Instruments and Methods to Search for Extraterrestrial Life

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ABSTRACT

Is Life restricted to the Planet Earth? or *Does life exist elsewhere in the Cosmos?* The existence of extraterrestrial life is the fundamental question of Astrobiology. Detecting evidence for living organisms beyond our planet is even more difficult finding evidence of fossilized remains of ancient biology. Microbiological investigations during the past century have established the fundamental physical and chemical requirements and limits for life on Earth. It is now known that life requires only water, a source of energy and a small suite of biogenic elements under a surprisingly wide span of environmental conditions. The discovery that microbial extremophiles live and grow over a very broad range of temperature, pH, salinity, pressure and radiation levels has greatly enhanced the possibility that life may be present on many bodies of our Solar System. Recent discoveries by Space Missions, Landers and Rovers have invalidated many long held paradigms regarding the distribution of water, organic chemicals and the possibility of life elsewhere in the Cosmos. This paper considers the discovery of water, ice and organics on distant planets, icy moons and comets and evidence for fossil organisms on Mars and in SNC and carbonaceous meteorites. Instruments and methods for using spectroscopy and fluorescence to remotely detect photosynthetic pigments for remote detection of conclusive evidence for extraterrestrial life is advanced. Optical Video Microscopy is discussed for direct means detection of extraterrestrial life with a small Optical Video Microscope with sufficient magnification to observe living organisms in samples collected by Rovers or Landers. Locomotion of living, swimming cells of bacteria, algae, diatoms or other microorganisms requires great expenditure of energy and can be readily distinguished by video microscopy from the movements (caused by Brownian Motion or Current Drift) of dead cells, dust particles or abiotic mineral grains.

Keywords: Extraterrestrial Life, Astrobiology, Microfossils, Meteorites, Orgueil, Polonnaruwa, Viking, Mars, Comets, Icy Moons

1. INTRODUCTION

In order to carry out metabolism, all living organisms on Earth have an absolute requirement for water, energy and a small group of biogenic elements. The coexistence of these necessary components is essential for the organism to build proteins, DNA, RNA, ATP and all other life-critical biomolecules needed for growth, the replication of new cells and motility. However, the absence of these components does not mean that a living organism will necessarily die. Complete cells or spores can remain alive for great periods of time in the absence of water, energy and new biogenic elements. Microorganisms can remain alive while desiccated for several hundred million of years encased within salt crystals in the total darkness of deep salt mines.[1-3] Bacteria and a host of other living cells can be preserved by lyophilization.[4] During the lyophilization process, the cells are exposed to hard vacuum and extremely low (<-50 ^{o}C) temperatures. These conditions are such as would be encountered in deep space or on the surface of a comet, asteroid or icy moon. Bacteria, algae and higher plants (e.g., moss) can also survive for thousands to millions of years while cryopreserved in glaciers or frozen in permafrost.[5-8] Under these conditions many of the cells appear to be in a state of deep anabiosis and may possibly be carrying out very slow metabolism to repair DNA or cell damage.[9,10] In thin films between ice and mineral grains within permafrost or in cryopegs and brines when salts are present, water remains in liquid state at temperatures far below zero. Don Juan Pond in the Wright Valley of Victoria Land, Antarctica is supersaturated calcium chloride brine with 474 g/l of total dissolved salts. It has a freezing point of -48 ^{o}C and pH 5.4. Diatoms and colonial microorganisms rich in carotenoids along with *Oscillatoria* and other cyanobacteria have been found growing in this frigid, hypersaline environment.[11,12] Novel bacteria and archaea have been isolated from tidal pools of Southern Patagonia and the super cooled water brines of cryopegs deep beneath the Siberian permafrost. [13-17]

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Several groups of prokaryotic and eukaryotic microorganisms live and grow in saltpans and other hypersaline environments.[18-20] The eukaryotes include species of pennate diatoms (e.g. *Achnanthes hauckiana, Pseudonitzschia seriata, Pleurosigma salinarum, Amphora* sp. and *Nitzschia* sp.) and centrics (e.g. *Cyclotella striata* and *Thallassionema eccentrica*). In 1975, while preparing an X-ray Telescope for launch, I found a shallow crystal clear hypersaline pool in the Woomera Rocket Range in the desert of South Australia.[21] Very large salt crystals cast shadows on the bottom of the pool and a thin golden brown film floated on the surface. Optical microscopy revealed the film was composed of diatoms, primarily of species of *Pleurosigma and Synedra*. The diatoms were living as they exhibited both motility and chromatophores, which are the chlorophyll containing photosynthetically active organelles of diatoms. The graceful curving swimming motion of members of the genus *Pleurosigma* is very distinctive and made it possible to immediately recognize that these diatoms were alive rather than just dead shells.

All living organisms need energy to carry out metabolism, growth, replication and a host of other life-critical biochemical processes. Photoautotrophs use light photons as the energy source to perform carbon fixation - the process by which inorganic carbon atoms from atmospheric CO_2 molecules are converted into organic carbon compounds by way of the complex metabolic pathways associated with the process of photosynthesis. The oxygenic photosynthesis process was first described by Calvin and Benson[22] and is now known as the Calvin Cycle. In the Calvin Cycle the enzymes, proteins and chlorophyll pigments found in the stroma of chloroplasts use the energy of sunlight to produce sugars and other carbohydrates and release oxygen from water and CO_2. In the first stage of this process the Ribulose-1,5-Biphosphate Carboxylase/Oxygenase enzyme (RuBisCO) incorporates carbon dioxide into the five-carbon sugar ribulose biphosphate (RuBP). The life-critical RuBisCO biomolecule is possibly the most abundant protein on Earth. It is present in the chloroplasts of diatoms, cyanobacteria, algae and most other plants. Adenosine triphosphate (ATP), which is the coenzyme that serves as the energy carrier in all living cells, is the energy conveyor and NADPH is consumed as the reducing power to add high energy electrons in the last step of the electron chain. The light reactions provide the energy for this complex process of oxygenic photosynthesis during which sugars are produced from atmospheric carbon dioxide. Other autotrophic carbon fixation cycles are known in living organisms, including the Arnon-Buchanan Cycle, which is a reductive citric acid or reverse Krebs cycle that occurs within anoxygenic photosynthetic bacteria (e.g.,green sulfur bacteria *Chlorobium thiosulfatophilum*)[23,24] and the Wood-Ljungdahl reductive acetyl Co-A pathway that is found in anaerobic and microaerobic Archaea and Crenarchaeota.[25]

Chemotrophic microorganisms can acquire energy by the oxidation of electron donors in their environment and perform carbon fixation in total darkness. Chemoautotrophs obtain the energy needed to fix carbon by reactions using sources such as molecular hydrogen, methane, hydrogen sulfide, elemental sulfur, ammonia, ferrous iron, etc. Carbon dioxide molecules can be broken up to make organic biomolecules with Oxygen released as a by-product. Most chemoautotrophs are extremophilic archaea and bacteria (e.g., thermoacidophiles, halophiles, methanogens, sulfur oxidizers, sulfur reducers) that inhabit deep crustal rocks and hydrothermal vents. Chemoorganotrophs obtain carbon and energy by consuming organic molecules as food. Chemolithotrophs extract carbon and energy from inorganic molecules.. Chemoheterotrophs are unable to fix their own carbon, but can obtain energy from sulfur or other inorganic sources or from organic sources such as lipids, proteins or carbohydrates. Organotrophs obtain energy and biomolecules by consuming organic matter manufactured by metabolic process within cells of a wide variety of other living organisms.

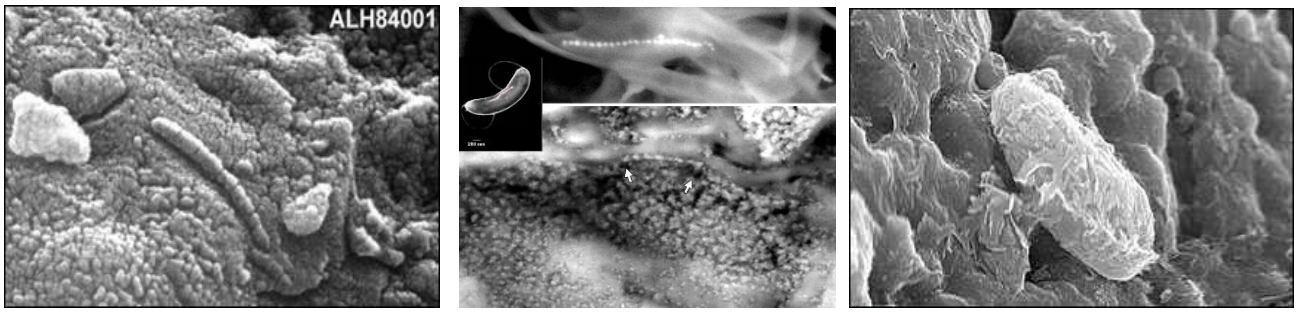
All known living organisms on Earth require a small group of approximately 20 “biogenic elements ” to construct all needed biomolecules. Six major biogenic elements (C, H, O, N, P and S) are absolutely essential to life and comprise >97% of all matter in living cells. Most abundant are C, H and O as they are present in all water and carbohydrates, and N is found in all amino acid and protein molecules in every cell. Although Nitrogen comprises almost 78% of our atmosphere, it cannot be used by living organisms until fixed. Atmospheric nitrogen is in diatomic nitrogen (N_2) molecules with the two N atoms held together by a strong triple bond. The N_2 molecule is a relatively inert and useless to life until converted to ‘organic nitrogen’ by the process of nitrogen fixation.[26] Biological Nitrogen Fixation (by far the dominant mechanism for nitrogen fixation on Earth) occurs when cyanobacteria or other microbes break the strong triple bond and reduce the inorganic N_2 molecule to molecules such as ammonia, nitrates, or nitrogen dioxide. Cyanobacteria play the dominant role in nitrogen fixation on planet Earth, typically achieving it by use if the nitrogenase enzyme which is present in the heterocysts of *Calothrix, Anabaena, Cylindrospermun, Nostoc* and many other genera of heterocystous cyanobacteria.[27] Phosphorus and sulfur are present in cells in smaller quantities. But phosphorus is essential for DNA, RNA, ATP, NADP and many life-critical proteins and enzymes. Sulfur is essential for some amino acids (methionine and cysteine) and hence a key component of many proteins. Five Minor Biogenic Elements (Ca, Cl, Mg, K, Na) that are

also life-critical but are found in cells in relatively small quantities. Trace biogenic elements (e.g., Si, Mn, Fe, Cu, Zn, As, Ni, I and V) are found in small quantities but needed for many essential chemical reactions and metabolic pathways.

Spectroscopy of stars, galaxies and giant molecular clouds and meteorite analysis has revealed that water is the most abundant compound in the Universe and that all life-critical biogenic elements are widely distributed throughout the Cosmos. The discovery of the wide distribution of life on Earth and the diversity of mechanisms and pathways that microorganisms use to obtain energy and fix carbon and nitrogen needed to manufacture life-critical biomolecules has greatly expanded the range of habitable environments in other bodies of the Solar System. These discoveries invalidated many long held paradigms accepted by scientists for reasoning that life on Earth is unique and thus evidence for extinct or extant extraterrestrial life represents an "*extraordinary claim"* for which "*extraordinary evidence*" is demanded.

