic matter. The abundance of filaments changed with time and suggests the growth and decline of a prokaryote population with a generation time of 5.2 days. The population statistics indicate an extant microbial community originating through terrestrial contamination. The discovery emphasizes that terrestrial biota can rapidly colonize extraterrestrial specimens even given contamination control precautions. The colonization of a space-returned sample emphasizes that extraterrestrial organic matter can provide a suitable source of metabolic energy for heterotrophic organisms on Earth and other planets.

INTRODUCTION

Numerous studies have reported the presence of microorganisms within chondritic meteorites (Hoover et al., 1998; Steele et al., 2002) and while most have concluded that these microbes are terrestrial contaminants (Burckle & Delaney, 1999; Or & Tornabene, 1965; Steele et al., 2002), others have argued for an extraterrestrial origin (Hoover et al., 1998, 2018; Rozanov et al., 2021). The discovery of extraterrestrial life within meteorites would have profound significance for the origins and distribution of life and would confirm that the transfer of microorganisms between planetary objects through panspermia is possible (e.g., McKay et al., 2022). Evidence cited in studies claiming an extraterrestrial origin for microorganisms in meteorites focuses on the pristine nature of recently fallen meteorites or the occurrences of microbes on internal surfaces. Meteorites, however, have been exposed to the terrestrial environment and it is, thus, not possible to exclude contamination by terrestrial microorganisms. Only the discovery of microbes within extraterrestrial materials returned to Earth by space missions, subject to stringent contamination controls, could provide compelling evidence for panspermia.

We report the discovery of rods and filaments of organic matter, consistent with extant filamentous microorganisms, on sample A0180 from asteroid 162173 Ryugu returned to Earth by the Hayabusa 2 mission. Although this observation could be interpreted as confirmation of panspermia, the population statistics of the microorganisms suggest population growth and decline after sample preparation, rather than after arrival on Earth, and thus suggest the microbes are terrestrial contamination. The contamination control applied to these space-returned samples underlines that microorganisms are able to rapidly colonize extraterrestrial materials, even given limited exposure to the terrestrial environment and that microbiota even within space-returned samples cannot be assumed to be extraterrestrial. They also demonstrate that meteoritic organic matter provides a suitable nutrient source to sustain survival of populations of microorganisms.

MATERIALS AND METHODS

Sample A0180 is a 1 × 0.8 mm regolith particle collected by the JAXA Hyabusa 2 mission to asteroid 162173 Ryugu. Samples were collected from Ryugu during close passes of the spacecraft by capturing surface particles during two touchdown events, with the second touchdown occurring after the use of kinetic impactors to reveal subsurface materials. Sample A0180 was recovered in the first collection attempt. The particles were transported to Earth in a hermetically sealed chamber that was opened in nitrogen in a class 10,000 clean room at JAXA (Yada et al., 2022). Individual particles were picked with sterilized tools and placed in airtight containers under nitrogen for distribution to participating science teams. Prior to study the Ryugu samples had no exposure to the terrestrial environment and the JAXA contamination control protocols were of the highest standard (Yada et al., 2022).

Prior to polished block preparation sample A0180 was analyzed by Nano-X-ray computed tomography. Ryugu sub-samples (A/B) were removed from the nitrogen container and were mounted in pipette tips and scanned using a Zeiss Versa X-ray micro-computed tomography scanner at the Natural History Museum, London. X-rays were generated from a tungsten source, with a voltage of 90 kV and a current of 89 μA, using the inbuilt LE4 filter to reduce beam hardening effects. For each scan, 2401 projections were collected across a 360° rotation. Each projection was magnified by a 4× objective lens and recorded using a 2000 × 2000 CCD plane (16-bit pixel depth) at exposure times of 33 s and 28 s for A0180-A and A0180-B, respectively, with no binning. Spatial resolutions (in voxels) were 0.625 μm for A-0180A and 0.672 μm for A-0180B. Image stacks were created using the Zeiss Reconstructor software.

