Mars: Evolution of Life in the Oceans? Episodes of Global Warming, Flooding, Rivers, Lakes, and Chaotic Orbital Obliquity

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Abstract

Mars has been subject to repeated waxing and waning episodes of extreme chaotic obliquity (axial tilting) for at least four billion years. Obliquity is currently at 25.19 degrees and has exceeded 80°. Each time obliquity exceeds 40° increased Martian atmospheric pressures and global temperatures cause the melting of glaciers and permafrost and subsurface ice, and result in oceans, lakes and rivers of water flooding across the surface then stabilizing and enduring for hundreds of thousands of years or longer. There is evidence that within these seas evolved stromatolite constructing cyanobacteria, green algae, acritarchs, foraminifera, seaweed, and marine metazoan invertebrates including sponges, tube worms, crustaceans, reef-building corals, bivalves, and those resembling *Kimberella*, *Namacalathus* and *Lophophorates;* all of which (with the possible exception of algae, fungi, lichens) may have become extinct. The last episode of extreme obliquity may have begun over a million years in the past and endured until 110,000 years ago. Subsequently, as axial tilting declined, the waters of Mars seeped back beneath the surface forming vast aquifers and glacial deposits of water-ice and the remainder froze at the poles and atop dusty layers of icy-sediment: the remnants of previous obliquity-driven freeze-thaw cycles that may have caused life to evolve and oceans and lakes to repeatedly form, stabilize, endure then freeze.

Key Words: Cyanobacteria, Green Algae, Fungi, Lichens, Microbial Mats, Stromatolites, Greater Barrier Reefs, Reef building Corals on Mars, Mollusks, Life on Mars

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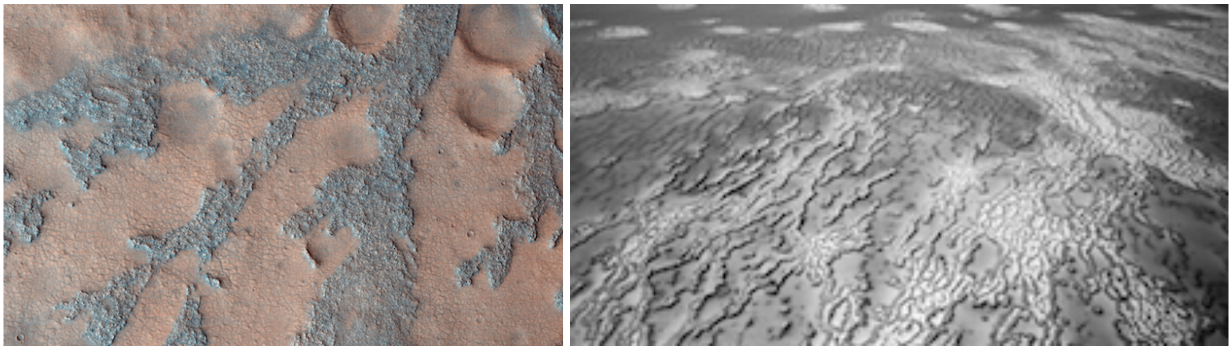
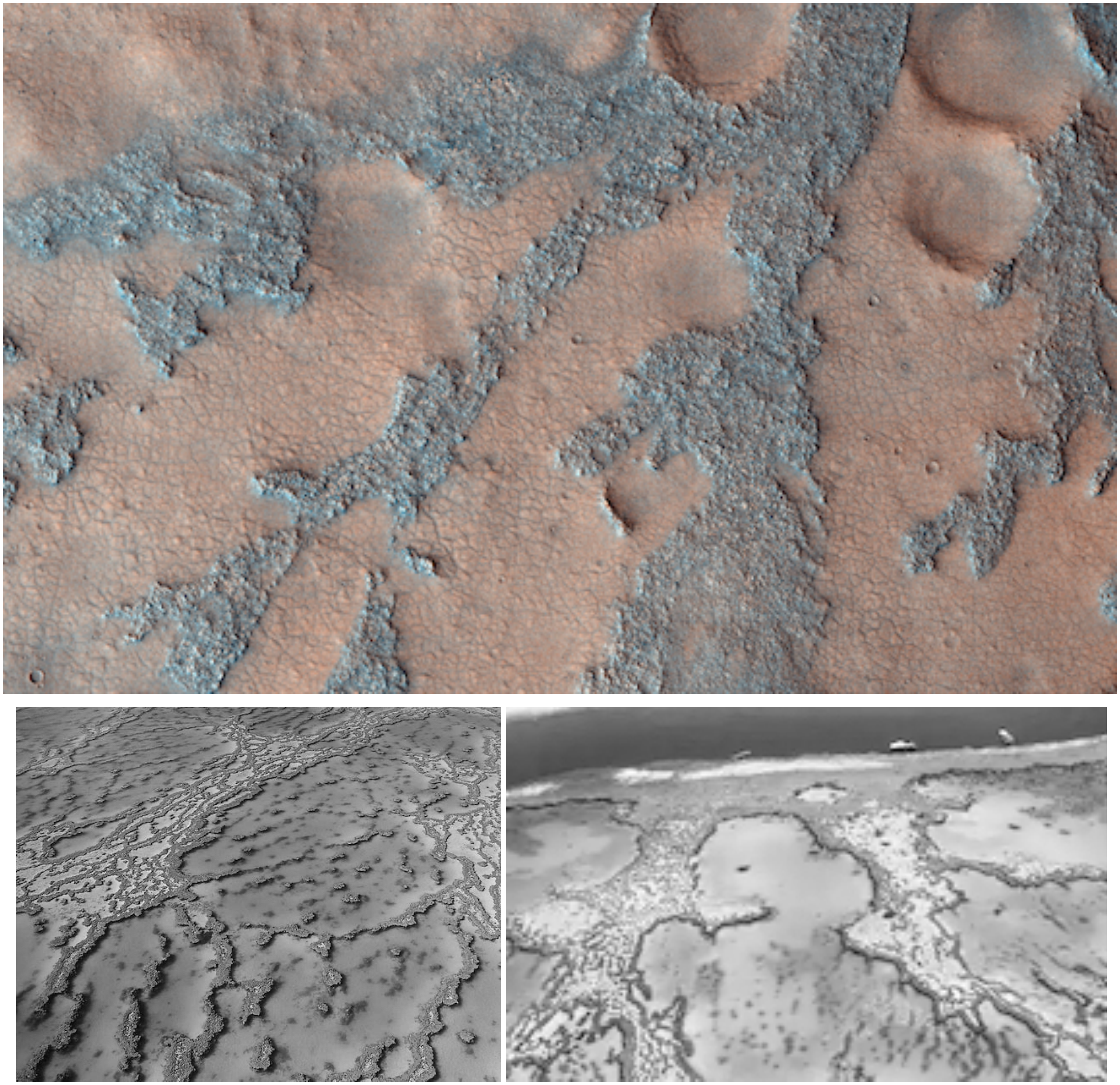
Evolution of Martian Life and Chaotic Obliquity