2. PARADIGMS LOST

The concept that *"An extraordinary claim requires extraordinary proof"* was introduced in 1978 by Marcello Truzzi, the skeptic who founded the Committee for Scientific Investigations of Claims of the Paranormal.[28] Carl Sagan[29] altered the phrase to: "*Precisely because of human fallibility, extraordinary claims require extraordinary evidence"* in the February 27, 1996 NOVA PBS Program while discussing Claims of Alien Abductions and the Sagan Maxim seems to have entered the lexicon of mainstream science soon thereafter. In August, 1996, McKay *et al.*[30] reported that independent observations revealed that possible nanofossils **(Fig. 1.a)** were found in close proximity to biomarkers (PAH's, carbonate globules and magnetite grains) in the Mars meteorite ALH84001. They interpreted these results as providing evidence for relic biogenic activity on ancient Mars. This landmark paper triggered the initiation of the NASA Astrobiology Program, which then established "Virtual Astrobiology Institutes" to study the limits of life on Earth and the origin and distribution of life in the Universe. However, soon after the Astrobiology Program was established, the ALH84001 paper came under severe criticism. The Sagan Maxim "*Extraordinary claims require extraordinary evidence"* was so often repeated by scientists in conferences and papers in an effort to dismiss and discredit all reports of evidence for biomarkers and microfossils in the Mars meteorite (ALH84001) and carbonaceous chondrites that it became a common way of thinking of many Astrobiologists.[31] Many scientists accepted the premise that any evidence for past or present life on Mars or in SNC or carbonaceous meteorites would be truly "extraordinary" and the demand for "extraordinary proof" was so often repeated it became a paradigm. They failed to recognize that where, how and when life originated is unknown. No scientific evidence exists to support the underlying hypothesis that life of Earth originated *de novo* on ancient Earth. Furthermore, it is now known that H_2O (in liquid or solid state), biogenic elements, organic chemicals and energy sources exist on comets, icy moons and all planets (even Mercury and Pluto) of our Solar System. This paradigm became so firmly entrenched within the scientific community that when additional data and biosignatures in ALH84001 and Nakhla meteorites from Mars, the new evidence was still dismissed as from modern biological contaminants. The new observational data from Mars meteorites included distinctive and unique microbiological and mineralogical biosignatures such as truncated hex-octahedral magnetite grains[32] and magnetosomes in "chain of pearls" configurations.[33]



a. **b.** **c.**

Fig. 1.a. Putative nanofossils in ALH84001 and **b.** "chain of pearls" magnetosomes aligned in images at top of terrestrial bacterium *Magnetospirillum magnetotacticum*[33] and between the arrows in image from the Mars meteorite ALH84001; **c.** FESEM image of possible larger microfossil in the Nakhla SNC meteorite from Mars.

The "chain of pearls" magnetosomes are seen aligned in the image of the banana shaped terrestrial magnetotactic bacterium, *Magnetospirillum magnetotacticum*, **(Fig. 1.b** upper left and top**)** and in the image at the bottom of the "chain

of pearls" magnetosomes shown between the arrows in the Mars meteorite ALH84001. Larger microfossils were also found in the Nakhla meteorite from Mars **(Fig. 1.c)**[34,35] but these results were dismissed as controversial and not constituting sufficiently "extraordinary evidence."[36]

While the Truzzi maxim as adapted by Carl Sagan may be entirely appropriate while considering claims of supernatural or paranormal matters, ghosts or alien abductions it has absolutely no place in physics, chemistry, paleontology, meteoritics or any of the hard sciences. Who determines when an observation or measurement constitutes an "Extraordinary Claim" and what qualifies as the required "Extraordinary Evidence"? Evidence is evidence and no case of "extraordinary evidence" has ever been presented that satisfies the nebulous and arbitrary "extraordinary proof" requirement. Science must be concerned only with the objective study of natural phenomena and the introduction of an undefined requirement shifts science into the subjective realm. Therefore this politically correct subjective paradigm should be rejected as junk science as it is adverse the objective study of natural world and detrimental to the Science.

3. EVIDENCE FOR WATER AND LIFE ON MARS

3.1. Evidence for Water on Mars

Norman Horowitz was the first person to argue that there could be no life on Mars because there was no liquid water on the Red Planet: *"Viking found no life on Mars, and just as important, it found why there is no life on Mars…it is devoid of any liquid water whatsoever."*[37] The "*Mars is bone dry*"[38] paradigm was often advanced as one of the major objections to any evidence for past or present life on the red planet. This paradigm became so widely accepted by the scientific community that soon after the ALH84001 results were announced, the NASA Mars Exploration Program adopted the mantra *Follow the Water.* [39] It was argued that since water is essential for life, evidence for life required finding if water ever existed on Mars. This position was indeed strange as it has long been known that water exists on Mars. The Mariner 9 Mars Orbiter returned images **(Fig. 2.a)** in 1971 showing ancient dry riverbeds or arroyos on Mars. In 1976, the Viking Orbiters imaged water ice and snow at the North Polar Cap **(Fig. 2.b)**. The Spokane Daily Chronicle reported a white substance was imaged by Viking 2 Lander Camera. Kenneth Jones of the Lander Camera Team interpreted it as carbon dioxide frost: "It is unlikely to be water ice, because there doesn't seem to be enough water in the atmosphere at that latitude to produce it." The first direct evidence for liquid water on present-day Mars was obtained by Viking 2. Moore et al.[40] reported that on Sol 41 at 14.21 (local lander time), the soil temperature rose to 273 degrees K (the melting point of water ice), and *did not rise above that* during the subsequent "10-minute or more" measuring interval. As Levin[41] pointed out, nothing else behaves this way but ice melting to liquid water. Furthermore, the fact that the observed melting point of the ice was 273K constitutes observational proof that it was virtually pure water ice rather than frozen brine as many have suggested. If salts had been present, then the melting point would have been lower than 273 K (still in a range monitored by Viking). The phase change temperature at which a compound changes from solid to liquid phase (defined as the melting point) is a distinctive characteristic of the compound. However, this evidence for liquid water contained within the Viking measured data was ignored. NASA used the purported absence of water at the Viking Lander site as one of the primary reasons why life could not have been detected on Mars.

On May 18, 1979, the camera at the Viking 2 Lander Site (48N, 226W) produced a dramatic color image (23I1093) using red, green and blue filters **(Fig. 2.c)**. Many images were obtained showing white substance on rocks near the Lander. NASA called the observations "*frost monitoring*" and was widely assumed to be CO_2 frost rather water (H_2O) snow. However, the measured detector temperature was -18.1 ^oC. It was well known at the time the images were obtained that it is physically impossible since dry ice (solid CO_2) sublimes to CO_2 gas at -78.5 ^oC. The absence of the white material on vertical surfaces indicates this is water snow or sleet (freezes in the atmosphere and falls to the surface) rather than water frost (condenses from the atmosphere and freezes on cold surfaces). This color image was obtained by NASA in 1979, but not released publicly until 1997 when it appeared on the NASA poster: "*Postcards from Mars*".[42] This beautiful image showing frozen water on the Mars surface is profoundly important to Astrobiology and should have been widely reported during the Mission rather than released two decades later. **Figure 2.d** from the NASA Mars Orbiter Laser Altimeter data shows the 3-D configuration of the water ice-rich *Planum Boreum* deposit at the North Polar Cap of Mars. The SHallow RADar SHARAD instrument revealed this dome contains approximately 1.3 million km^3 of high purity (95%) water ice. Furthermore, the South Polar Layered Deposits and contain even more (~1.6 million km^3) of nearly pure water ice.[43] This represents an enormous amount of water present today on the surface of Mars and a program seeking to discover whether or not water ever existed on Mars is not necessary.

Studies in the polar regions of Earth have shown that solar heating of dark rocks entrained in glaciers can cause melting and produce cryoconite ecosystems sealed within the ice. Microbial ecosystems might be able to inhabit the polar ice and permafrost of Mars. Deep crevasses in the Mars North Polar Cap (**Fig. 2.d)** are consistent with moulins that carry meltwater deep within glaciers on Earth. **Figure 2.e** is a Mars Global Surveyor (MOC2-150) image showing polygonal patterned ground in the floor of an old impact crater at 86 ^{o}N.[44] In1998, Paepe *et al.*[45] and Hoover *et al.*[46] interpreted the double rimmed polygons on Mars as providing evidence of present day liquid water. Sorted patterned ground polygons are characteristic periglacial features often found in the polar regions of Earth.[47,48] Double rimmed polygons with low centers are formed over very long periods of time by the repetitive seasonal freeze/thaw cycles in subsurface ice. Thermal expansion and contraction of ice wedges produce these features on the periphery of glaciers in Earth's polar regions (**Fig. 2.f).** Double rimmed polygons and ice wedges were investigated by Roland Paepe in the Taylor Valley of Antarctica[47] and by Hoover in the Fox Permafrost Tunnel of Alaska and the Kolyma Lowlands of North Siberia.[49]

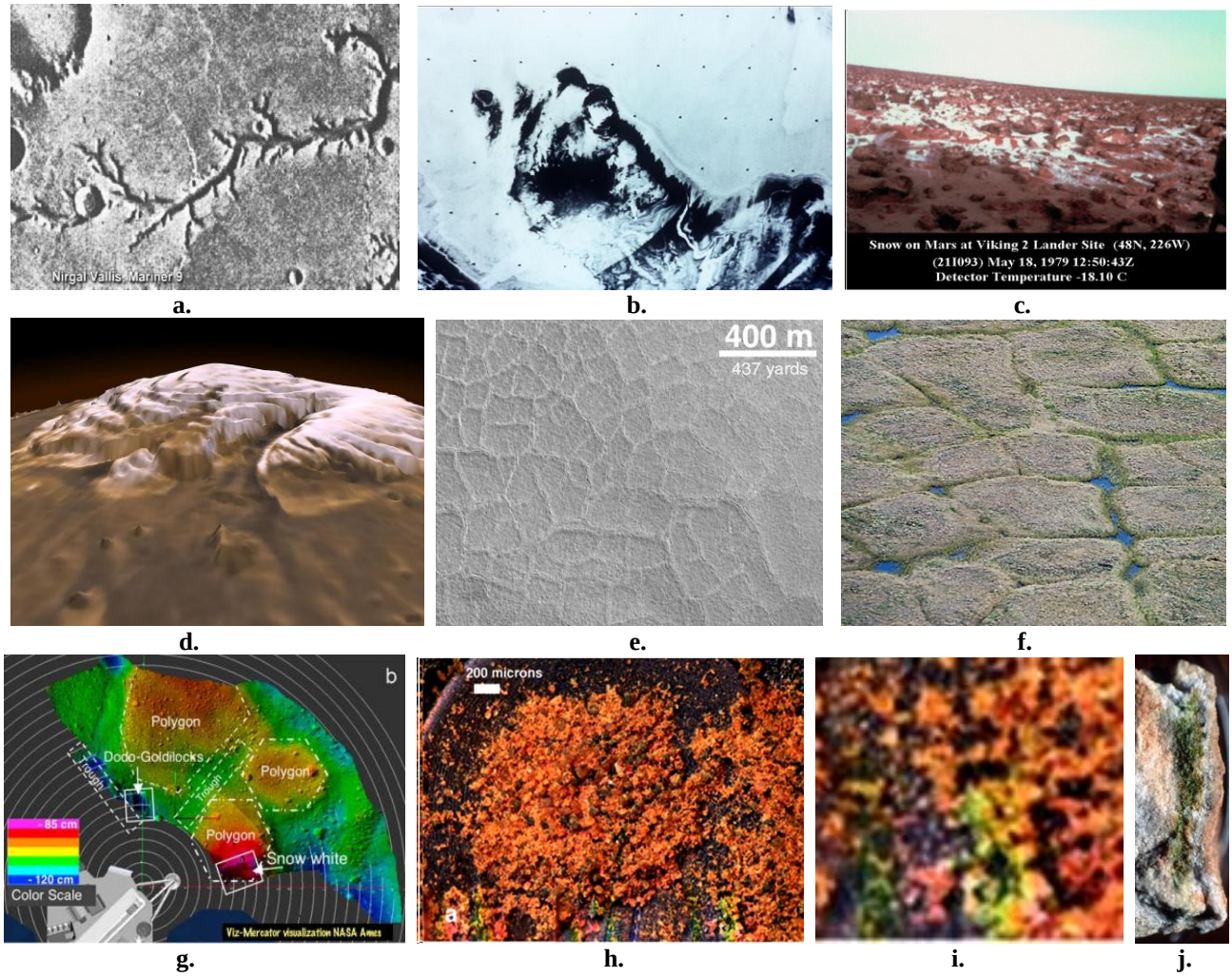


Fig. 2.a. Mariner 9 image of dry riverbeds of Mars (1971); **b.** Water ice and snow discovered by Viking Orbiter I in 1976 at the Mars North Polar Cap; **c.** H_2O snow on Mars at Viking 2 Lander site on May 18, 1979 with detector temperature -18.1 ^{o}C; **d.** MOLA image of *Planum Boreum* deposit of high purity water ice at Mars North Polar Cap. **e.** Mars Global Surveyor image of patterned ground with double-rimmed polygons; **f.** Double-rimmed polygons in periglacial thermal contraction wedges of the Kolyma Lowlands in North Eastern Siberia; **g.** Mercator visualization of location of Phoenix trenches with respect to polygons and **h.** MECA OM color image of Mars soil from Dodo Goldilocks Trench and **i.** enlargement showing greenish component of extracted Mars regolith and **j.** green and pink cryptoendolithic cyanobacteria (*Synechococcus* sp.) in translucent rock from Schirmacher Oasis, Antarctica *Image Credits:* ***a.-d.*** *NASA/GSFC/JPL*; **e.** *NASA/Malin Space Science Systems* (MOC2-150); **f. & j.** *Richard B. Hoover;* **g.-i.** *NASA/Phoenix Team*