Sub specimen B was embedded in an epoxy resin block using Struers Specific resin. The specimen was polished using 0.1 μm aluminum oxide paste under ethanediol solvent using a fresh polishing pad. This work was conducted in the Rock Preparation Laboratory of the Natural History Museum on the November 3 and 4, 2022. The sample was carbon-coated under a pressure of 3 Pa and then stored under air in a sealed plastic container. The coat was ~50 nm thick. Filaments were observed during scanning electron microscopy using a Hitachi TM4000+ Desktop scanning electron microscope in the Department of Earth Science and Engineering at Imperial College London (15 kV accelerating voltage and 2 nA current at a vacuum pressure of 60 Pa) and a Hitachi S4700 field emission gun scanning electron microscope (20 kV accelerating voltage and 10 μA) at the University of Kent. The first SEM analysis was conducted on the XX at Imperial College, with a second analysis (at Kent) on the XX, and a third conducted on XX at Imperial College. The morphology and abundance of rods and filaments of organic matter were characterized by backscattered and secondary electron microscopy and X-ray elemental mapping. The whole sample surface was surveyed to provide the abundances of the structures. The curation, preparation and analysis timeline of sample A0180 is shown in Table 1.

RESULTS

Petrology and Mineralogy

Sample A0180, like other Ryugu samples, strongly resembles CI chondrites and is dominated by a fine-grained matrix of serpentine-smectite mixed layer clays, dolomite, pyrrhotite and magnetite indicating significant aqueous alteration (Ito et al., 2022; Yokoyama et al., 2023) (Figure 1a). In contrast to most Ryugu particles A0180 contains lower abundances of magnetite, sulfide, and carbonate (2.26, 0.8, and 1.4 vol% compared with 3.6–6.8, 2.5–5.5, and 2–21 vol%, respectively; Genge et al., 2024; Ito et al., 2022). Magnetite occurs mostly as clusters of framboids, however, magnetite platelets and spheroidal magnetite are also present. Sulfides in the specimen often form euhedral platy crystals, while dolomite consists of irregular, embayed crystals that are often associated with mantles enriched in organic matter. Finally, the specimen features a network of thin fractures thought to be pre-terrestrial in origin (Genge et al., 2024).

Occurrence of Organic Filaments and Rods

Rods and filaments of organic matter (RF-OM) were observed in Ryugu sample A0180 and were identified by scanning electron microscopy (SEM) owing to their

TABLE 1. Curation, handling and analysis timeline for Ryugu sample A0180.

Action	Date(s)	Contamination Protocols
Collection by Hayabusa 2 spacecraft	February 22, 2019	Collection instrument sterilized prior to mission (Hajime). Hermetic storage in sample container
Return to Earth	December 6, 2020	Opening of sample container in the Clean Chamber under a pressure of $<10^{-5}$ Pa at JAXA. Manipulation of sample particles with sterilized tools
Storage in class10000 clean room JAXA		Storage under a nitrogen atmosphere during initial sample characterization by optical microscope, near-infrared spectro-imager, and microbalance
Transport to UK	July 22, 2022	Transport within sealed container under nitrogen
XCT Analysis within pipette tips	October 14, 2022	Removal of sample from nitrogen and exposure to terrestrial atmosphere. Transfer of sample to a sterilized pipette tip. Following storage within a sealed desiccator (Natasha)
Embedding in resin, polishing and carbon-coating	November 3 and 4, 2022	Transfer of sample to a mold and embedding in resin. Exposure to terrestrial atmosphere. Polishing on a new polishing pad under ethanediol. Carbon-coating under a pressure of 3 Pa for 10 min. A ~30 nm carbon coat was applied
Dry Storage	November 4 and 11, 2022	Subsequent storage in a sealed plastic container under terrestrial atmosphere
Analysis by SEM (Imperial College)	November 11, 2022	Exposure for 6 h at 60 Pa pressure and 15 kV electron beam with a current of 2 nA
Infrared analysis (Kent)	November 16, 2022	Infrared mapping under air. Sample stored dry in plastic container in desiccator
Analysis by FEG-SEM (Kent)	November 30, 2022	Exposure for 4 h at 60 Pa pressure and 20 kV electron beam with a current of 10 μA
Analysis by SEM (Imperial College)	January 14, 2023	Exposure for 8 h at 60 Pa pressure and 15 kV electron beam with a current of 2 nA
Repolishing	February 7, 2023	Repolishing under ethanediol using a new polishing pad
Analysis by SEM (Imperial College)	February 15, 2023	Exposure for 8 h at 60 Pa pressure and 15 kV electron beam with a current of 2 nA

cylindrical shapes and carbon-rich nature, as determined by X-ray mapping (Figure 1). Most of the RF-OM were observed on the surface of a polished block of the specimen, and secondary electron images confirmed their three-dimensional shapes and occurrence encrusting the surface (Figure 1). Several filaments were also observed within cavities containing porous material and some appear to penetrate matrix (Figure 1d).