Due to its elongated elliptical orbit and lack of a large stabilizing moon, Mars has been subject to repeated chaotic episodes of extreme obliquity (axial tilt) up to 80 degrees and more, and has experienced repeated periods of global warming, and increases in atmospheric pressure, humidity and sedimentary thermal conductivity that melted glaciers and permafrost thereby causing massive floods and the formation of oceans, lakes and inland seas that endured and remained stable for hundreds of thousands and perhaps millions of years (Figures 1-25, 27-29). As obliquity decreased, the surface waters of Mars began to recede, evaporate and freeze; and then this chaotic cycle would repeat. And, there is published evidence that within these episodic Martian oceans and lakes: bacteria, cyanobacteria, green algae, acritarchs, foraminifera (protists), and other marine organisms may have flourished and evolved including metazoan fauna resembling sponges, tube worms, crustaceans, *Kimberella, Namacalathus*, *Lophophorates* and other marine invertebrates (Figures 30-120) including rock-boring bivalves and corals that may have fashioned massive elevated elongated formations reminiscent of great coral reefs (Figures 1-4, 75-77).

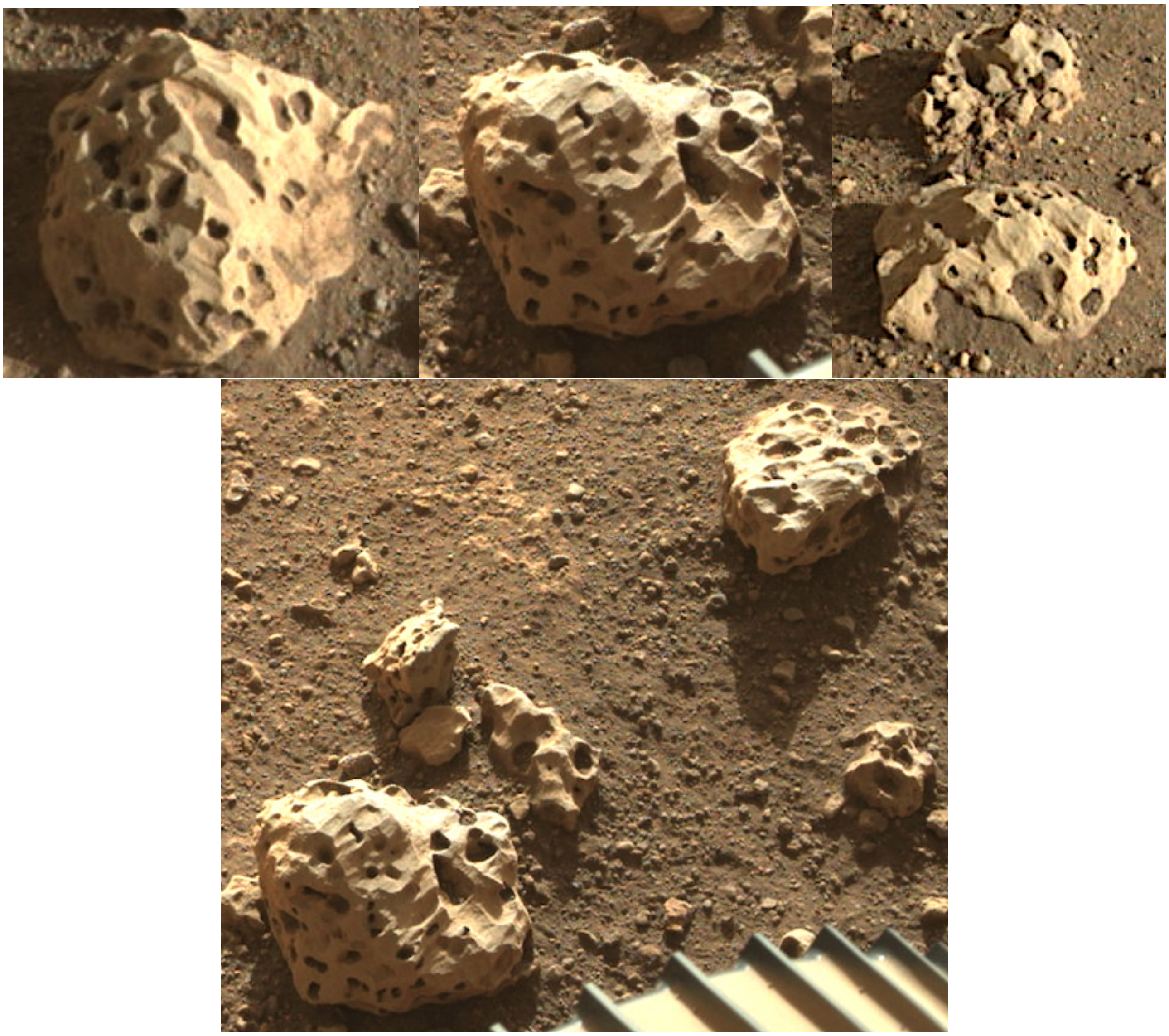
Orbital observations and surface level studies conducted via the Mars rovers (Duran et al. 2019; Fawdon et al. 2018; Poulet et al. 2005; Rampe et al. 2020), document that water repeatedly flowed and pooled upon the surface forming rivers and lakes (e.g., Barnhart et al., 2009; Hynek et al., 2010; Matsubara et al., 2013; Ramirez & Craddock, 2018), and providing a habitable environment even billions of years ago (Ehlmann et al. 2011; Grotzinger et al., 2014; Squyres et al. 2004, Thomas-Keprta et al., 2009). That Mars also had oceans is evident based on geological features including the smooth flat lowland basin circling the northern hemisphere bordered by rugged highlands in the southern hemisphere (Duxbury 2000; Parker et al. 1986, Head et al. 1999, Ivanov et al. 2014; Ramirez et al. 2020). There is also evidence of hundreds of paleolakes and paleoshorelines in the northern lowlands (Scott et al. 1995, Fairén et al. 2003; Carr & Head 2015), and catastrophic floods (Dickeson & Davis 2020; Fairén et al. 2003; Warner et al., 2014) that formed lakes and rivers for unknown lengths of time (Treiman 2008; Davis et al. 2018) which were heated by volcanic and hydrothermal forces ((Ehlman et al., 2011; Ruff et al. 2011; Michalski et al., 2017; Joseph et al. 2021a,b; Suamanarathna et al. 2021a); and then, these waters would rapidly recede (Figures 78-81) as also indicated by prograding channels (Fawdon et al. 2018). However, that these episodic floods repeatedly produced rivers, lakes and oceans that remained stable and endured would have also enabled a variety of Martian marine organisms to flourish including colonies of rock-dwellers and reef builders.