Double-rimmed polygons are formed because water expands upon freezing. This unique property of water is not shared by carbon dioxide or by other liquids. Double rimmed polygons on Mars were interpreted as providing direct observational evidence for liquid water films around subsurface ice wedges on present-day Mars. This is significant to Astrobiology since microorganisms live in thin films within permafrost, glaciers and ice wedges on Earth and therefore similar features on Mars might support indigenous microbial ecosystems.[50] The conclusion that the double rimmed polygons provided direct observational evidence for present day liquid water on Mars was largely dismissed as it violated the widely accepted *"Mars is Bone Dry"* paradigm. On May 25, 2008, the NASA *Mars Scout Mission Phoenix* landed at high latitude (68.22°N, 234.25°E) in the floor of a deep crater (-4.1 km elevation). The *Mars Odyssey Orbiter* had previously detected evidence of abundant subsurface hydrogen at this landing site.[51] The entire area of the crater floor was covered with the sorted polygonal patterned ground periglacial features of freeze-thaw phenomena in near surface ice on Earth. The *Phoenix Lander* detected high purity near-surface water ice and liquid water in the shallow trenches dug at the landing site.[52,53] Due to boundary effects, pure water (not just brines) can exist at temperatures well below 0 ^{o}C in liquid state in thin films between sand grain and ice crystals in rocks and permafrost. Regimes containing near surface ice and thin films of liquid water in polar regions of Mars are ideal locations to search for photosynthetic microorganisms like cryptoendolithic cyanobacteria and bacteria.[50]

Figure 2.g shows a labeled Mercator visualization of where the Phoenix trenches were dug in relation to the nearby polygons. The color image of a regolith sample **(Fig. 2h)** collected from the *Dodo Goldilocks Trench* was produced by the Phoenix Microscopy, Electrochemistry and Conductivity Analyzer color Optical Microscope (MECA OM). The MECA OM illuminates the sample with Red, Green and Blue LED's and produces color images at spatial resolution ~16 μm/pixel**.** The image **(Fig. 2h)** was published in the Stoker *et al.*[54] paper on the habitability of Mars. The nature of the bright green and pink components visible in the enlarged image **(Fig. 2.i.)** was explained in detail. The green component may be particulates of olivine, peridot $(Mg,Fe)_2SiO_4$ or other pyroxene rich minerals, but the pink particulates were ignored. However, the green and pink particulates might also be biological in origin. These colors are commonly produced by pigments of chlorophyll *a* and phycoerythrins as are present in many species of cyanobacteria. Cyanobacteria comprise the most abundant photosynthetic life forms on Earth.[50] In the polar regions of our planet, many species of small coccoidal cyanobacteria (e.g., red and pink *Gloecapsa* spp. and the green and blue green *Synechococcus* spp. and *Chrococcidiopsis* spp.) inhabit thin films of liquid water between ice and sand grains in the translucent rocks that host the cryptoendolithic ecosystems **(Fig. 2.f)**.[55]

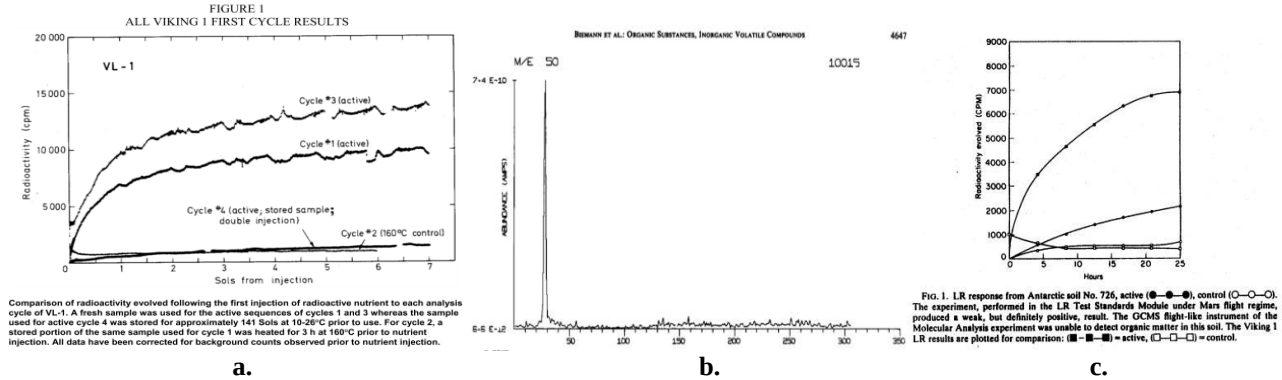
Chloromethane or methyl chloride (CH_3Cl) and dichloromethane or methylene chloride (CH_3Cl_2) were discovered by Viking on Mars in 1976 by the Biemann GC-MS life detection experiment- but then immediately dismissed as terrestrial contaminants. Cyanobacteria species *Synechococcus* spp. and *Prochlorococcus* spp. (the most abundant photosynthetic organism on Earth) along with the diatoms *Thalassiosira Weissflogii* and *Phaeodactylum tricornutum* play the dominant role in the biological production of methyl chloride (CH_3Cl) and other methyl halides and their release into the Earth's atmosphere.[56-58] *Curiosity* recently confirmed presence of chloromethane and dichloromethane in the regolith of Mars.

3.2. Evidence for Extant Life on Mars

On July 20, 1976 the NASA Viking 1 Lander touched down on the surface of Mars in the western *Chryse Planitia* (22.70 ^{o}N, 48.22 ^{o}W) at a reference altitude of -2.69 km and Viking 2 landed on September 3, 1976 in *Utopia Planitia* (48.27^{o}N, 225.99 ^{o}W) at -4.23 km altitude. The two identical Viking Landers each carried three experiments designed to search for microbial life and one instrument to identify any organic compounds in samples scooped from the upper layers of the regolith of Mars.[59] The *Gas Exchange Experiment* (GEX) of Vance Oyama used a Gas Chromatograph to search for evidence of life by the consumption or release of gasses by metabolism of organisms. The soil was first exposed to water vapor alone in a sealed chamber purged with a mixture of Krypton, CO_2 and Helium gases and then was wet with a complex aqueous solution of metabolites. The preliminary results of the GEX indicated a substantial release of O_2 (upon humidification alone) and CO_2 and small changes in N_2 gas (after wetting). These results were initially interpreted as being consistent with actively metabolizing microorganisms on Mars.[60] However, soon thereafter Oyama and Bergahl[61] concluded that the N_2, CO_2, and Ar evolutions were mainly due to soil surface desorption caused by the water vapor, while the evolution of O_2 gas was primarily associated with decomposition of superoxides inferred to be present in the Martian regolith and hence did not represent evidence for life. The *Pyrolitic Release Experiment* (PR) of Norman Horowitz carried $^{14}CO_2$ and ^{14}CO to search for evidence of living microorganisms by the detection of carbon assimilation. The experiment was designed to search for the incorporation of the radioactive carbon into the cells of

photoautotrophs by photosynthetic carbon fixation and dark fixation. In their initial report, Horowitz *et al.*[62] reported: *The amount of carbon fixed is small by terrestrial standards; highest yields were observed in the light, but some dark activity was also detected; and heating the surface material to 90°C for nearly 2 hours had no effect on the reaction, but heating to 175°C for 3 hours reduced it by nearly 90%. ... In view of its thermostability it is unlikely that the reaction is biological.* The primary problem of the Horowitz PR experiment was sensitivity. The low positive PR responses on Mars had been exceeded by test runs on Earth using sterile glass beads as the sample. The counts came from UV in the high pressure Xenon lamp converting the CO to organic matter. Horowitz was aware of this and stated, *"The amount produced could be significant for biology"*, but this was not revealed during the Viking Mission. Positive responses on Earth had to be in the thousands of CPM to be accepted as evidence for life because of this interference. The tiny results (96 CPM) on Mars were well below the sterile results detected on Earth (up to 300 CPM)--even after an optical filter had been installed in the PR to prevent the UV reaction. Horowitz finally concluded the response was non-biologic because of its low value and the survival of the active agent upon heating for the control run.

The *Labeled Release Experiment* (LR) of Gilbert Levin and Patricia Straat provided the most solid evidence for the detection of living microorganisms in the Mars regolith. The LR experiments used radiorespirometry to search for metabolic activity by living organotrophic microorganisms.[63] A very dilute solution of simple organic substrates (formate, glycolate, glycine, D- and L-alanine and D- and L-lactate) each equally, lowly and uniformly labeled with radioactive ^{14}C constituted the nutrient medium. No other ingredients were added, it being assumed that any living organisms were getting their needs from their environment. These precautions were taken to avoid the possibility of toxicity from overly strong organic concentrations, high radioactivity or extraneous compounds. A small (0.5 cm^3) sample of Mars soil was placed inside a test cell that was connected to a chamber equipped with 2 solid state beta detectors by a 0.2 cm ID X 33 cm long tube. The background radiation was measured for 24 hours. Then the center of the sample in the test chamber was injected with 0.115 ml of the radiolabeled nutrient allowing the solution to spread across the sample in a concentration gradient hoping to supply the correct concentration at some spot. The basis of the experiment was that if organotrophic microorganisms consumed any of the nutrients provided, then radioactive gas would be released as a result of their metabolic activity. gas. The gas evolved in LR tests was primarily CO_2, but any gas produced would be radioactive if made from any of the ^{14}C nutrients. Thus, the CH_4 produced by methanogens is also radioactive. This became of much interest when CH_4 was subsequently detected on Mars and its biological origin was conjectured. When the ^{14}C atoms in the evolved gas enter the detection chamber and decay, beta particles are given off, detected, and counted. The method is so sensitive that as few as 10 cells have been detected within several hours, with even low-population soils detected immediately upon injection of the nutrient. There is no lag phase, and no growth is required, making the method remarkably efficient, quick, and more likely to obtain a response from extraterrestrial microorganisms. The count rate was measured over the incubation cycle of 8 Sols. Vigorous production of the radioactive gas was observed **(Fig. 3.a)** immediately upon injection of the nutrient**.** The result was a characteristic growth curve as had been observed to result from microbial activity in a variety of soils on Earth.



a. **b.** **c.**

Fig. 3.a. Response curves of the Viking 1 Labeled Release (LR) experiment shows radioactive gas evolved after injection of the radioactive nutrient and control sample heated to 160 C for 3 hours; **b.** Methyl Chloride CH_3Cl peak detected by Viking *Molecular Analysis* GC-MS; **c.** Plot shows Viking GC-MS fails to detect organics in Antarctic sample No. 726 containing 0.03% Organic Carbon as living microbes readily detected by the Viking LR experiment. Credit: **a.&c.** G. Levin & P. Straat; **b.** K. Biemann