The size of the RF-OM varies significantly with widths of 0.18–1.14 μm and lengths of 0.68–18.3 μm. Filaments with large aspect ratios (>4) occur over the whole size range, however, rods tend to be <0.9 μm in width. Shape also varies with RF-OM being either parallel-sided or tapering. Some filaments have indents along their length suggesting the presence of multiple elliptical components within an enclosing sheath. The size distribution of RF-OM is broadly log-normal (Figure 2), however, the most elongate filaments represent outliers at larger sizes.

The abundance of RF-OM in the specimen changes with their occurrence. The majority of objects (64%) were associated with dolomite grains with organic mantles (Figure 1e,g,i). Around one dolomite crystal a dense cluster of overlapping RF-OM was observed (Figure 1g). Twenty eight percent of filaments were found within cavities on the specimen, some of which are lined by organic matter (Figure 1d). Only 10% of RF-OM were found as individuals in other areas on the polished surface of the specimen.

The number of RF-OM present on the specimen changed with time. Nano X-ray computed tomography data, collected on the sample prior to preparation of the polished block, shows no evidence for the presence of RF-OM within the matrix of the sample, although only the largest of the RF-OM would have been detectable given the resolution of the XCT data of 0.67 μm. The low X-ray attenuation of organic matter compared with silicates (REF), however, should have allowed them to be identified, if present. Eleven were observed in the first SEM examination, 7 days after polishing on November 11, 2022. On the November 30, 147 rods and filaments were observed including a dense cluster around a dolomite grain (Figure 1g). Finally, 36 objects were found on the January 14, 2023. These values are, however, likely to be minimum estimates since the clustering of RF-OM means individuals are difficult to resolve. After repolishing of the