Figures 1: **Mars (Left)**, Antoniadi Basin. HiRISE photograph of a 1km (0.6 mile) section of Antoniadi Crater (330 km / 230 mi in diameter) that may have hosted an inland sea. The branched ridges are approximately 1 to 5 m high. **Earth** (Right), the Great Barrier Reefs of Australia, orbital view, desaturated photo.



Figures 2: **Mars (Top)**. Antoniadi Basin. HiRISE photograph of a 1km (0.6 mile) section of Antoniadi Crater (which is 330 km / 230 mi diameter) and likely hosted an inland sea. The branched network of ridges are approximately 1 to 5m high and were formed in association with lake water and consist of an unknown hard substance and were not formed by river or fluvial channels (Nicolas et al. 2021; Mangold, et al. 2021). Instead, they resemble the Great Barrier Reefs of Australia as viewed from space and may be the fossil remains of coral reefs constructed by vast colonies of stony corals (scleractinians / polyps) which have skeletons of calcium carbonate. As colonies grow, reproduce and die, the next generation builds upon their skeletal remains. Reefs include the fossil remains of sponges, mollusks, clams, oysters, and a variety of crustaceans. Evidence of Martian bivalves can be viewed in Figures 3, 4. Corals form a symbiotic relationship with algae (zooxanthellae) which provide the polyp with energy via photosynthesis and calcium carbonate which these organisms also extract from seawater and forms a hard exoskeleton that protects their soft, sac-like bodies. As documented in this report, there is substantial evidence of algae on Mars. Corals typically build reefs in shallow bodies of water. **Earth** (Right), the Great Barrier Reefs of Australia, orbital view, desaturated photos.



Figures 3: Mars. Sol 3. Jezero Crater is believed to have hosted an ocean of water and the holes in these rocks are remarkably similar to those produced by marine organisms (mollusks / bivalves). Photo by Rover Perseverance

Figures 4: Earth. Rocks found along ocean shorelines. These holes are formed by marine organisms, including mollusks (bivalves) which drill and tunnel into rocks along the sea shore creating a tiny "cave" in which they can dwell. As these bivalves grow they chisel away more of the surrounding rock. Long term exposure to sea water will destroy their shells leaving empty holes (Left photo by Dr. Jessica Winder. Right Photo by R. Joseph).

Like the waters of Earth, much of the oceans and seas of Mars were most likely initially deposited from space and originated in the hundreds of thousands of watery comets and asteroids that bombarded the planets of the inner solar system over 3.8 billion years ago (O'Brien et al. 2018; Lis et al. 2019; Marov & Ipatov 2018). And it is highly probable this watery-stellar debris harbored microbial life, including cyanobacteria and fungi (Beech et al. 2018; Joseph 2000; Joseph et al. 2020a; Mileikowskya et al. 2000; Galdman et al. 2005) and/or that life was repeatedly transferred to and fro between Earth and Mars (del Gaudio 2014; Joseph et al. 2019). Thus, there is evidence of life on Earth (Manning 2006; Mojzsis et al. 1996; O'Neil et al. 2008; Rosing & Frei 2004) and Mars dated to over 3.7 billion years ago (Clement et al. 1998; Macey et al. 2020; McKay et al. 1996, 2009; Norland et al. 2010; Thomas-Keprta et al. 2009) including, in the waters of Mars, chemolithoautotrophic and sulfur oxidizers (Macey et al. 2020) as well as carbonate- iron-eating and magnetotactic bacteria and cyanobacteria: an interpretation supported by polycyclic aromatic hydrocarbons, magnetite crystals, and carbonate globules discovered in Martian Meteorite ALH 84001 (Clemett et al. 1998; McKay et al. 1996, 2009; Thomas-Keprta et al. 2002, 2009) and which are "compatible with living processes" (Martel et al 2012). Moreover, these organisms lived within an oxygenated aqueous environment (Halevy et al. 2011; McKay et al. 1996, 2009; Thomas-Keprta et al. 2009; Shaheen et al. 2015). As oxygen is produced primarily via biological photosynthesis with cyanobacteria serving as the main non-plant source of carbon fixation and are the only known prokaryote capable of photosynthesis, the presence of oxygen supports the hypothesis that ocean and lake-dwelling photosynthesizing, oxygen producing and stromatolite-building cyanobacteria had also colonized Mars over 3.7 billion years ago (Noffke, 2015; Joseph et al. 2019, 2020b; Elewa 2021) at around the same time as life and stromatolites appeared on Earth (Allwood et al. 2009; Garwood 2012; Nemchin et al. 2008; Nutman et al., 2016; Tashiro et al., 2017).

Analysis of ALH 84001 indicates that biological activity and oxygen production may have fluctuated in response to repeated episodes of waxing and waning aqueous activity (Shaheen et al. 2015) including within "a gradually evaporating, subsurface water body--likely a shallow aquifer" perhaps a few meters below the surface and with wet followed by dry spells; and with water levels gradually evaporating (Halevy et al 2011) only to be followed by another episode of hydration (Shaheen et al. 2015). The episodic presence of liquid water supports the likelihood Mars was subject to waxing and waning cycles of extreme obliquity over 3.7 billion years ago (Ward 1973; Head et al. 21003; Laska et al. 2002), such that, as axial tilting approached and increased to 40° then 60° or more, glaciers and permafrost melted and flooded the surface, forming ponds, lakes, inland seas, and oceans that remained stable due to global warming and increased atmospheric pressure, only to eventually evaporate and freeze as obliquity waned and atmospheric pressures and temperatures dropped. And then the cycle would repeat (Head et al. 2003; Kite et al. 2017; Toon et al. 1980; Jackosky et al. 1995). This scenario is compatible with evidence presented in this report and orbital, telescopic, and surface based studies that provide evidence of repeated episodes of catastrophic floods that waxed, stabilized, and then waned (Dickeson & Davis 2020; Fairén et al. 2003; Warner et al. 2014; Davis et al. 2018) due to chaotic fluctuating extremes in the angle of axial tilt.

Within the last several million years, the axial tilt of Mars has inclined to between 60° and 80° (Head et al. (2003; Laska et al. 2002, 2004). These episodic, chaotic episodes of obliquity, and catastrophic alterations of the biosphere would have also caused mass extinctions (Elewa & Joseph, 2009; Joseph 2010a). Because the changing environment acts on gene selection, these extreme changes may have rapidly promoted evolutionary innovation, change and adaptations, possibly leading to a Martian "Cambrian Explosion" of life much sooner and at a much faster rate as compared to life on Earth (Joseph 2000, Joseph & Duvall 2021); though it is equally possible life evolved more slowly on Mars, and/or that life was repeatedly transferred via bolides and solar winds. What is notable are the published observations of Martian specimens that resemble metazoan invertebrates (Figures 75, 76, 78, 82, 90-108) as well as those completely unlike the organisms of Earth (Figures 115-118).