The Viking LR results were entirely consistent with microbial metabolic activity. After the cycle was completed, the second 0.5 cm^3 portion of a duplicate of the original sample was sealed in a clean test cell and heated to 160 ^oC for 3 hours. This was considered adequate for to kill any living microorganisms that might have been present in the soil of Mars. The test chamber was then cooled and the background counted for 2 hours before the nutrient medium was injected. There was no productivity of radiolabeled gas, which was consistent with what would be expected from a sterilized soil sample. The Viking 1 LR results clearly established that a heat-labile reaction had occurred with the Mars soil. Similar results were obtained by the Viking 2 LR experiment carried out in *Planitia Unitia* some 4000 miles away on Mars. In all, four test and five control experiments were run by the LR instruments. The results of these experiments were all consistent with biology and initial press reports were that Viking discovered life on Mars. However, pressure from NASA was so heavy that Levin did not make and publish his conclusion that the LR had detected life until 1997.[41]

The Viking *Molecular Analysis* experiment of Klaus Biemann was designed to identify organic compounds widely expected on Mars. Coming from the same original sources as those on Earth, a wide variety of organics was anticipated. Scooped samples of the regolith were ground up to reduce grain size and then inserted into an oven and heated to 500 ^oC to drive off volatile organics that were then analyzed by a Gas Chromatograph-Mass Spectrometer (GC-MS).[65] If organic molecules from living or dead cells or from the metabolic end products of microorganisms were detected, this would be interpreted as evidence of life. However, Biemann *et al.*[65, 66] reported that the GC-MS had detected only water and carbon dioxide and no organics indicating that neither living or dead cells were present at either of the Viking Lander sites on Mars. They argued: *"The absence of organic compounds seems to preclude their production on the planet at rates that exceed the rate of their destruction. It also makes it unlikely that living systems that behave in a manner similar to terrestrial biota exist, at least at the two Viking landing sites."*[66] The consensus of the scientific community rapidly became that the GEX, PR, and LR results must have all been caused by some type of oxidants, superoxides or other unexplained abiotic chemical reactions in the Martian regolith rather than by microbial life. This was reported despite the fact that the Biemann GC-MS data had included the detection of a sharp peak (~15 ppb) of Methyl Chloride CH_3Cl and a number of weak organic peaks the Viking 1 site (**Fig. 3.b**.). Furthermore, the Viking *Molecular Analysis* GC-MS had also detected Methylene Chloride CH_3Cl_2 but no Methyl Chloride at the Viking 2 site. These halogenated organics were dismissed by Biemann as being terrestrial contaminants from solvents used to clean the hardware on Earth. In making these assertions, he completely ignored the fact that neither of these organics was found in the Cruise Phase Blank (CPB) experiments that had been run as controls with empty ovens during the Cruise Phase of the flight to Mars. He based his conclusion that these organics had to be terrestrial contaminants on the reasoning that other organics were absent in the Mars samples which should also have been formed by indigenous abiotic chemical reactions: *"The methyl chloride, or part of it, could conceivably be indigenous to Mars. However, if it were, one would expect that other related compounds like ethyl chloride or methyl bromide would also be formed, but none were detected."* [65, 66] These related compounds had also been found in terrestrial geochemical sources (e.g., volcanoes) with methyl chloride, methylene chloride and other halogenated hydrocarbons formed in nature. [67,68]

In the mid-1970's, methyl halides were known almost exclusively as industrial chemicals. At that time scientists were only beginning to recognize that methyl halides could be produced by living organisms.[69] It is now well understood that a wide variety of bacteria, cyanobacteria and other organisms synthesize large quantities of metabolites including methyl chloride and methylene chloride. Many gram negative organotrophic bacteria can use these halogenated hydrocarbons as substrates for growth. [70] By the mid-1990's, it had been recognized that marine bacteria usually produce brominated compounds and terrestrial bacteria preferentially synthesize chlorometabolites, however the halogenating enzyme that was involved in the biosynthesis of halogenated compounds was still unknown.[71] It is now well established that while abiotic chemical reactions often result in mixtures of methyl halides, it is not unusual for microorganisms to produce or consume specific or monospecies halogenated compounds.[72,73] Recent discoveries have revealed much about the enzymes, genes, and metabolic pathways employed by a number of these novel microorganisms that have been isolated and described. *Methylobacterium chloromethanicum* CM4 is an aerobic α-proteobacterium which is able to grow using chloromethane as the sole source of carbon and energy.[74] For this reason the large peak of methyl chloride detected in the GC-MS experiment on Mars at the Viking 1 site may now be interpreted as more supportive of biology than chemistry. Failure of the Viking *Molecular Analysis* GC-MS to detect methyl chloride and methylene chloride in the Cruise Phase Blank experiments should have immediately ruled out the "*terrestrial contamination*" interpretation.
There is no doubt that the reported failure of the *Molecular Analysis GC-MS* experiment to detect organics in the Mars regolith led the scientific community to the widespread belief that the LR result was due to chemistry rather than biology and the adoption of the paradigm that no life exists on Mars.[75] In an effort to find an abiotic chemical nonbiological

explanation for their LR data, Levin and Straat[76] conducted exhaustive experiments and they were never able to replicate the Viking LR data by abiotic methods. However, one of these studies revealed that the Viking LR experiment was able to detect biology in the sparsely populated Antarctic Soil Sample No. 726 that contained 0.03% organic carbon.[77] This same sample had been documented by Cameron[78] and was maintained by NASA. Lavoie[79] reported that tests with the Viking Molecular Analysis GC-MS failed to detect any organics after this sample was volatilized but respiration of microbiota within the sample was detected by the Viking LR radiorespirometry experiment. **Figure 3.c.** shows the response of the LR experiment as compared with the GC-MS data for Antarctic Sample No. 726. These results indicate the Labeled Release experiment was far more sensitive than the other Viking Life Detection experiments or the Viking GC-MS. The reported failure of the *Molecular Analysis* experiment was primarily responsible for widespread belief that there were no organics in the Martian regolith and the consensus of the scientific community that the LR experiment data must have been caused by unexplained chemical reactions rather than the respiration of living microorganisms.

In an attempt to obtain an abiotic explanation for results of the Viking Biology Experiments, several hypotheses were advanced proposing exotic chemical compounds (e.g., supermetalloperoxides, carbon suboxide polymer, superoxides, or peroxides) in the regolith of Mars.[80] These proposals neglected the fact that these compounds are extremely unstable and break down rapidly when exposed to light. Furthermore, if they were present in the soil, then the levels of oxygen and peroxide in the Mars atmosphere should have been vastly higher than observed. These superoxidizers have never been detected by subsequent missions to Mars. However, in 2008 the *Phoenix* Lander's *Thermal Evolved Gas Analyzer* (TEGA) detected perchlorate and water in the Mars regolith.[81-83] It was suggested that perchlorates are "toxic" and calcium perchlorate in the Martian soil would make Mars unsuitable for life. It was also argued that perchlorates might have destroyed organics in the soil and could account for the failure of the GC-MS and Viking Biology Experiments.[84] This neglects the positive findings of the LR experiment. Perchlorate survives much higher temperatures than the control temperatures to which the LR active agent succumbed. Therefore perchlorate is not a candidate oxidizing agent to explain the Viking LR data. It is important to note that perchlorate is a very powerful chemoautotrophic energy source. It could be used by microorganisms living in total darkness deep within the permafrost or subsurface ices and well protected from radiation conditions at the surface of Mars.[85] Several novel bacteria such as *Dechlorospirillum* spp. and *Magnetospirillum* spp. are capable of dissimilatory perchlorate-reduction.[86,87] New information concerning the evolution and regulation of the metabolic pathway for dissimilatory perchlorate-reduction was obtained when the entire genome was sequenced for the exotic microorganism, *Dechloromonas aromatica*. This organism is not only able to reduce perchlorate, but it can also oxidize Fe(II), H_2S, chlorobenzoate, toluene and xylene.[88] The "chain of pearls" configuration of magnetosomes (in the terrestrial *Magnetospirillum magnetitacticum* shown in the upper left image of **Fig. 1.b**.) are similar to the biosignature of the "chain of pearls" magnetosomes found in ALH84001 **(Fig. 1.b. Right)**.

The *Phoenix* detection of water and perchlorates on Mars was confirmed by the Sample Analysis at Mars (SAM) instrument suite on NASA's *Curiosity* rover. *Curiosity* also detected in the Sheepbed Mudstones of Gale Crater the landing site for the Curiosity rover. It is thought that Gale Crater was once the site of a lake billions of years ago, and the mudstones formed from sediments in the lake. This mudstone was found to contain 20 percent smectite clays. On Earth, such clays are known to provide high surface area and optimal interlayer sites for the concentration and preservation of organic compounds when rapidly deposited under reducing chemical conditions. In addition to the smectite clay, *Curiosity* also discovered a suite of organics including chlorobenzene (at concentrations of 150-300 parts/billion) and dichloroalkanes: dichloroethane, dichloropropane and dichlorobutane.[89] The toxic and carcinogenic nature of these organics was mentioned suggesting they are detrimental to life. However, some terrestrial bacteria grow using chlorobenzene as the source of carbon and energy,[90] and the great diversity of organohalogens produced by bacteria, cyanobacteria and other microorganisms on Earth has been well known for over a quarter of a century.[91]

On Feb. 8, 2013 the NASA *Curiosity* rover drilled into *John Klein* rock on Mars and detected chloromethane and methylene chloride. These results were then immediately dismissed as resulting from terrestrial contaminants.[85] In view of the extensive discussion regarding the purported contamination of the Viking GC-MS data by these chemicals, there really could be no excuse for the *Curiosity Science Team* to allow these chemicals anywhere near a spacecraft with instruments designed to search for organics on Mars. The controversial debates after Viking resulted in widespread acceptance of the *Mars is Bone Dry* Paradigm and that the surface of Mars is currently inhospitable to life. This may explain why NASA has flown no life detection experiments to Mars since Viking. This includes experiments to distinguish between abiotic chemical reactions and metabolism (e.g., Levin Chiral Labeled Release Experiment)[92, 93] or

detect complex biomolecules (e.g., DNA, RNA, proteins, enzymes or photosynthetic pigments) by spectroscopy or fluorescence microscopy[94] and High Resolution Optical Video Microscopy could detect life from future Rovers.

3.3. Evidence for Extinct Life on Mars

Biosignatures in Mars meteorites, such as microfossils in proximity to biogenic magnetite grains and magnetosomes in "chain of pearls" configurations provides some evidence for microbial life on ancient Mars. However, even more dramatic evidence appears to have been obtained by the NASA Mars Exploration Rover *Opportunity* as it explored the small crater called *Meridiani Planum* where it had landed on Jan. 24, 2004.