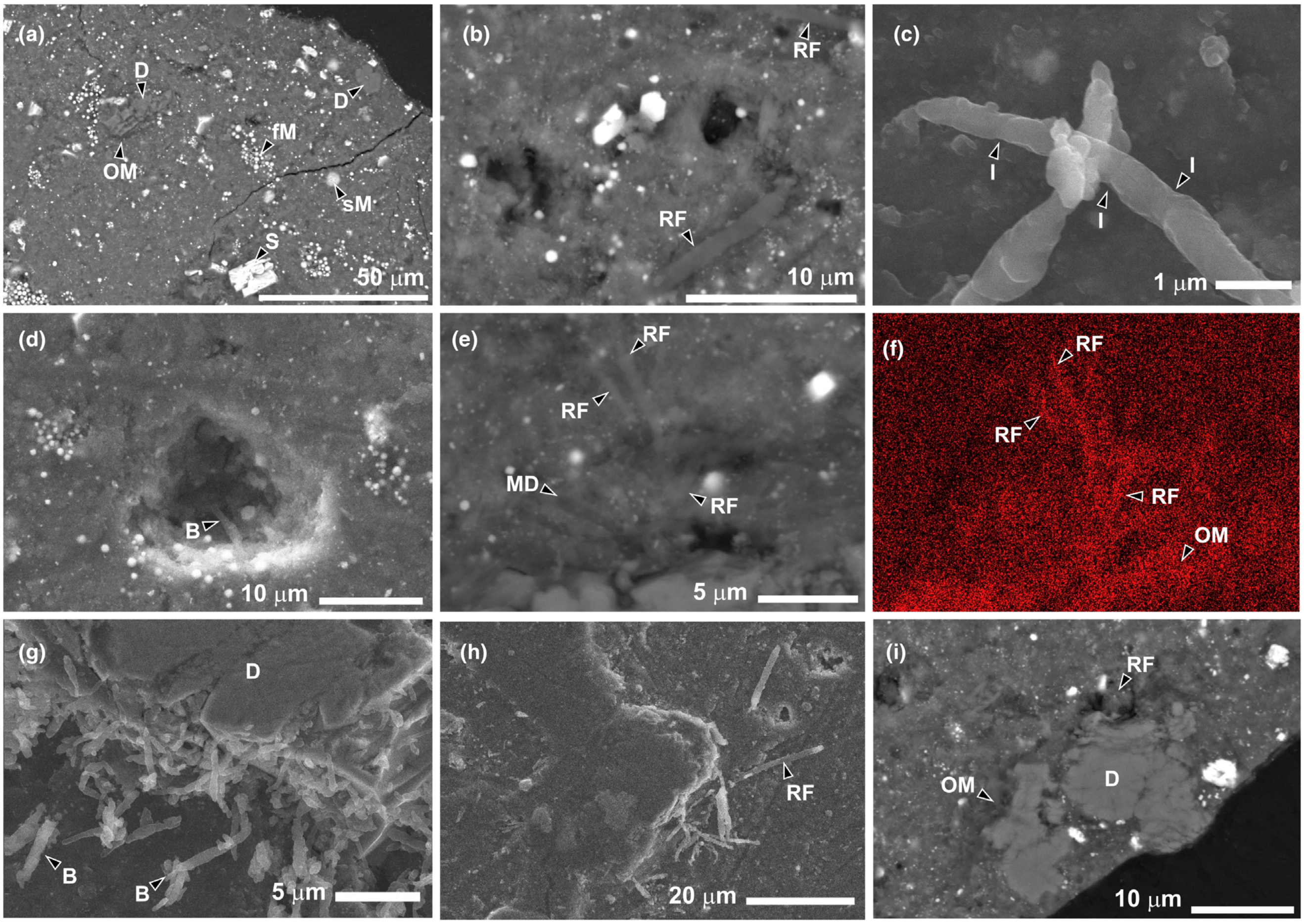

FIGURE 1. Electron microscope images of sample A0180. (a) A backscattered electron image (BEI) showing a matrix dominated by phyllosilicate with framboidal (fM) and spheroidal (sM) magnetite, dolomite (D), and sulfide (S). Areas containing abundant organic matter (OM) are present. (b) A BEI of rods and filaments (RF) on the surface of the specimen. (c) A secondary electron image (SEI) showing the detailed morphology of filaments with indents denoting individual cells. (d) A SEI of the cavity shown containing an organic rod structure. (e) A BEI showing cluster of rods and filaments around a dolomite grain. A cylindrical mold (MD) is also present. (f) A carbon Kα map of the image shown in e illustrating that filaments are carbon-rich (RF) and showing a C-rich rim on the dolomite grain. The contrast of the map has been enhanced using a linear filter. All pixels with an intensity of >50% are saturated (g) A secondary electron image showing highly elongate filaments. (i) A BEI of a dolomite grain surrounded by matrix containing abundant organic matter. A cluster of filaments is also present. Images were obtained on the November 11, 2022 (a–d), November 30, 2022 (g, h), and the January 14, 2023 (e, f).

specimen, no rods or filaments were subsequently observed over a period of 4 months.

A survey of common fibers in the laboratory environment was performed, including human hair, fibers from clothing, laboratory wipes, and polishing pads, to compare with the observed RF-OM (Figure 3). Hair had much larger dimensions than the RF-OM. The smallest fibers were derived from wipes and polishing pads and had similar widths to the observed RF-OM. All fibers, however, had significantly larger length to width ratios (>50), with thin fibers having highly sinuous morphologies. All the examined fibers have irregular terminations rather the smooth rounded forms of the RF-OM.

DISCUSSION

Identification of Microorganisms

Definitive identification of microorganisms by DNA extraction, amplification and sequencing was not attempted, given the low number of putative organisms detected on the sample and the difficulty of extraction after carbon-coating of the specimen. Numerous previous studies have, however, reported microorganisms within chondritic meteorites on the basis of morphology by scanning electron microscopy (Hoover, 2011; Hoover et al., 1998, 2018; Steele et al., 2002). A wide range of morphological forms have been identified with