After these oceans of water flowed upon the surface for hundreds of thousands and even millions of years, only to gradually recede in response to waning obliquity, they left behind paleolakes, inland seas, and water filled craters (Duxbury et al. 2001; Scott et al. 1995, Fairén et al. 2003, Carr 2007; Carr & Head 2015) that also eventually receded, evaporated, or flowed back and froze beneath the surface leaving in their wake evidence of what are believed to be microbialites (Bianciardi et al. 2014, 2015; Joseph 2014; Noffke 2015; Small, 2015, Rabb 2018; Rizzo & Cantasano 2009, 2015), concentric and layered stromatolites (Joseph et al. 2020b, 2022) and fossilized cyanobacteria, green algae and acritarchs (Kazmierczak 2016 , 2020; Rizzo et al. 2020, 2021; Bianciardi et al. 2021; Joseph et al. 2020c); and over billions of years of time, the fossilized remnants of specimens that resemble siliceous filamentous sponges, crustaceans, and assemblages similar to *Kimberella, Namacalathus* and *Lophophorates* (Joseph et al. 2020d), as well as sponges, corals (Armstrong 2022) and tube worms (DiGregorio 2018; Joseph et al. 2020c,d, 2021a; Baucon et al. 2020; Armstrong 2021a; Suamanarathna et al. 2021a).

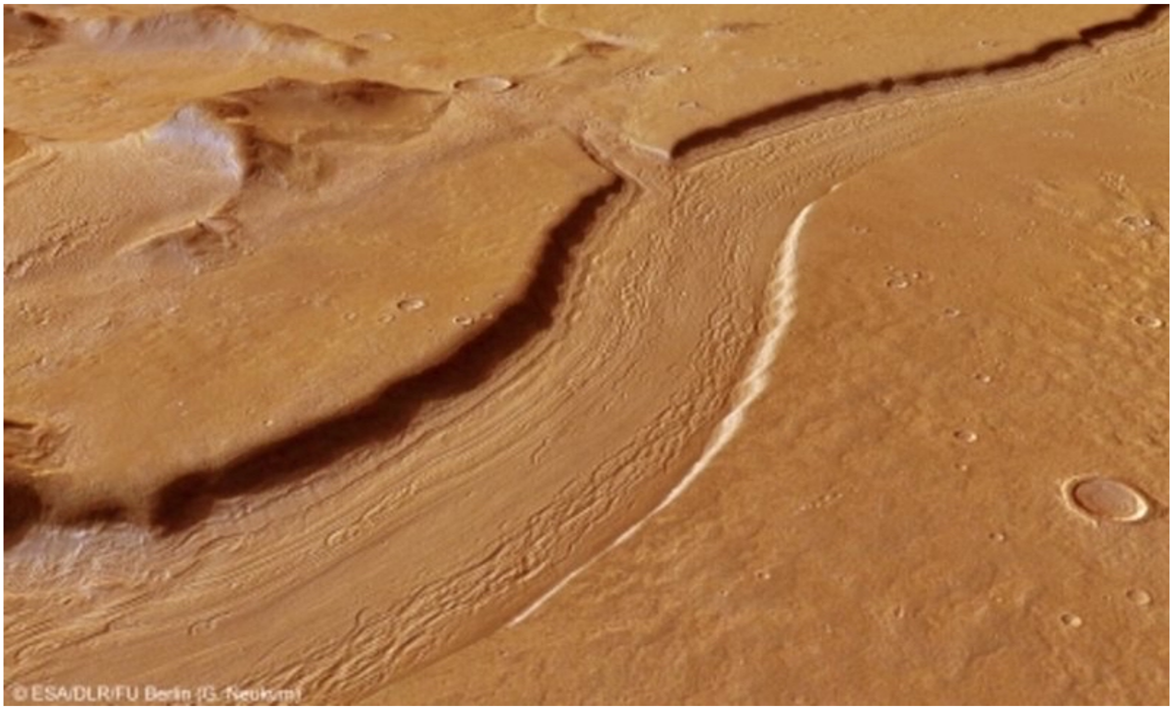

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Figure 5: **Mars.** Computer-generated perspective view of a massive river bed over 300 km in length, running through Reull Vallis, Mars. Created from data obtained via ESA's Mars Express High-Resolution Stereo Camera photographed at a respective apoareion and periareion altitude of 10,107 km (6,280 mi) and 298 km (185 mi) above Mars.

Figure 6: **Mars.** Massive lake and branching river beds over 300 m in length running through Reull Vallis, Mars. Photographed by ESA's Mars Express. High-Resolution Stereo Camera.