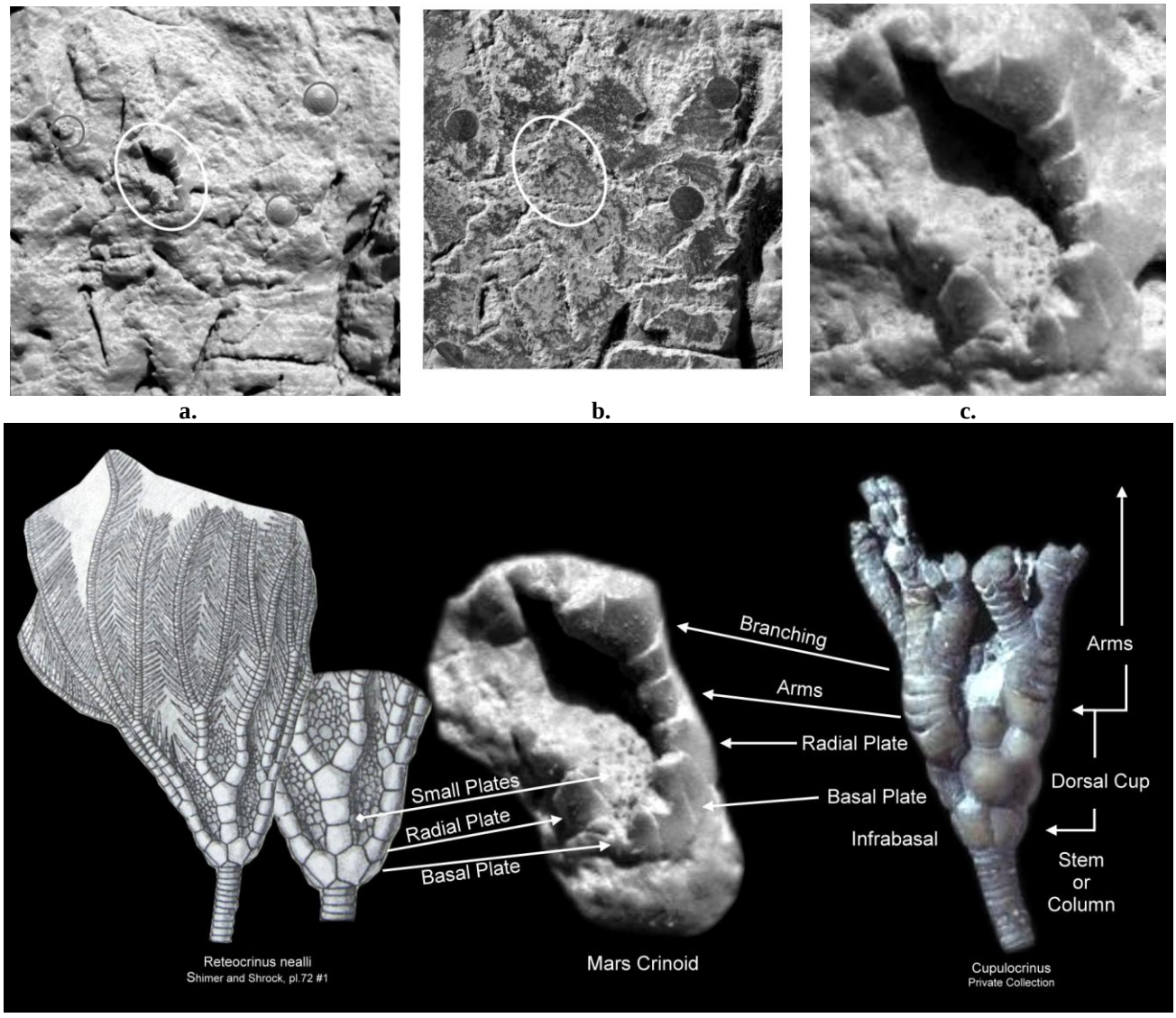


Fig. 4.a. NASA *Opportunity* image (1M131201699EFF0500P29933M2M1.jpg)[95] of crinoid (in oval) in *El Capitan* outcrop recorded on Sol 34 at 11:30:35 Mars Local Time by Microscopic Imager (MI) CCD. **b.** MI image 1M131212854EFF0500P2959M2M1.jpg[96,97] obtained at 14:34:10 (2 hrs 56 min later) shows region (in oval) where crinoid was located after grinding with the Rock Abrasion Tool (RAT). **c.** Enlargement of Mars crinoid image showing labeled morphological features (e.g. dorsal cup, radial plates, basal plates, pentagonal primibrachial plates, small plates and well rounded, segmented arm plates and pentagonal primibrachial branching arms that exhibit some pustule ornamentation) **d.** as compared with characteristics of terrestrial Ordovician crinoids *Reteocrinus nealli* (Hall) and *Cupulocrinus* sp. *Image Credits*: **a.-c.** *NASA;* **d.** *Shimer and Shrock*[100] and Richard Keyes.

On Sol 34 at 11:28:59 Mars Local Solar Time the Right Front Hazcam of *Opportunity* took NASA Image (1F131201440EDN0500P1111L0M1.jpg) showing the Robotic Arm of the rover hovering just above *Opportunity Ledge* at the *El Capitan* outcrop. The arm carries four instruments designed to photograph, grind, brush and analyze chemical composition of the Martian rocks. One minute thirty-six seconds later, (11:30:35 Mars Local Time) the Microscopic Imager Dust Cover was opened and the image (1M131201699EFF0500P29933M2M1.jpg) of a very complex fossil crinoid (in oval)was recorded with the MI CCD camera (**Fig. 4.a)** [95] Details of this complex partial crown are more clearly seen in the enlargement provided in **Figure 4.c.** A crinoid crown consists of the theca (calyx and tegmen) and rays. The calyx is comprised of thin walled plates (ossicles), forming a hollow cup enclosing the viscera of the animal. Each radial represents the first and most proximal ossicle of a ray or arm of the crinoid. The image (**Fig. 4.c)** shows a calyx embedded in a rock on the surface of Mars with the many unique, complex, distinctive and recognizable characteristics comparable to those known in terrestrial crinoids. The recognizable features of the Mars crinoid calyx include the dorsal cup (mostly embedded in the rock matrix), radial and basal plates, pentagonal primer brachial plates, small interambulacral plates along with well rounded, segmented and pentagonal branching arms with pustule ornamentation on the arms. The arms are clearly rounded where they can be seen to have become disarticulated at segmentation just above the first branch. The upper regions of the arms are missing in the Mars form. These branched upper arms (where the pinnules and cirri are located to gather plankton for food) are shown in the image of the full crown of the primitive Ordovician terrestrial crinoid *Reteocrinus nealli* (Hall) that has been provided for comparison (**Fig. 4.d).** This drawing and the photo of the *Cupulocrinus* sp. are shown to illustrate diagnostic characteristics of terrestrial crinoid characteristics, and it is not suggested that the form on Mars belongs to either of these genera known in the fossil record of Earth. It is unfortunate that it does not appear that additional images were taken from closer positions and the needed angles to allow the Mars form to be seen in 3-D. Images of this remarkable find should have also been recorded as different orientations and sun angles could have provided extremely valuable scientific data. Furthermore, the *Alpha Particle X-ray Spectrometer* (APXS) should have been used to determine the elemental composition of the form and the nearby rock matrix, but if these data were obtained have not as yet been released in any scientific paper or report. Several crinoids are often found in the same strata on Earth. This unique find should have documents with close-up images at different angles. Careful search for similar forms in the these strata on *Opportunity Ledge* and exact position should have been documented so it could have been retrieved on a future Mars Sample Return Mission for detailed study on Earth. Unfortunately these actions were not taken before this important possible fossil was destroyed.

On Sol 34 at 14:34:10 Mars Local Solar Time (2 hours and 56 minutes later), Opportunity recorded the image (1M131212854EFF0500P2959M2M1.jpg) (**Fig. 4.b)** with oval in precisely the same place on the rock reveals this exciting possible fossil ground to dust **.** [96,97] The ovals were place using the relative location of the Martian Hematite Spherules ("blueberries") and the fractures present in both images in the lower right corner of the rock **(Fig. 4.a** and **Fig. 4.b).** [96, 97] From these images it is clear that the Rock Abrasion Tool (RAT) was used grind away the possible crinoid fossil **(Fig. 4.a, c & d)**.[95] Even though the Opportunity Rover was not equipped with a scale to allow exact size measurements, the Mars Hematite Spherules in *Meridiani Planum* occur in a very restricted range of sizes (~4 mm to 6.2 mm maximum). Therefore they provide a natural scale bar for this image.[98] Assuming the large Hematite spherule is ~5 mm diameter it is possible to estimate that the possible crinoid crown on Mars is ~15 mm from the bottom of the dorsal cup to the place where the pentagonal arm is broken just above the first branch. Estimating from the image of the complete crown of *Reteocrinus nealli* with unbroken arms **(Fig. 4.d)**, the crown of the Mars crinoid could have been over 50 mm tall, which is well within the correct size range for *Reteocrinus nealli* fossil crinoids found on Earth.

The discovery of the remains of a possible fossil crinoid in a rock on Mars represented a truly astonishing find. Crinoids are far more sophisticated than microfossils of bacteria, archaea or even colonial cyanobacteria with specialized cells such as heterocysts. Fossil crinoids represent a well established branch of invertebrate paleontology. Their systematic taxonomy is based entirely on the unique detailed morphological features of the crown and stalk largely in accordance with the system set forth in 1897 by Charles Wachsmuth and Frank Springer. [99] Crinoids are very complex multicellular marine invertebrate animals of the Phylum Echinodermata, Class Crinoidea. The Crinoid skeleton is composed of calcite plates (ossicles) and they exhibit pentameral (fivefold) symmetry like starfish, echinoids and other echinoderms and their detailed characteristics have been extensively documented. [99-103] Living crinoids are relatively common on Earth today but they were among the most prolific forms of life in the Paleozoic. Most living crinoids inhabit shallow seas, like most crinoids of the past, and are free swimming with only vestigial stalks (feather stars). Recent discoveries have revealed dense clusters of stalked crinoids (sea lilies) living at depths greater than 9,000 m attached to hard rocks at the bottom of the *Izu-Ogasawara* deep ocean trench off the coast of Japan.[103, 104] This paradigm altering possible biological form that

exhibited multiple complex morphological and morphometric characteristics that if found in Ordovician rocks on Earth there would be no question it was a fossil crinoid. The destruction soon after discovery (without extensive imaging and element composition analysis) raises serious questions about NASA protocols for the search, preservation and study of evidence of extant or extinct life if found on Mars or Astromaterials and the protocols in place for future space missions.

3.3. Evidence for Extant and Extinct Life on Comets

On September 10, 2014, the ESA Rosetta Spacecraft began orbiting comet 67P/Cheryumov-Gerasimenko and the Philae Lander touched down on Nov. 12, 2024. Water ice is abundant on the comet with Deuterium/Hydrogen ratio three times greater than that of terrestrial water. The Cometary Sampling and Composition (COSAC) instrument of the Philae Lander Detected 16 Organic Chemicals, many of which were nitrogen bearing species and some never before detected on comets.[105] The Narrow Angle Camera of the Rosetta OSIRIS (Optical, Spectroscopic, and Infrared Remote Imaging System is equipped with 11 optical filters (245nm to 1000nm) that allow it to obtain images in different regions of the electromagnetic spectrum. High quality color images can be produced by combining images taken with the filters centered in the Red, Green and Blue portions of the spectrum. On Dec. 2, 2014 a color image of the comet produced by using the R, G, B filters **(Fig. 5.a)** was released by CBS News. [106]