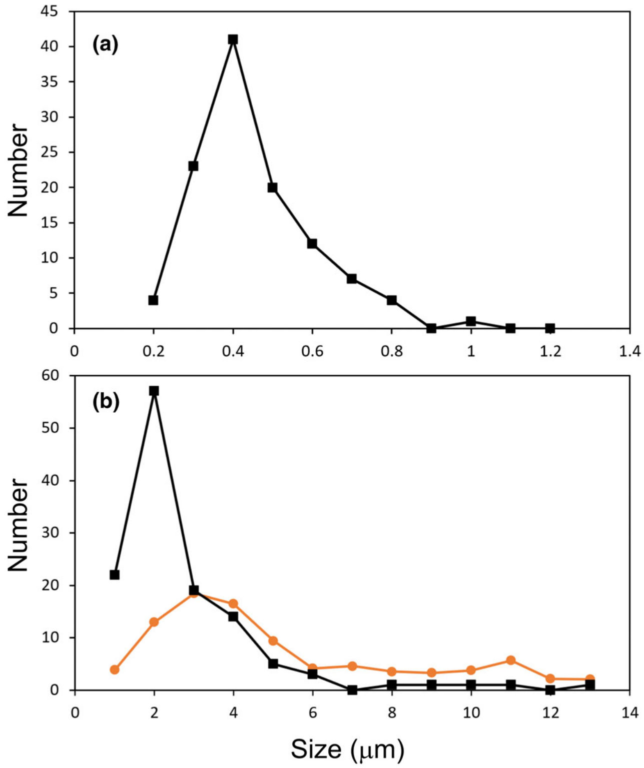

FIGURE 2. The size distribution of microorganisms showing (a) maximum width and (b) length. Size bins show the maximum value. There were four filaments longer than 13 μm with the largest 18 μm. The measurements were taken on the November 30, 2022, 26 days after polishing. A filament length size distribution for a single population of cultivated Bacillus subtilis is shown as circles. Data are from Liu et al. (2022) and its abundance is in percent.

filamentous shapes commonly reported. Numerous types of bacteria, archaea and fungi have been suggested from these morphologies including cyanobacteria (Hoover, 2011). However, many of these identifications are controversial.

Several properties of the RF-OM observed in sample A0180 are consistent with prokaryote microorganisms. Firstly, they have broadly cylindrical carbonaceous structures with sizes in the range of terrestrial organisms (Portillo et al., 2013), indeed their log-normal size distribution is compatible with a population dominated by a single species (Portillo et al., 2013; Teimouri & Mukherjee, 2020). This differs from the structures reported on Martian meteorite ALH84001, which were significantly smaller than terrestrial organisms at <0.08 μm (McKay et al., 1996), and are now thought not to have been microorganisms (Steele et al., 2022). Secondly, rod and filamentous morphologies observed in sample A0180 are common amongst microorganisms, and although not specific to a particular genus, the bacteria Bacillus is arguably the commonest example within soil and water (Vijaypayal et al., 1998). As an ecological generalist Bacillus readily colonizes new ecological niches (Xu et al., 2022) making it a plausible invasive colonizer of extraterrestrial specimens. The presence of both rods and filaments within sample A0180, furthermore, do not preclude a single species population, since the filamentous form can also be an adaptation to local environmental stress (Rai et al., 2008; Wolf et al., 2013) meaning individuals in the population can vary. The occurrence of one filament in A0180 composed of separate short rods surrounded by a sheath is, furthermore, suggestive of cell division (Figure 1c) and is thus consistent with microbial growth. Finally, the occurrence of RF-OM in the vicinity of organic mantles around carbonates and within cavities is compatible with heterotrophic organisms. Previous studies of the organic matter within Ryugu have shown the presence of aliphatic and aromatic hydrocarbons (Nakamura et al., 2022), together with small amounts of the amino acids uracil (Oba et al., 2023), N,N-dimethylglycine, β-alanine, and β-glycine (Potiszil et al., 2023). Many heterotrophic prokaryotes are capable of metabolizing a wide range of organic compounds.

Observation of cell division and growth are a viable means of identifying an extant microbial organism, either through the growth of cultures or microscopy. The change in the abundance of RF-OM with time in sample A0180 likewise testifies to the growth of a microbial population that is not consistent with other forms of abiotic organic contamination. The observation of an initial increase in the population of RF-OM from 11 to 147 individuals is consistent with the log-growth phase of microorganisms and gives a maximum generation time of 5.1 days (calculated using Equation 1). This value is much larger than the 120 min observed for Bacillus subtilis 168 under ideal closed system conditions (Burdett et al., 1986). Under stressed conditions, however, Bacillus subtilis growth is significantly less, with values of 6.6 days derived during continuous low-pressure conditions at 5 kPa, with only partial recovery of generation time occurring on equilibration to atmospheric pressure (Nicholson et al., 2010). Considering exposure to low pressures of 30 Pa for periods of a few hours during SEM analysis, the generation time observed here is thus in the range measured for this genus, although this provides no real diagnostic information since many microorganisms have similar generation times. The final decrease in the population reported here to 36 individuals over a longer period could be interpreted as the cell death stage, which is typical of microbial populations in a closed system. The disappearance of dead cells might be explained by cannibalism, which has been reported for sporulating Bacillus subtilis (González-Pastor, 2011), especially in single species populations (Nandy et al., 2007). Significantly, the change in the abundance of RF-OM with