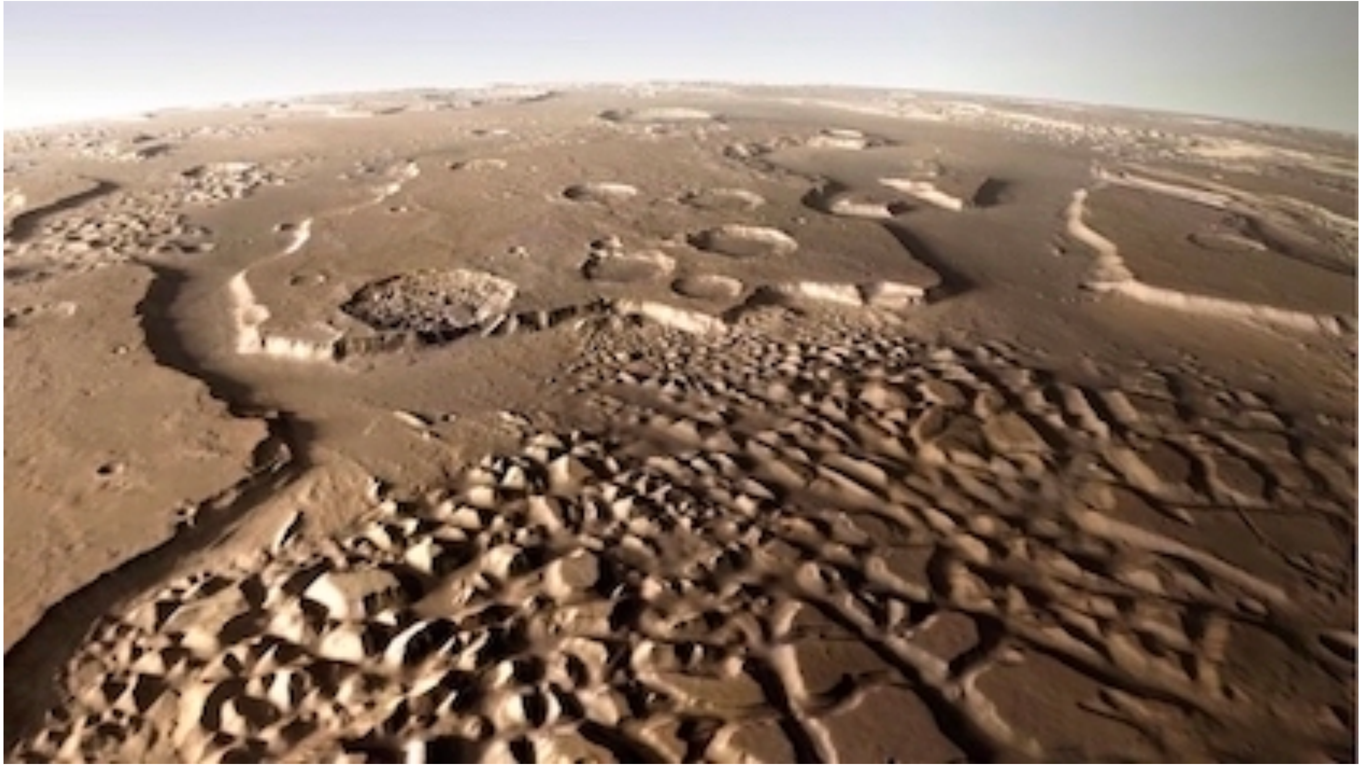


Figure 7: Mars. Rivers, lakes, and an inland sea, in the Hydraotes Chaos, Mars. Photographs by ESA's Mars Express at a apoareion and periareion altitude of 10,107 km (6,280 mi) and 298 km (185 mi) above Mars.

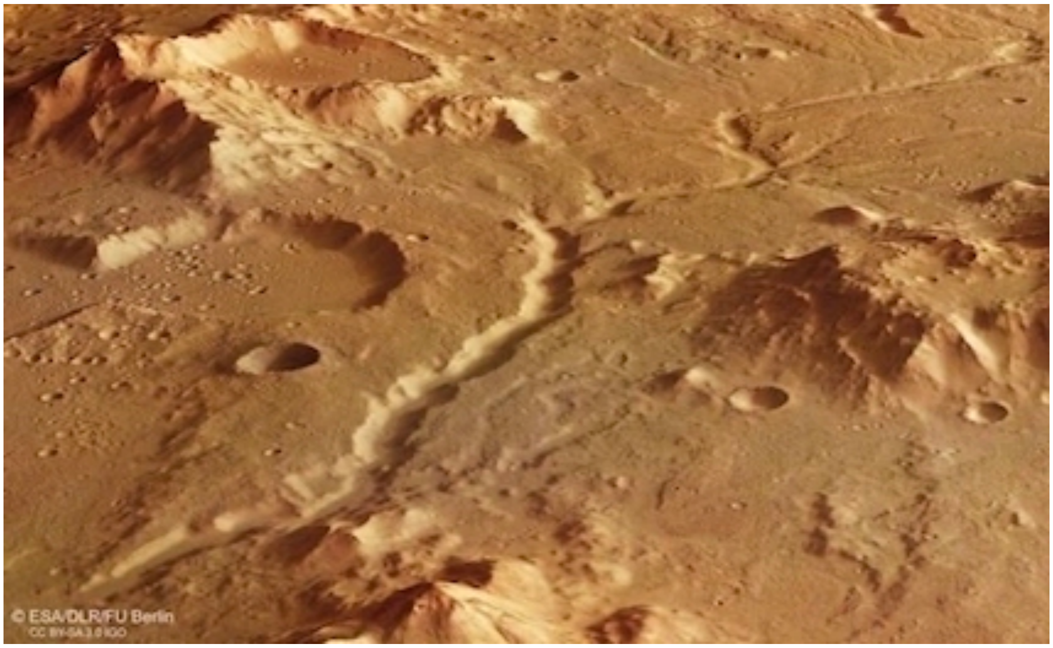


Figure 8: **Mars.** Orbital photo, at a respective apoareion and periareion altitude of 10,107 km (6,280 mi) and 298 km (185 mi) above Mars. Dried lakes and a long winding river channel over 500 km in length in the Libya Montes region close to the equator on Mars. The lake and the river were fed by numerous tributaries arising from rainfall, flooding, and surface runoff. Orbital photographs by ESA's Mars Express. High-Resolution Stereo Camera.

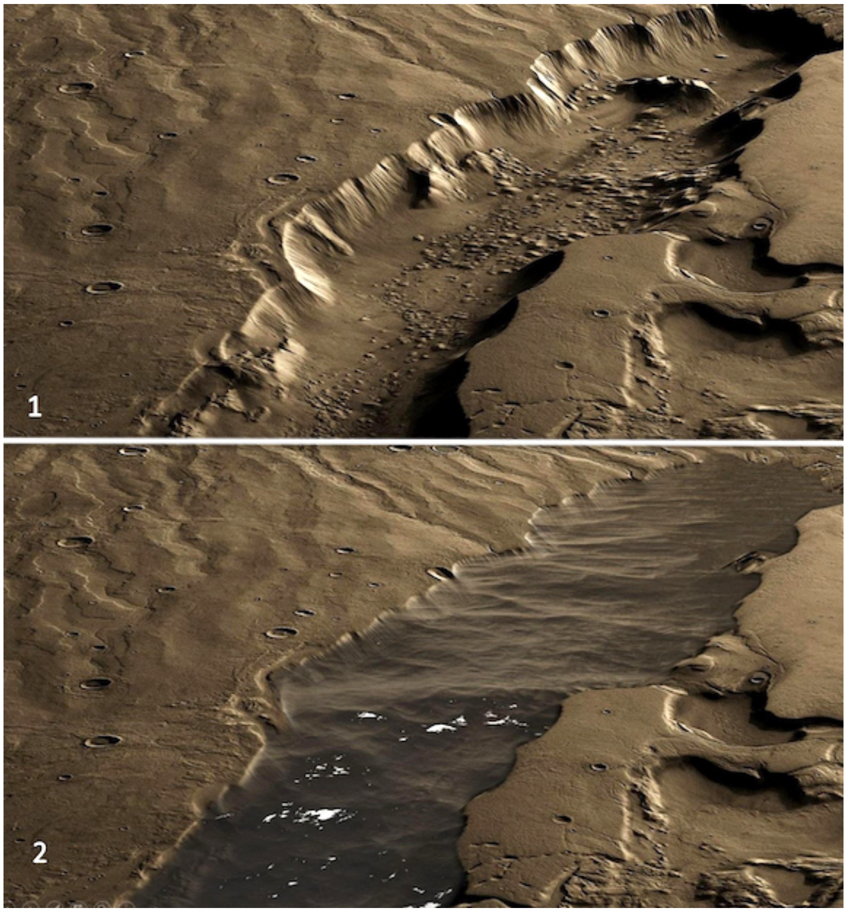


Figure 9: (**Mars** Top-1): Dao Vallis river valley. A vertically exaggerated, false-color view of a wide and lengthy water-carved channel (ESA/DLR/FU Berlin, CC BY-SA 3.0 IGO. 3D rendered and colored by Lujendra Ojha). (Bottom-2). Modified 3d reconstruction of river flow in Dao Vallis river valley (Suamanarathna et al 2021b).