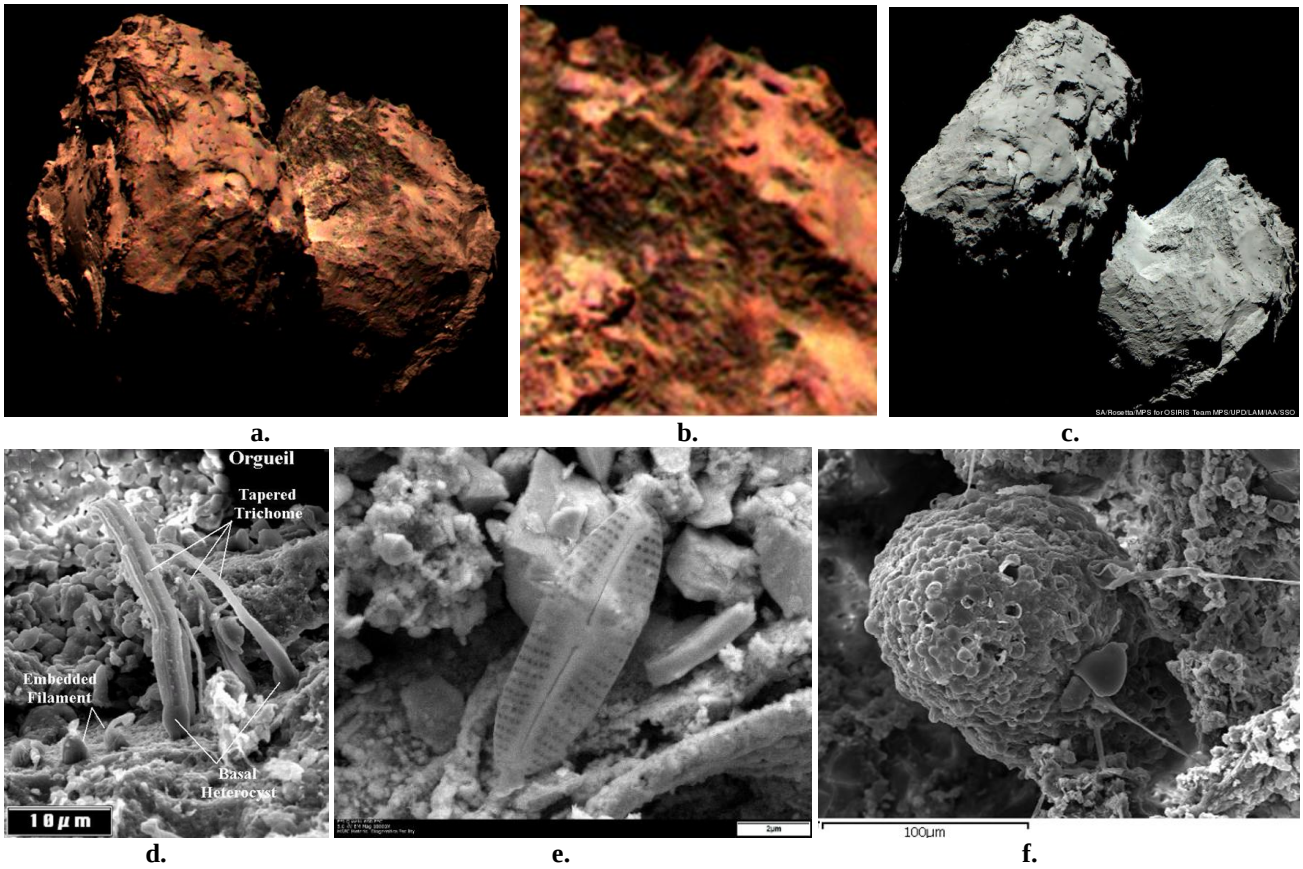


Fig. 5.a. Comet 67P/Cheryumov-Gerasimenko RGB image with reddish color and variegation of surface **b.** enlarged to more clearly show the pink, red, and green regions in the node just to right of neck; **c. RGB** red image replaced with grey "true color" image to show what "it would look like to earthlings."[108] FESEM images of extinct life forms in comets **d.** Heterocystous cyanobacteria filaments in Orgueil CI1 meteorite and microfossils in Polonnaruwa meteorite of **e.** embedded pennate diatom cf. *Reimeria sinuata* and **f.** Ancient hystrichosphere with carbon content >80% and nitrogen level below EDS detection limit. *Image Credits* **a.-c.** ESA Rosetta Osiris Team; **d.** Richard B. Hoover and Greg Jerman**; e. & f.** Richard B. Hoover, Nori Miyake and N. C. Wickramasinghe

This color image was included in the scientific paper on "Color Variegation on 67P/Cheryumov-Gerasimenko" presented in San Francisco at the American Geophysical Union 2014 AGU Fall Meeting. [107] An enlarged part of this image (just to the right of the neck) shown in **Fig. 5.b.** reveals that the overall color of the comet nucleus is brownish with

regions of pink, red, green and blue-green. It appeared in a Huffington Post article on Dec. 15, but was very quickly replaced by the entirely different dark grey image of **Fig. 5.c.** Holger Sierks, principal Investigator of the Rosetta OSIRIS camera was quoted as saying "An earlier image showed the comet to be a reddish color, but the agency said that's because 67P reflects red light more efficiently than other wavelengths and not what it would look like to earthlings."[108] This must be erroneous, since if comet "67P reflects red light more efficiently than other wavelengths" then it is red and would look red to earthlings if properly illuminated. Hviid[107] indicated the color image was recorded under "good illumination condition at 1m/pixel as part of the pyramid arc phase." If this RGB image did represent the true color of the comet, then a study of "color variegation observed on the comet surface and its relationship to surface morphology and cometary activity" would be of no scientific value. While the colors observed may be due to inorganic mineral components, they could also result from the absorption characteristics of complex and undeniably biological molecules such as photosynthetic pigments (e.g., Chlorophyll a, Chlorophyll b, β Carotene, Phycoerythrin and Phycocyanin). These photosynthetic pigments have very distinctive and identifiable patterns of absorption of wavelengths of visible light.[109] The chlorophyll pigments more efficiently absorb violet blue light and low energy photons in the orange-red portion of the spectrum--- but do not efficiently absorb photons of green light--hence the chlorophyll pigments in the grass and green algae cause them to be green. The blue-green Phycocyanin pigments are responsible for the color of many cyanobacteria called "blue-green algae." However, some cyanobacteria, such as those found in stromatolites growing in low light conditions on the floor of Lake Untersee in Antarctica, are pink and red in color because they use the red phycoerythrin pigments for photosynthesis.[110] Ocean color remote sensing methods use satellites to detect photosynthetic pigments in phytoplankton blooms in the oceans of Earth. [111] Chlorophyll, phycoerythrins and other photosynthetic pigments are complex biomolecules with distinctive absorption, emission and fluorescence spectra. They could provide definitive and unambiguous evidence of extraterrestrial life by remote detection of biomolecules on Mars, Pluto, comets, icy moons or other Solar System bodies.

There is evidence that the orbit of the Orgueil CI1 meteorite was consistent with the Jupiter family of comets and the cometary origin is not contradicted by the mineralogy and cosmochemistry data for the CI1 carbonaceous meteorites.[112] Hence the microfossils that have been detected in the Orgueil meteorite may be interpreted as providing evidence for extinct life on comets.[113-115] **Figure 5.d** is a FESEM image of the remains of microfossils embedded in a freshly fractured surface of the Orgueil meteorite. The filaments exhibit size and detailed morphological characteristics of *Calothrix* sp., a filamentous cyanobacteria with basal heterocysts used for nitrogen fixation. The Rosetta Mission discovered that density[116] of the nucleus of comet 67P/Cheryumov-Gerasimenko is 0.4 gm/cm^3, only slightly below the Polonnaruwa stones (~0.6 gm/cm^3) that were observed to fall in Sri Lanka on Dec. 29, 2012. The Polonnaruwa stones are unlike known meteorite groups but have anomalous Triple Oxygen Isotope ratios far away from those of Earth and Moon rocks, which lie near the Terrestrial Fractionation Line ($\Delta^{17}O = 0$). Independent studies of Polonnaruwa stones by Andreas Pack, Univ. of Göttingen, Germany[117] ($\Delta^{17}O = 0.335‰$) agreed with data from two runs ($\Delta^{17}O = -.328$ and $\Delta^{17}O = -.296$) by Eizo Nakamura of Okayama University, Japan. FESEM studies at the NASA/MSFC (USA) and University of Cardiff (UK) showed these unique stones contained embedded and fossilized remains of freshwater and marine diatoms[117] **(Fig. 5.e)** and extinct eukaryotes **(Fig. 5.f)** such as hystrichospheres[118] and acritarchs.[119]

4. CONCLUSIONS

Many paradigms long held by the consensus of the scientific community have been found to be invalid. It is now known that water ice exists in polar craters on Mercury and our Moon and water is abundant on comets, and in permafrost and the Polar Caps of Mars and the outer planets and their icy moons. Living organisms thrive in deep sea trenches, deep crustal rocks, hot vents, permafrost, glaciers and virtually every niche of Earth where water, energy, and life-critical biogenic elements co-exist. No scientific rationale has been advanced that precludes the co-existence of these life-critical components throughout the present-day Universe. The *Opportunity*, *Spirit*, *Phoenix*, and *Curiosity* missions have confirmed discoveries about water and organics on Mars made by the *Viking* Orbiters and Landers but rejected for reasons that are no longer tenable. Future space missions should carry well designed instruments to distinguish abiotic minerals and chemicals from metabolic products and complex biomolecules such as chlorophyll and phycoerythrins. These are distinctive photosynthetic biomolecules that are not produced by abiotic mechanisms. High Resolution Video Optical Microscopy can distinguish locomotion of bacteria, cyanobacteria, diatoms and other living motile microbes from Brownian Motion and current drift of abiotic particulates. Locomotion requires great expenditure of energy and represents the possibility for remote recognition of definitive evidence of life on Mars, comets or icy moons.

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6. REFERENCES

[1] Dombrowski. H., "Bacteria from Paleozoic Salt Deposits." Annals of the New York Academy of Sciences, 108, 453-460, (1963).

[2] Stan-Lotter, H., Pfaffenhuemer, M., Legat, A., Busse, H., Radax, C. and Gruber, C. "*Halococcus dombrowskii* sp. nov., an archaeal isolate from a Permian alpine salt deposit. " Int. Jour. Systm. Evol. Microbiol. 52, 1807-1814 (2002).

[3] Satterfield, C. L., Lowenstein, T. J., Vreeland, R. H., Roenzweig, W. D. and Powers, D. W. "New evidence for 250 Ma age of halotolerant bacterium from a Permian salt crystal. " Geology 33, 265-268, (2004).

[4] Heckly, R. J. "Preservation of Bacteria by Lyophilization." *Advances in Applied Microbiology 3*, (W. W. Umbreit, Ed.) Academic Press, New York, 1-76 (1961).

[5] Gilichinsky, D.A., Wilson, G.S., Friedmann, E.I., Mckay, C.P., Sletten, R.S., Rivkina, E.M., Vishnivetskaya, T.A., Erokhina, L.G., Ivanushkina, N.E., Kochkina, G.A., Shcherbakova, V.A., Soina, V.S., Spirina, E.V., Vorobyova, E.A., Fyodorov-Davydov, D.G., Hallet, B., Ozerskaya, S.M., Sorokovikov, V.A., Laurinavichyus, K.S., Shatilovich, A.V., Chanton, J.P., Ostroumov, V.E. and Tiedje, J.M. "Microbial Populations in Antarctic Permafrost: Biodiversity, State, Age, and Implication for Astrobiology. " Astrobiology. 7, 275-311 (2007).

[6] Marsic, D., Hoover, R. B., Gilichinsky, D. and Ng, J. D. "Extraction and Amplification of DNA from an Ancient Moss." (1999). http://www.promega.com/~/pdf/resources/pubhub/enotes/extraction-and-amplification-of-dna-from-an-ancient-moss/

[7] Elster, J. and Benson, . E. "Life in the Polar Terrestrial Environment with a Focus on Algae and Cyanobacteria. " in *Life in the Frozen State* (Fuller, B. J., Lane, N. and Benson, E. E., eds.) CRC Press, USA, pp. 111-150 (2004).

[8] Ponder, M., Vishnivetskaya, T., McGrath, J. and Tiedje, J. "Microbial Life in Permafrost: Extended Times in Extreme Conditions." in *Life in the Frozen State* (Fuller, B. J., Lane, N. and Benson, E. E., eds.) CRC Press, USA, pp. 151-171 (2004).

[9] Abyzov, S. S., Hoover, R. B., Imura, S., Mitskevich, I. N., Naganuma, T., Poglazova, M. N., and Ivanov, M. V., "Comparative Results of Using Different Methods for Discovery of Microorganisms in Very Ancient Layers of the Central Antarctic Glacier above Lake Vostok." *Advances in Space Research, Cospar*, 33, 1222-1230, (2004).

[10] Abyzov, S. S., Duxbury, N. S., Bobin, N. E., Fukuchi, M., Hoover, R. B., Kanda, H., Mitskevich, I. N., Mulyukin, A. L., Naganuma, T., Poglazova, M. N. and Ivanov, M. V. "Super-long anabiosis of ancient microorganisms in ice and terrestrial models for development of methods to search for life on Mars, Europa and other planetary bodies." *Advances in Space Research, Space Life Sciences*, **38,** 1191-1197 (2006).

[11] Siegel, B. Z., McMurty, G., Siegel, S. M., Chen, J and Larock, P. "Life in the calcium chloride environment of Don Juan Pond, Antarctica. " Nature, 280, 828-829 (1979).

[12] Siegel, B. Z., Siegel, S. M., Chen, J. and Larock, P. "An extraterrestrial habitat on Earth: the algal mat of Don Juan [correction of Jaun] Pond. " Adv. Space Res. 3, 39-42 (1983).