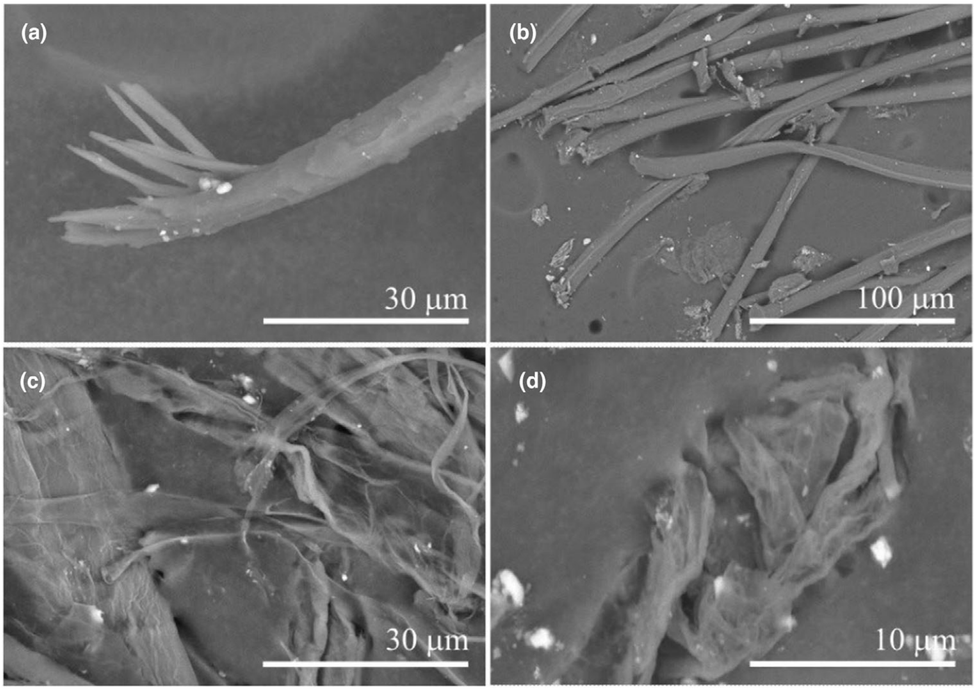

FIGURE 3. Backscattered electron images of fibers that could be potential contaminants. (a) Human hair, with split ends. (b) Cotton fibers. (c) Fibers in lab wipes. (d) Fibers in polishing pads. Note that the fibers vary significantly in scale with the smallest in wipes and polishing pads having similar widths to the observed RF-OM. All fibers have significantly larger length to width ratios, with thin fibers having highly sinuous morphologies. All the examined fibers have irregular terminations rather the smooth rounded forms of the RF-OM.

time is not consistent with an origin as an abiotic precipitate since no re-appearance of the RF-OM occurred after repolishing of the specimen, despite exposure to the same environmental conditions. The abundance of RF-OM is, therefore, strong evidence for their microbial identity and suggests serendipitous culturing of microorganisms on a space-returned sample.

$$\text{Doubling time} = \frac{\text{Duration.ln}(2)}{\left(\ln\left(\frac{\text{Final Concentration}}{\text{Initial Concentration}}\right)\right)} \tag{1}$$

Contamination and Colonization

The change in the population of microorganisms over the course of 64 days suggests the sample was contaminated with microorganisms during the preparation of the polished block. Indeed, the sterile handling and storage under which the sample was kept from its return to Earth (Yada et al., 2022) until it was removed from a nitrogen atmosphere, immediately prior to XCT analyses, makes it highly unlikely it was contaminated prior to sample preparation. The possibility that the sample contained indigenous spores is also unlikely since only a small number of microorganisms were initially present despite the 280 days it had spent at ambient temperature since the return of Hayabusa 2. The nitrogen atmosphere, in which the sample was stored during this time, can be a bactericide for some, but not all, Bacillus species owing to the reduced water activity associated with the dry atmosphere (Munsch-Alatossava & Alatossava, 2014). The bactericidal effects of such atmospheres are not restricted to Bacillus, and thus provides no diagnostic information. Any indigenous microorganism, nevertheless, would have either grown or would have been killed during storage. The absence of RF-OM within the specimen prior to sample preparation is also suggested by the Nano-XCT data, albeit with uncertainty owing to resolution. Likewise, the lack of reappearance of microbes after repolishing the specimen also suggests the microorganisms had colonized only the exposed surface, and to no more than a few microns depth. Finally, the log-normal size distribution suggests contamination by a single spore or organism since it is consistent with a population dominated by a single species.