Chaotic Obliquity and Moonless Nights Prevent Evolution of Intelligent Extraterrestrial Life

A large moon (in addition to the sun and other planets) exerts a gravitational coupling effect on a planet's equatorial bulge that affects the precession of the spin axis and axial tilt as it orbits the sun. A moonless planet, especially if it has an extreme elliptical orbit, will undergo large-amplitude, chaotic fluctuations in obliquity on time scales of 10 myr; conditions that would profoundly affect global temperatures, atmospheric pressure and the evolution of life (Laskar & Robutel 1993). Hence, although there is substantial evidence that cyanobacteria, green algae, fungi, lichens and other organisms have colonized Mars (Armstrong 2021b; del Gaudio, 2014; Dass, 2017; Joseph, 2014, 2016; Joseph et al. 2019, 2020c,e,f, 2021c; Latif et al. 2021; Rabb, 2018; Small 2015) and that invertebrates may have evolved (Joseph et al. 2020d, 2021a,b, 2022; Baucon et al. 2020; Elewa 2021; Armstrong 2021a; 2022; Suamanarathna et al. 2021a) there is no evidence of Martian fish, reptiles or "higher life forms."

Likewise, although there may be hundreds of millions of Earth-like planets in this galaxy, if they lack a large stabilizing moon and have a highly eccentric orbit, then life on these worlds may have evolved only to the level of metazoan invertebrates. If we consider the unique circumstances in which Earth's moon was formed and how uncommon this must be among habitable planets; then, because of chaotic obliquity, the evolution of intelligent, human-like life in this and other galaxies would be extremely rare even on Earth-like water worlds. Instead, on Earth-like moonless water worlds, evolution may have progressed only to the level of cartilaginous-bony fish, amphibians, and reptiles that physically adapted to these extremes; organisms capable of long periods of dormancy or life within aquifers, caves and tunnels beneath the surface.

The Frozen Oceans, Rivers, and Lakes of Mars

Estimates are that the Martian oceans had an initial depth ranging from 50 to 80 meters (Barth 1974; Zhang et al. 2012) to over 1 kilometer (Lasue et al. 2013). It is also evident that Martian lakes, rivers, inland seas and oceans have repeatedly flowed upon the surface, only to become frozen at or beneath the surface in the distant past (Duxbury et al. 1999; Fairén et al. 2010, Head et al. 1999, 2003; Kite et al. 2017); a likely function of chaotic and extreme increases in axial tilt followed by reductions in obliquity. And as these waters froze, they became dust and CO_2 covered surface and subsurface glaciers and layered ice sheets (Holt et al. 2008; Head et al. 1999; Barker & Bhattacharya 2018, Janhunen 2002; Clifford, 2018); evidence of repeated cycles of extreme obliquity.

How much of the Martian oceans are buried beneath the soil is unknown. However, an estimated 3.2 million cubic km of water ice in layers approximately 2 to 3 km thick appears to be concentrated at the poles (Carr & Head 2003; Plaut et al. 2007; Byrne et al. 2009; Sori et al. 2019) and which are topped by slabs of CO_2 that are believed to be 1 meter to 8 meters thick respectively (Kiefer et al. 2006; Fishbough 2001). Rivers and lakes of pure water-ice have been detected beneath the southern polar caps (Byrne et al. 2009; Sori et al. 2019; Orsei et al. 2018, 2020; Lauro et al. 2020); and approximately 90% of the frozen polar region consists of pure water-ice (Bierson et al. 2016; Foss et al. 2017; Thomas et al. 2016). In addition, Conway et al. (2014) detected 30-meters of thick layers of dust-covered ice extending from the poles to the midlatitudes, covering at least 23% of the surface, containing between 46% and 95% ice by volume and accounting for ~104 km^3 of near-surface ice. Neutron spectroscopy determined that ice sheets extend upward from the south pole into the lower latitudes (Feldman et al. 2002). The

Dorsa Argentea Formation, in particular, appears to consist of a large body of ice water which may be the remnants of a much larger glacier that had melted, flooded, and the remainder partially refroze (Fastook et al. 2012).

Dust covered glacial deposits and subsurface water-ice have also been detected in the Hellas region of Mars by the Shallow Radar on the Mars Reconnaissance Orbiter (Holt et al. 2008); and cliffs composed of layered sheets of water ice over 100 meters thick, extending 1-2 meters beneath the surface have been reported (Dundas et al. 2018). Putzig et al. (2014), employing the Shallow Radar on the Mars Reconnaissance Orbiter reported 2900 km^2 of ground ice in a depression at the northern Phoenix landing site extending from the near surface to ~15–66 m below ground. Using ground-penetrating reflecting radar, a mixture of ice, air, and dirt, and up to 14,300 km^3 of water-ice has been reported by Stuurman et al. (2016) in the Utopia Planitia region, whereas Bramson et al. (2015), reports a widespread, decameters-thick layer of water-ice in this same area, ~104 km^3 in volume.

There are also numerous ice-filled craters throughout the northern and southern latitudes (Conway et al., 2012; Massé, 2010; Shean, 2010) as well as glaciers on the Tharsis volcanoes (Head & Marchant, 2003; Shean et al., 2005). Moreover, Valles Marineris, the vast canyon system along the Martian equator --which has a depth 7 km (4 mi) and length of 4000 km (2500 mi)-- has been repeatedly glaciated; and it has been estimated that various chiasmas have been covered with glaciers with a thickness ranging from 700 m to 2000 m, and a total thickness of more than $0.3 \cdot 10^6$ km^3, and a total ice volume of more than 10^6 km^3 (Gourronc et al 2013). And these glaciers have repeatedly melted, causing catastrophic floods to fill the canyons of Valles Marineris and form rivers and lakes that stabilized and endured (Warner et al. 2014; Davis et al. 2018). In fact clouds water-ice produced by melt-water vapor continue to form above Valles Mariners (Noctis Labyrinthus) as first documented by the Viking 1 orbiter (Figure 10) whereas substantial amounts of ice-water are buried about 1 meter beneath the surface (Mitrofanova et al. 2022a); and this indicates the last episode of global warming came to an end approximately 100,000 years ago, as will be explained.