[13] Pikuta, E. V., Hoover, R. B., Bej, A. K., Marsic, D., Whitman, W. B., Krader, P. E. and Tang, J. **"***Trichococcus patagoniensis* sp. nov., a facultative anaerobe that grows at –5 °C, isolated from penguin guano in Chilean Patagonia." *Int J Syst Evol Microbiol*, **56,** 2055 – 2062 (2006).

[14] Hoover, R. B. and Gilichinsky, D. "Significance to Astrobiology of Microorganisms in Permafrost and Ice." In *Permafrost Response on Economic Development, Environmental Security and Natural Resource Potential*, NATO-ARW held in Novosibersk, Siberia, 12-16 Nov. 1998. (Roland Paepe, Ed.) Klewer Publishing, New York, pp. 553-580, (2001).

[15] Hoover, R. B. and Pikuta, E. V. "Psychrophilic and Psychrotolerant Microbial Extremophiles in Polar Environments." In *Polar Microbiology: The Ecology, Biodiversity and Bioremediation Potential of Microorganisms in Extremely Cold Environments* (Eds. Asim K. Bej, J. Aislabie and Ronald M. Atlas) CRC Press, pp. 115-157. (2009). http://www.routledge.com/books/Polar-Microbiology-isbn9781420083842

[16] Gilichinsky D., Rivkina E., Bakermans, C., Shcherbakova, V., Petrovskaya, L., Ozerskaya S., Ivanushkina, N., Kochkina, G., Laurinavichuis, K., Pecheritsina, S., Fattakhova, R. and Tiedje, J. M., "Biodiversity of Cryopegs in Permafrost. " FEMS Microbiol. Ecol., 53, 117-28 (2005).

[17] Pecheritsyna, S. A., Rivkina, E. M., Akimov, V. N., Shcherbakova, V. A. "*Desulfovibrio Arcticus* Sp. Nov., A Psychrotolerant Sulfate-Reducing Bacterium from a Cryopeg." Int. J. Syst. Evol. Microbiol. 62, 33-37 (2012).

[18] Clavero, E., Hernández-Mariné, M., Grimalt, J. O. and Garcia-Pichel, F. "Salinity Tolerance of Diatoms from Thalassic Hypersaline Environments." J. Phycol. 36, 1021-1024 (2008)

[19] Nagasathya, A. and Thajuddin, N. "Diatom Diversity in Hypersaline Environments. " Jour. Fish. Aquatic Sci. 3, 328-333 (2008).

[20] Rahaman A. A. "Plankton Communities in Hypersaline Waters of Indian Solar Saltworks." Proc. 1st Int. Conf. on the Ecological Importance of Solar Saltworks, Santorini Island, Greece 20-22 October, (2006).

[21] Hoover, R. B. “Those Marvelous Myriad Diatoms.” National Geographic, 155 (6), 870-878 (1979).
[22] Calvin, M. and Benson, A. A. "The Path of Carbon in Photosynthesis. IV. The Identity and Sequence of the Intermediates in Sucrose Synthesis. Univ. Calif. Radiation Laboratory Report UCRL-254, 1-12 (1948).
[23] Evans, M. C., Buchanan, B. B. and Arnon, D. I., "A new ferredoxin-dependent carbon reduction cycle in a photosynthetic bacterium." *Proc Natl Acad Sci U S A.* 55, 928–934 (1966).
[24] Buchanan, B. B and Arnon, D. I. "A reverse KREBS cycle in photosynthesis: consensus at last." Photosynthesis Res. 24, 47–53 (1990).
[25] Berg, I. A., Hugo Ramos Vera, W., Petri, A., Huber, H. and Fuchs, G. “Study of the distribution of autotrophic CO2 fixation cycles in Crenarchaeota.” Microbiology 156, 256-269, (2010).
[26] Postgate, J. *Nitrogen Fixation, 3rd Edition*. Cambridge Univ. Press, Cambridge UK, pp. 1-124 (1998).
[27] Donze, M., Haveman, J. and Schiereck, P. “Absence of photosystem 2 in heterocysts of the blue-green alga Anabaena.” Biochim. Biophys. Acta 256**,** 157–161 (1972).
[28] Truzzi, M. “On the Extraordinary: An Attempt at Clarification .” Zetetic Scholar, 1, 11 (1978).
[29] http://www.pbs.org/wgbh/nova/space/sagan-alien-abduction.htmlA | Carl Sagan on Alien Abduction
[30] McKay, D. S., Gibson, Jr., E. K., Thomas-Keprta, K. L., Vali, H., Romanek, C. S., Clemett, S. J., Chillier, X. D. F., Maechling, C. R. and Zare, R. N. “Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001. ” Science 273, 924-930 (1996).
[31] Markley, R. “Missions to Mars: Reimagining the Red Planet in the Age of Spaceflight.” in *Exploring the Solar System: The History of Science and Planetary Exploration* (Launius, R. D., Ed.) Palgrave Macmillan, New York, p. 258 (2012).
[32] Thomas-Keprta, K. L., Clemett, S. J., Bazylinski, D. A., Kirshvink, J. L., McKay, D. S., Wentworth, S. J., Vali, H., Gibson, Jr., E. K. and Romanek, C. S. “Magnetofossils from Ancient Mars: A Robust Biosignature in the Martian Meteorite ALH84001.” Applied and Environ. Microbiol. 68, 3663-3672 (2002).
[33] Friedmann, E. I., Wierzchos, J. and Ascaso, C. “Chains of magnetite crystals in the meteorite ALH84001: Evidence of Biological Origin.” Proc. Nat. Acad. Sci. 98, 2176-2181 (2002).
[34] BBC News | Sci/Tech | Life on Mars - new claims
[35] McKay, D. S., Thomas-Keprta, K. L., Clemett, S. J. and Gibson, Jr., E. K. “Life on Mars: New Evidence from Martian Meteorites. ” Proc. SPIE, 7441, 744102 (2009).
[36] https://crisisinphysics.wordpress.com/2011/07/03/15-years-since-nasa-claimed-martian-life-in-alh84001/ (2011).
[37] Horowitz, N. H. “*To Utopia and Back*.” W. H. Freeman and Co. New York, p.145 (1986).
[38] Mullen, L. “Born Bone Dry.” Astrobiology Magazine (2004). http://www.astrobio.net/news-exclusive/born-bone-dry/
[39] Deciphering Mars: Follow the Water - Astrobiology Magazine (2005).
[40] Moore, H.J. *et al*., "Surface Materials of the Viking Landing Sites," J. Geophys. Res., 82, 4497-4523 (1977.)
[41] Levin, G.V. “The Viking Labeled Release Experiment and Life on Mars,” Proc. SPIE, 3111, 146-161 (1997).
[42] NASA, Education Resources Catalog: Posters (1997).
[43] Selvans, M. M., Plaut, J. J., Aharonson, O. and Safaeinili, A. “Internal Structure of Planum Boreaum from Mars Advanced Radar for Subsurface and Ionospheric Sounding Data.” Jour. Geophys. Res. Planets, 115, 1991-2012 (2010).
[44] Mars Global Surveyor MOC2-150 Release
[45] Hoover, R. B. and Gilichinsky, D. “Significance to Astrobiology of Microorganisms in Permafrost and Ice.” In *Permafrost Response on Economic Development, Environmental Security and Natural Resource Potential*, Proc. NATO-ARW, NOVOSIBIRSK, SIBERIA, 12-16 Nov. 1998, *NATO Science Series* 76 (Roland Paepe, Ed.) Klewer Publishing, New York, 553-580, (2001).
[46] Paepe, R., Hoover, R. B. and Van Overloop, E. “Patterned Ground as Evidence of Water on Mars,” in *Permafrost Response on Economic Development, Environmental Security and Natural Resource Potential*, Proc. NATO-ARW, NOVOSIBIRSK, SIBERIA, 12-16 Nov. 1998, *NATO Science Series* 76 (Roland Paepe, Ed.) Klewer, New York, 581-588 (2001).
[47] Paepe, R. and Paulissen, E. “Frost wedge forms in relation to their geomorphological and stratigraphical position in Taylor Valley (Antarctica) .” *Geological Survey of Belgium*, 3, 1-23 (1974).
[48] Kessler, M. A. and B. T. Werner, “Self-Organization of Sorted Patterned Ground.” Science, 299, 380-383 (2003).
[49] Hoover, R. B. and Pikuta, E. V. “Psychrophilic and Psychrotolerant Microbial Extremophiles in Polar Environments.” In *Polar Microbiology: The Ecology, Biodiversity and Bioremediation Potential of Microorganisms in Extremely Cold Environments* (Eds. Asim K. Bej, J. Aislabie and Ronald M. Atlas) CRC Press, 115-157 (2009).
[50] Hoover, R. B., “Microfossils and biomolecules in carbonaceous meteorites: implications to the possibility of life in water-bearing asteroids and comets.” Proc. SPIE 9226, 1-24 (2014).
[51] Smith, P. H., *et al.* “Introduction to special section on the Phoenix Mission: Landing Site Characterization Experiments, Mission Overviews, and Expected Science.” J. Geophys. Res., 113, 1029 (2008).
[52] Mellon, M. T.,*et al.* “Ground ice at the Phoenix landing site: Stability state and origin.” J. Geophys. Res.,114, 1991-2012, (2009).
[53] Smith, P. H., *et al.* “H_2O at the Phoenix landing site.” Science, 325, 58–61 (2009).
[54] Stoker *et al.* “Habitability of the Phoenix landing Site.” J. Geophys. Res. Planets, 115, E00E20, 1-24 (2010).
[55] Friedmann, E. I., Hua, M. and Ocampo-Friedmann, R. “3.6 Cryptoendolithic lichen and cyanobacterial communities of the Ross Desert, Antarctica.” Polarforschung 58, 251-259 (1988).

[56] Ambiru, K., Kurihara, M., and Hashimoto, S., "Methyl Chloride production by two marine cyanobacteria: *Synechococcus* sp. (CCMP 1334) and *Synechococcus* sp. (NIES 981). 2012 ASLO Aquatic Sciences Meeting. July 8-13, (2012). 2012 ASLO Aquatic Sciences Meeting: Voyages of Discovery

[57] Brownell, D. K., Moore, R. M. and Cullen, J. J. "Production of methyl halides by *Prochlorococcus* and *Synechococcus*." Global Biogeochemical Cycles, 24 GB2002 (2010).

[58] Scarratt, M. G. and Moore, R. M. "Production of methyl chloride and methyl bromide in the laboratory by cultures of marine phytoplankton." Marine Chemistry, 54, 263-272 (1996).

[59] Soffen, G. A. "The Viking Project." J. Geophysical Research 82, 3959-3970 (1977).

[60] Klein, H. P. *et al.*, "The Viking Biological Investigation: Preliminary Results." Science 184, 4260, 99-105 (1976).

[61] Oyama, V. A. and Berdahl, B. J. "The Viking Gas Exchange Experiment: Results from the Chryse and Utopia Surface Samples." J. Geophysical Research 82, 4669-4976 (1977).

[62] Horowitz, N., Hobby, G. L. and Hubbard, J. S. "Viking on Mars: The Carbon Assimilation Experiments." J. Geophysical Research 82, 4659-4662 (1977).

[63] Levin, G. V. and Straat, P. A. "Viking Labeled Release Biology Experiment: Interim Results." Science, 194, 1322-1329 (1976).

[64] Levin, G. V. and Straat, P. A. "Recent Results from the Viking Labeled Release Experiment on Mars." J. Geophysical Research 82, 4663-4667 (1977).

[65] Biemann, K., Oro, J., Toulmin III, P., Orgel, L. E., Nier, A. O., Anderson, D. M., Simmonds, P. G., Flory, D., Diaz, A. V., Rushneck, D. R. and Biller, J. E. "Search for Organic and Volatile Inorganic Compounds in Two Surface Samples from the Chryse Planitia Region of Mars." Science 184, 72-76 (1976).