The presence of microorganisms on a space-returned sample that had been subject to highly sterile storage and handling protocols (Yada et al., 2022) emphasizes the sensitivity of organic-rich extraterrestrial samples to contamination by terrestrial microbiota. Even minimal exposure to the terrestrial environment under relaxed contamination control can result in contamination. Rock preparation laboratories may be locations where such contamination is more likely than elsewhere owing to the proximity of non-sterile samples that may already have biota adapted to cryptoendolithic and/or soil environments. Filamentous morphology is indeed common amongst soil bacteria since it enables microorganisms to span pore space (Karasz et al., 2022) and may assist in invasive colonization.

The colonization of extraterrestrial samples by microbes has been shown to be possible through experimental culturing on carbonaceous chondrites (Roy, 1935). For microorganisms to survive within these meteorites they will need to create micro-environments through access to redox sensitive elements, such as carbon, sulfur, and iron, which can be used for metabolism and/or biomass production. They also require a source of bioavailable water. Hygroscopic minerals such as sulfates, halides, perchlorates, carbonates, Fe-oxyhydroxides, and smectites adsorb films of water to crystal surfaces and can accommodate H_2O within their crystal structures. Films of water are also enriched in mineral components and organic material, which may account for sufficient nutrient supply. Irregularities on a polished surface enhance absorption consistent with the observation that RF-OM were commonly observed within irregular cavities. Soil nutrient analysis of the Murchison CM2 chondrite, showed that there were biologically available levels of essential inorganic macronutrients, such as S, P, Ca, Mg, and K, and major micronutrients, Na and Fe, and a cation exchange capacity comparable with terrestrial agricultural soils (Mautner et al., 1997).

In sample A0180 conditions are likely to have been challenging for microbial colonization. The carbon-coat applied to the specimen will have acted as a barrier minimizing water absorption and forcing the organisms to exploit the meteoritic substrate for survival. How long the meteoritic material could support organisms will depend upon their access to the external environment. However, regular exposure to hard vacuum and an electron beam for periods of several hours will have caused additional stress, particularly owing to desiccation. That the organisms continued to grow, at least for the first 19 days, is a testament to their resilience and consistent with studies that show bacterial resistance to vacuum and irradiation (Saffary et al., 2002). Nevertheless, the small size of the population and its ultimate decline are likely to have been influenced by the challenging conditions presented by the nature of the specimen.

IMPLICATIONS

Previous studies have identified a variety of microorganisms within meteorites (Benzerara et al., 2010; Steele et al., 2002; Tait et al., 2022). Some studies have argued that microorganisms were indigenous (Hoover, 2011; Hoover et al., 1998, 2018; Rozanov et al., 2021) and thus imply that living organisms could be present on asteroids. Evidence such as the location of microbes on freshly broken surfaces, or recovery of a meteorite as a recent observed fall, are often cited to support an indigenous origin by inferring the samples had minimal opportunity for contamination. Studies of the weathering of meteorite falls, however, reveal that even those collected rapidly have experienced alteration in the terrestrial environment with the appearance of calcium oxalates reported in the Winchcombe meteorite (Jenkins et al., 2023). Such observations might relate to colonization since this material is secreted by some fungal hyphae (Arnott, 1995). While colonization of meteorite finds has previously been shown to occur (Benzerara et al., 2010) these samples have been exposed to the terrestrial environment for extended periods. The observation of terrestrial microorganisms within sample A0180 from Ryugu is thus important owing to its hermetic storage, which emphasizes that contamination can occur even with careful precautions, even with minor exposure to the terrestrial environment.

The occurrence of fossilized rather than extant microbes in carbonaceous chondrites has been suggested as evidence for an extraterrestrial origin (Hoover, 2011; Hoover et al., 1998, 2018; Rozanov et al., 2021). The absence of nitrogen Kα peaks in energy-dispersive X-ray spectra has been proposed as evidence for fossilization. In this study no nitrogen Kα peaks were observed in energy dispersive spectra (EDS) despite the extant nature of the microorganisms, and the use of a windowless solid-state detector sensitive for elements lighter than carbon. The absence of nitrogen in EDS analyses, therefore, is poor evidence for fossilization. Experimental studies in any case have shown that microorganisms can be fossilized in less than 24 h under favorable conditions (Toporski et al., 2002).