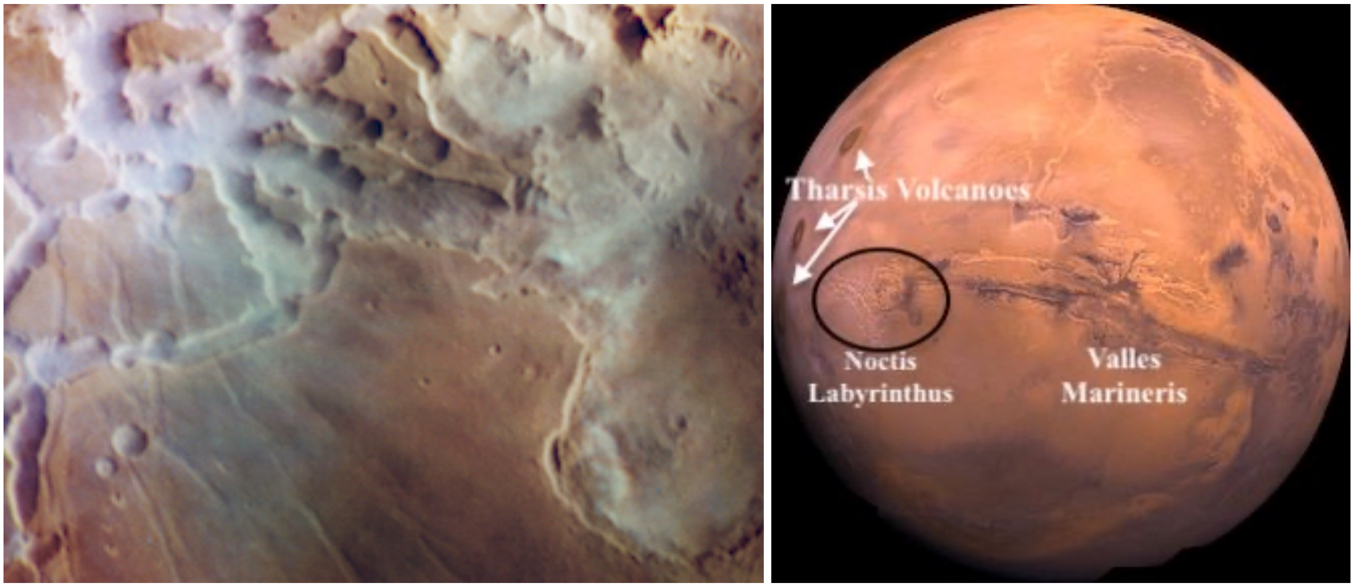


Figure 10: (Left) Clouds of water ice and fog rising above Noctis Labyrinthus, Valles Marineris (Viking 1 orbiter image).

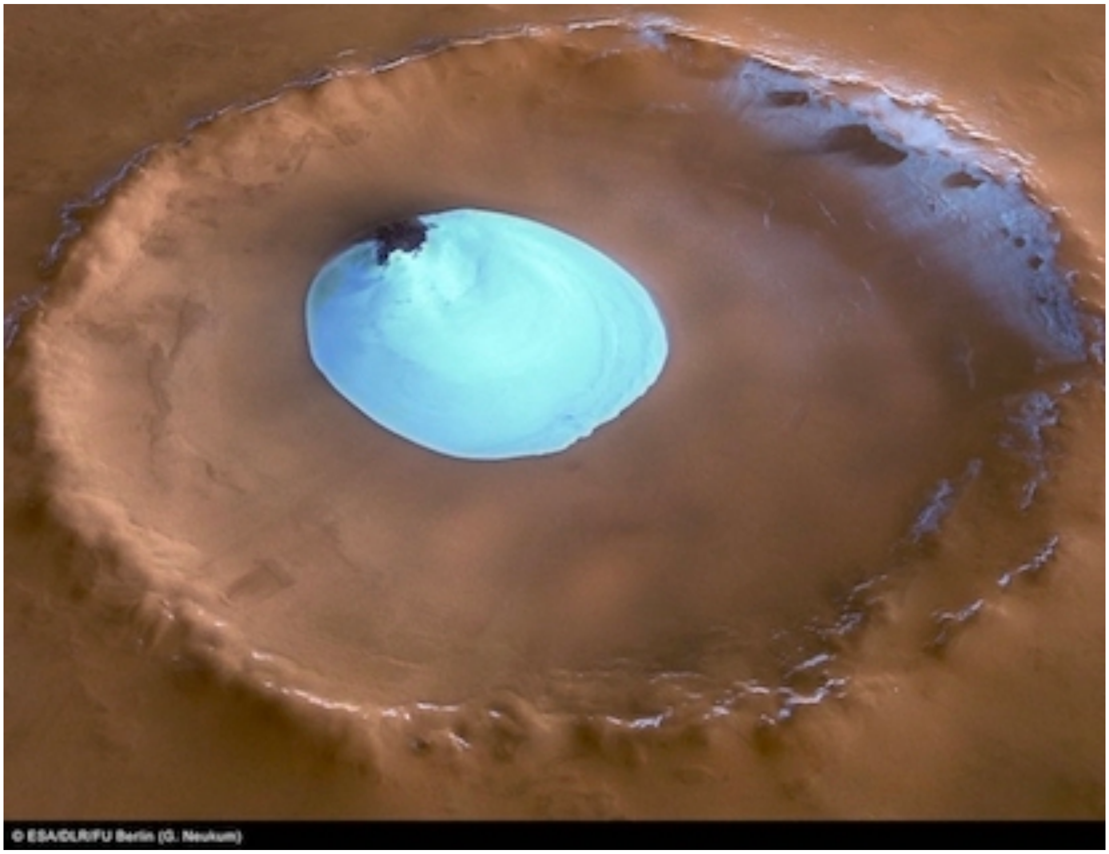


Figure 11: **Mars.** A lake of ice within a crater located in Vastitas Borealis, Mars. Photographed by ESA's Mars Express at a respective apoareion and periareion altitude of 10,107 km (6,280 mi) and 298 km (185 mi) above Mars. Frost and ice on the crater walls can also be viewed.