[66] Biemann, K., Oro, J., Toulmin III, P., Orgel, L. E., Nier, A. O., Anderson, D. M., Simmonds, P. G., Flory, D., Diaz, A. V., Rushneck, D. R., Biller, J. E. and Lafleur A. L. "The search for organic substances and inorganic volatile compounds in the surface of Mars." J. Geophysical Research 82, 4641-4658 (1977).

[67] Stiober, R. E., Leggett, D. C., Jenkins, T. F., Murrmann, R. P. and Rose, W. I. J. "Organic Compounds in Volcanic Gas from Santiaguito Volcano, Guatemala." Bull. Geol. Soc. Am. 82, 2299-2302 (1971).

[68] Jordan, A. "Volcanic Formation of Halogenated Organic Compounds. Natural Production of Organohalogen Compounds. The Handbook of Environmental Chemistry." (Gribble, G., Ed.) Berlin, Springer 3P, 56-79 (2003).

[69] Lovelock, J. (1975). "Natural halocarbons in the air and in the sea." Nature 256, 193-194 (1975).

[70] Van Pee, K.-H. "Biosynthesis of halogenated metabolites by bacteria." Ann. Rev. Microbiol. 50, 375-399 (1996).

[71] Rittmann, B. E. and McCarty, P. L. "Utilization of Dichloromethane by Suspended and Fixed-Film Bacteria." Appl. Environ. Microbiol. 39, 1225–1226 (1980).

[72] Mckay, C. P. "What is Life-And How Do We Search for It in Other Worlds." PLOS Biology 1, e302 (2004).

[73] Shapiro, R. and Schulze-Makuch, D. "The Search for Alien Life in Our Solar System: Strategies and Priorities." Astrobiology 9, 335-343 (2009).

[74] Studer, A., McAnulla, C., Büchele, R. Leisinger, T. and Vuilleumier, S. Chloromethane-Induced Genes Define a Third C_1 Utilization Pathway in *Methylobacterium chloromethanicum* CM4." Jour. Bacteriology, 184, 3776-3484 (2002).

[75] Klein HP. "Simulation of the Viking biology experiments: an overview." J. Mol. Evol. 14, 161-165 (1979).

[76] Levin, G. V. and Straat, P. A. "A Search for a Nonbiological Explanation of the Viking Labeled Release Life Detection Experiment." Icarus 45, 494-516 (1981).

[77] Levin, G. V. and Straat, P. A. "Antarctic Soil No. 726 and Implications For the Viking Labeled Release Experiment." Jour. Theor. Biol., 91, 41-45 (1981).

[78] Cameron, Roy E. "Antarctic soil microbial and ecological investigations." in *Research in the Antarctic* 137-189 (1971).

[79] Lavoie, J. M. Ph.D. Thesis, Massachusetts Institute of Technology (1979).

[80] Oyama, V. I., Berdahl, B. J., Woeller, F. and Lehwalt, M. "The chemical activities of the Viking biology experiments and the arguments for the presence of superoxides, peroxides, gamma-Fe2O3 and carbon suboxide polymer in the Martian soil." Life Sciences and Space Research 16, 3-8 (1978).

[81] Hecht, M. H., Kounaves, S. P., Quinn, R. C., West, S. J., Young, S. M. M., Ming, D. W., Catling, D. C., Clark, B. C., Boynton, W. V., Hoffman, J., DeFlores, L. P., Gospodinova, K., Kapit, J., and Smith, P. H., "Detection of perchlorate and the soluble chemistry of Martian soil at the Phoenix Lander site", Science, 325, 64-67 (2009).

[82] Smith, P. H., Tamppari, L. K., Arvidson, R. E., Bass, D., Blaney, D., Boynton, W. V., Carswell, A., Catling, D. C., Clark, B. C., Duck, T., DeJong, E., Fisher, D., Goetz, W., Gunnlaugsson, H. P., Hecht, M. H., Hipkin, V., Hoffman, J., Hviid, S. F., Keller, H. U., Kounaves. S. P., Lange, C. F., Lemmon, M. T., Madsen, M. B., Markiewicz, W. J., Marshall, J., McKay, C. P., Mellon, M. T., Ming, D. W., Morris, R. V., Pike, W. T., Renno, N., Staufer, U., Stoker, C., Taylor, P. Whiteway, J. A., and Zent, A. P., "H_2O at the Phoenix Landing Site." Science, 325, 58-61 (2009).

[83] Sutter, B., Ming, D. W., Boynton, W. V., Niles, P. B., Hoffman, J., Lauer, H, V., Golden, D. C., "Summary of results from the Mars Phoenix Lander's Thermal Evolved Gas Analyzer." 40th Lunar Planet. Sci. Conf., Abstract 8004 (2009).

[84] Ming, D. W., Lauer, Jr., H. V., Archer, Jr., P. D., Sutter, B., Golden, D. C., Morris, R. V., Niles, P. B., and Boynton, W. V., "Combustion of organic molecules by the thermal decomposition of the perchlorate salts: Implications for organics at the Mars Phoenix Scout Landing site:, 40th Lunar Planet. Sci. Conf., Abstract 2241 (2009).

[85] Kolb, V. M. and Hoover, R. "Perchlorates are Compatible with Life on Earth-Why Not Mars?" Proc. SPIE 8865, *Instruments, Methods, and Missions for Astrobiology XVI*, 886504 (2013)

[86] Coates, J. D. and Achenbach, L. A. "Microbial Perchlorate Reduction: Rocket Fueled Metabolism." Nature Reviews Microbiology, 2, 569-580 (2004).
[87] Thrash, J. C., Ahmadi, S., Torok, T. and Coates, J. D. "*Magnetospirillum bellicus* sp. nov., a Novel Dissimilatory Perchlorate-Reducing Alphaproteobacterium Isolated from a Bioelectrical Reactor." Appl. and Environ. Microbiol. 76, 4730-4737 (2010).
[88] Salinero, K. K, Keller, K., Feil, W. S., Feil, H., Trong, S., Di Bartolo, G. and Lapidus, A. Metabolic analysis of the soil microbe *Dechloromonas aromatica* str. RCB: indications of a surprisingly complex life-style and cryptic anaerobic pathways for aromatic degradation. BMC Genomics 10:351, pp. 1-23 (2009).
[89] NASA Goddard Instrument's First Detection of Organic Matter on Mars | NASA
[90] Reinekel, W. and Knackmuss, H-J. "Microbial Metabolism of Haloaromatics: Isolation and Properties of a Chlorobenzene-Degrading Bacterium." Appl. and Environ. Microbiol. 47, 395-402 (1984).
[91] Gribble, W. "The Diversity of Naturally Produced Organohalogens." Chemosphere, 52, 289-297 (2003).
[92] Levin, G. V., Miller, J. D., Straat, P. A., Lodder, R. A. and Hoover, R. B. "Detecting Life and Biology-Related Parameters on Mars, IEEE Aerospace Conference, vol. 1, (2007).
[93] Levin, G. V. "Solving the Problems with Chirality as a Biomarker for Alien Life." Proc. SPIE, 7819, 14-24 (2010).
[94] http://mars.nasa.gov/mer/technology/si_in_situ_instrumentation.html
[95] http://mars.nasa.gov/mer/gallery/all/1/m/034/1M131201538EFF0500P2933M2M1.HTML
[96] Mars Exploration Rover Mission: Multimedia: All Raw Images: Opportunity: Microscopic Imager: Sol 034
[97] http://mars.nasa.gov/mer/gallery/all/1/m/034/1M131212854EFF0500P2959M2M1.JPG
[98] Misra, A. K., Acosta-Maeda, T. E., Scott, E. R. D., and Sharma, S. K. "Possible Mechanism for Explaining the Origin and Size Distribution of Martian Hematite Spherules." Planetary and Space Science, 94, 16-23 (2014).
[99] Wachsmuth, C. and Springer, F.., "*The North American Crinoidea Camerata*." Mem. Mus. Comp. Zool. Harvard, Vol. XXI, Cambridge, U.S.A. p.197, Pl. 9, Fig.1a (1897).
[100] Shimer, H. S. and Shrock, R. "Index Fossils of North America." Wiley and Sons, pp. 1-837 (1959).
[101] Moore, R. "Ray Structures of Some Inadunate Crinoids." *Echinodemata 5*, Univ. of Kansas Paleontological Contributions Article 29, pp. 1-48, (1962). https://kuscholarworks.ku.edu/handle/1808/3803
[102] https://kuscholarworks.ku.edu/bitstream/handle/1808/3803/paleo.article.029op.pdf?sequence=3&isAllowed=y
[103] Oji, T., Ogawa, Y., Hunter, A., & Kitazawa, K. "Discovery of Dense Aggregations of Stalked Crinoids in Izu-Ogasawara Trench, Japan." *Zoological Science*, 26, 406-408 (2009).
[104] Amaziane, N. and Roux, M. "Biodiversity and Historical Biogeography of Stalked Crinoids (Echinodermata) in the Deep Sea." Biodiversity and Conservation 6, 1557-1570 (1997).
[105] Goesmann *et al.*, "Organic compounds on comet 67P/Churyumov-Gerasimenko revealed by COSAC mass spectrometry." Science 349, 689-702 (2015).
[106] Schupak, A. "Rosetta's First Color Photo of Comet." CBS News, Dec. 2, 2014 11:33 AM (2014). http://www.cbsnews.com/news/rosettas-first-color-photo-of-comet/
[107] Hviid, S. *et al.* "Color Variegation on 67P Churymov/Gerassimenko." AGU Fall Meeting, Paper 22395, San Francisco 15-19 Dec. (2014). 2014 AGU Fall Meeting
[108] http://www.huffingtonpost.com/2014/12/15/color-comet-photo_n_6325622.html
[109] http://aventalearning.com/courses/BIOx-CR-A09/a/unit2/section2_03.html
[110] Anderson, D. T., Sumner, D. Y., Hawes, I., Webster-Brown, J., and McKay, C. P. "Discovery of Large Conical Stromatolites in Lake Untersee, Antarctica." Geobiology, 9, 280-293 (2011).
[111] Blondeau-Patissier, D., Gower, J. F. R., Dekker, A. G., Phinn, S. R. and Brando, V. E. "A review of ocean color remote sensing methods and statistical techniques for the detection, mapping and analysis of phytoplankton blooms in coastal and open oceans." Progress in Oceanography, 123, 123-144 (2014).
[112] Gounelle, M., Spurn, P. and Bland, P. A. "The orbit and atmospheric trajectory of the Orgueil meteorite from historical records." Meteoritics and Planetary Science." 41, 135-150 (2006).
[113] Hoover, R. B. "Comets, Carbonaceous Meteorites and the Origin of the Biosphere" *in* Biosphere Origin and Evolution (N. Dobretsov, N. Kolchanov, A. Rozanov and G. Zavarzin, Eds.) Springer US, New York 55-68, (2008). http://www.springerlink.com/content/u173842732801741/
[114] Hoover, R. B. "Fossils of Cyanobacteria in CI1 carbonaceous meteorites: Implications to Life on Comets, Europa, and Enceladus." In *Biological Cosmology, Astrobiology, Origins and Evolution of Life* (Eds. R. Joseph, R. Schild and C. Wickramasinghe) pp. 58-94 (2010).
[115] Hoover, R. B. **"**Fossils of Prokaryotic microorganisms in the Orgueil meteorite," *Instruments, Methods, and Missions for Astrobiology IX*, Proc. SPIE **6309,** 630902 (2006).
[116] http://sci.esa.int/rosetta/14615-comet-67p/
[117] Hoover, R. B., Wallis, J., Wickramarathne, K., Samaranayake A., Williams, G., Jerman, G., Wallis, D. H. and Wickramasinghe, N. C. "Fossilized Diatoms from Recent Falls in Sri Lanka." Proc. SPIE 8865, 886506 (2013).
[118] http://www.theregister.co.uk/2013/03/11/comet_algae_hystrichospheres/
[119] Hoover, R. B. and Rozanov, A. Yu. "Acritarchs in Carbonaceous Meteorites in Terrestrial Rocks." Proc. SPIE 8865, 8865, 886507 (2013).