The occurrence of living microorganisms on asteroids at some stage in their history is implausible, but not impossible. Although most carbonaceous chondrites have mineralogies that testify to alteration by liquid water, this occurred early in their histories as a result of the melting of ice by heat generated by the decay of short-lived radionuclides (Alexander et al., 2018). Water is unlikely to have existed longer than ~3 million years on such objects (Alexander et al., 2018)—a period of time that minimizes the opportunity for biological evolution of prokaryotes from the first self-replicating organism. If indigenous extraterrestrial organisms were discovered in an asteroid it would, therefore, have profound implications for the timescales of the origins and evolution of life. Furthermore, it would imply that life could be delivered to the surface of all the terrestrial planets by primitive impactors. Considering the profound nature of these implications exceptionally strong evidence would be required to demonstrate the indigenous nature of microorganisms in asteroid materials, which the current study suggests is highly likely to be compromised by the potential for contamination.

The rapid colonization of a Ryugu sample by terrestrial organisms also poses some significant issues for the analysis of extraterrestrial samples. Microbes can cause chemical and isotopic changes in the primary nature of a sample in both its organic and inorganic material (Tait et al., 2022). Furthermore, more than 50 minerals are known to be precipitated by microorganisms (Hoffmann et al., 2021), including organic films, producing structures that might be interpreted as produced abiotically in the early solar system. The potential for microbial contamination is thus a significant issue for current sample return missions such as NASA OSIRIS-REx (Lauretta et al., 2017), and future missions to a wide range of Solar System bodies.

Given the high quality of Ryugu curation procedures prior to sample preparation (Yada et al., 2022) the occurrence of microorganisms in sample A0180 indicates that colonization can occur very rapidly after exposure to the terrestrial environment. Sample preparation presents a particular risk owing to the presence of other samples, which may host microbial communities. The risks are, however, low since routine preparation of meteorite specimens does not commonly result in microbial colonization. Contamination nevertheless can occur as a result of a single organism or spore.

Several procedures can be used to minimize the likelihood of colonization. Preparation of thin sections in an area separate from terrestrial samples is recommended. Storage of samples in a dry inert atmosphere, such as nitrogen, provides a means of inhibiting microbial population growth simply through the minimization of adsorbed water. Direct observation of samples by scanning electron microscopy is also shown to be effective in identifying the presence of extant microbial communities, through analysis of their population statistics. No other microorganisms have been reported on Ryugu samples, emphasizing the low, but non-zero chance of contamination. Importantly sample A0180 suggests penetration of microorganisms into only the upper few microns of a polished surface, giving confidence that contamination can be removed.

Finally, the presence of microorganisms in sample A0180 has interesting implications for astrobiology since it emphasizes that some heterotrophic organisms can readily metabolize organic matter from primitive meteorites. While on present day Earth such meteorites are rare and comprise an exceedingly small proportion of organic matter available to microorganisms, in other regions of the Solar System, extra-planetary organic matter may be comprise a significant proportion of the organic matter inventory. This may be particularly true where the flux of meteorites and extraterrestrial dust to the surface is higher than on Earth. On Mars, for example, the extraterrestrial flux is thought to be several hundred times larger than on Earth, and micrometeorites survive atmospheric entry with less heating preserving some of their organic components (Wilson et al., 2019). Even on Earth extraterrestrial organic matter may have been important during periods of extensive ice cover, such as during the Cryogenian glaciations of the Neoproterozoic (Hoffman et al., 1998). The rapid colonization of Ryugu sample A0180 by terrestrial organisms suggests that extra-planetary organic matter could allow the survival of microbial life on the surface of other planets and sustain ecosystems in environments where indigenous metabolic energy sources are scarce. Thus, both inbound and outbound missions to celestial bodies should be reassessed for contamination control and planetary protection procedures.

CONCLUSIONS

The presence of filaments of organic matter are reported on a space-returned sample of carbonaceous asteroid Ryugu. The size and morphology of these filaments is consistent with microorganisms, in particular the bacteria Bacillus. The population of filaments was observed to change over the course of several months indicating they were an extant colony. The long generation time, and growth and cell death stages of the bacterial life cycle suggest organisms under severe stress and strongly suggest these organisms are terrestrial contaminants. The removal by polishing and lack of reoccurrence of filaments confirms their terrestrial origin and implies contamination of only the upper few microns of the surface. The presence of terrestrial microorganism within a sample of Ryugu underlines that microorganisms are the world's greatest colonizers and adept at circumventing contamination controls. The presence of microorganisms within space-returned samples, even those subject to stringent contamination controls is, therefore, not necessarily evidence of an extraterrestrial origin.

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Data Availability Statement—The data that support the findings of this study are available from the corresponding author upon reasonable request.

Editorial Handling—Dr. Scott Sandford

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