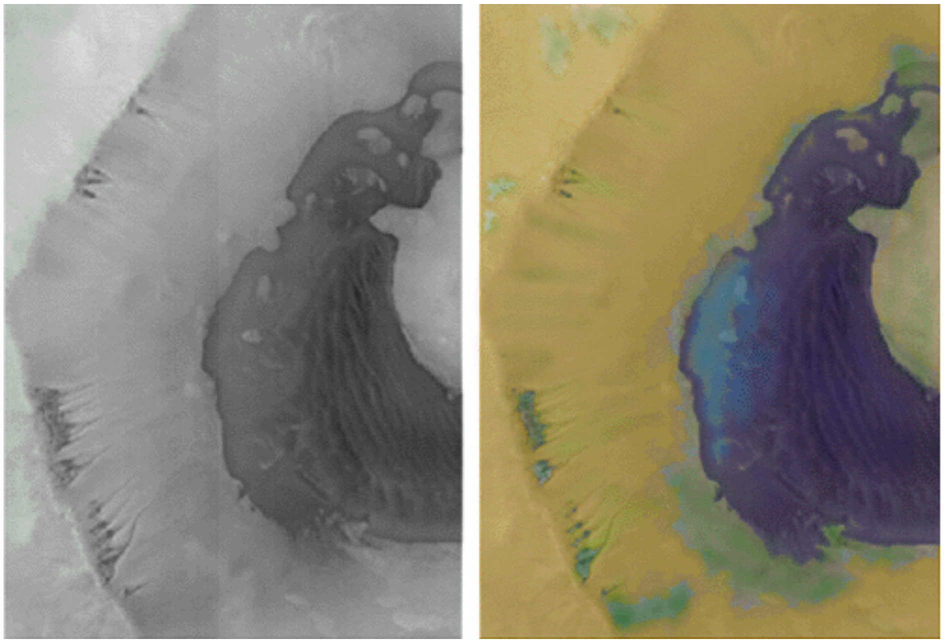
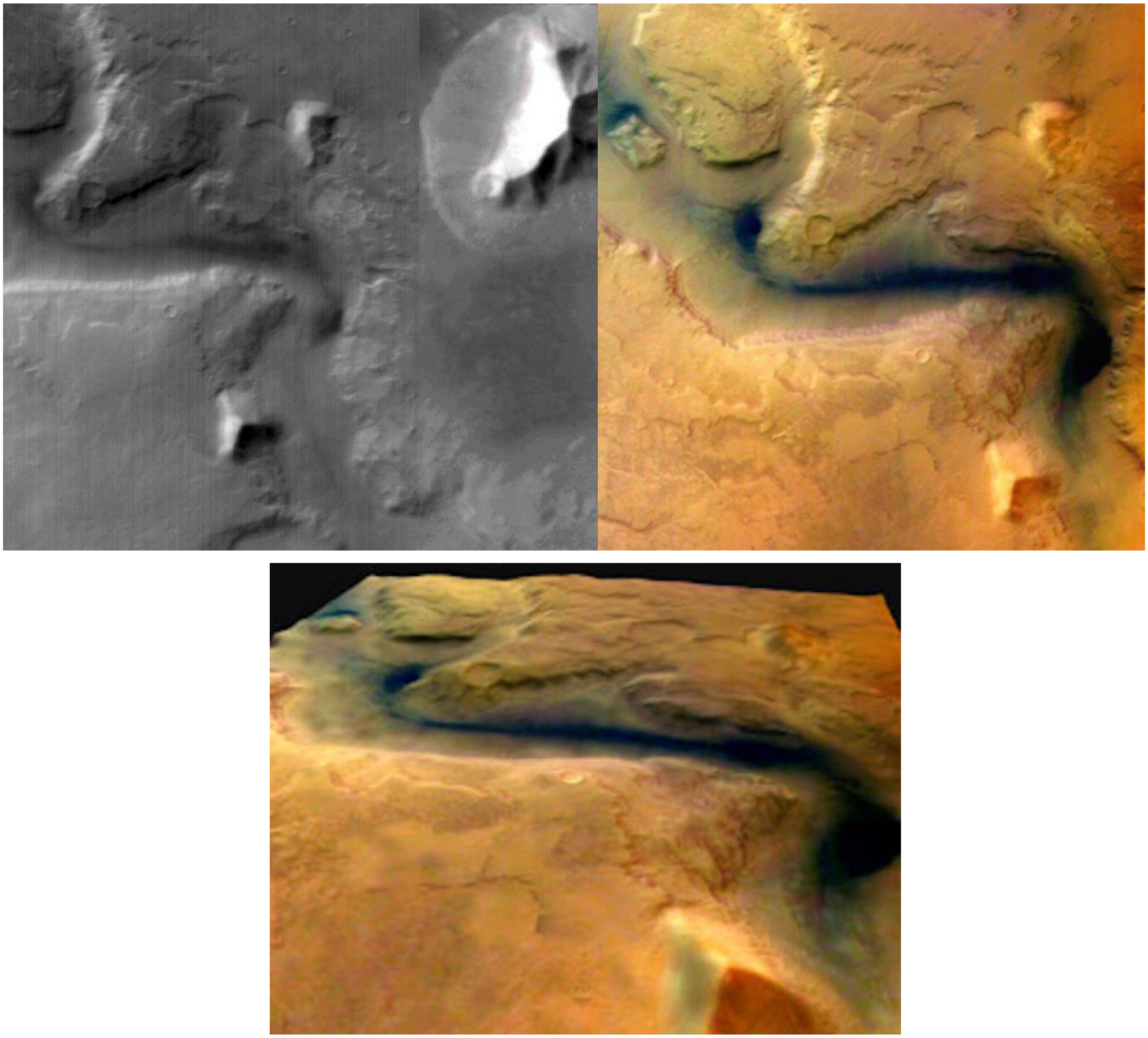


Figure 12: MOC image 7707 depicts a portion of the wall and floor of the cratered terrain of Noachis Terra that is 50 kilometer (31 miles) in diameter. Rippled striations are characteristic of water draining and pooling downward toward the remains of a pond or lake. The boundary between the dark (blue) at the bottom of the crater vs the lighter colors of the crater wall suggests the crater recently filled with water and water-ice. Mars Global Surveyor Mars Orbiter Camera MOC2-74 / 567897575.7707



Figures 13: Mars. (**Top Left**) Southern wall of Reull Vallis river valley located in the northern latitudes in the Hellas quadrangle (MOC red wide-angle context image M02-00302, photographed on May 22, 2000). (**Top Right**) ESA color photo nearly four years later (January 22, 2004) at the onset of the Martian Spring and approaching its closest distance (1.5 AU) to the sun. Note bluish-dark color possibly indicative of water or water-ice and what may be the growth of dark pigmented organisms. According to The ESA's Gerhard Neukum (Free University of Berlin): "These... are not shadows" "these are rivers."**(Bottom):** 3-D image of Ruell River Valley (ESA/DLR/FU)

Chaotic Obliquity (Axial Tilt) From 0° to 80° and Back Again: Global Warming vs Snowball Mars

Obliquity (axial tilt) is the angle between a planet's orbital and rotational axis as determined by a line perpendicular to its orbital plane. At 0 degrees obliquity, the rotational axis is perpendicular to the orbital plane. At 0° the Martian polar ice caps would cover most of the planet, atmospheric pressure would drop and global temperatures would fall below freezing, creating a "snow ball Mars" (Figure 15).

The obliquity of Mars is currently about 25.19° (vs 23° for Earth) and the polar regions are tilted 25° toward the sun. However, because Mars lacks a large moon and due to its extremely eccentric orbit, the angle of the tilt varies chaotically. As summarized by Ward (1973) "Large-scale variations in the obliquity of the planet Mars are produced by a coupling between the motion of its orbit plane due to the gravitational perturbations of the other planets and the precession of its spin axis which results from the solar torque exerted on the equatorial bulge of the planet. The obliquity oscillates" and the "amplitude of this oscillation itself varies periodically... Significant climatic effects must be associated with the phenomenon."

Head et al. (2003) have determined, based in part on the extent and layering of the polar ice caps, that the obliquity of Mars has repeatedly exceeded 30° whereas Laska et al. (2004) have estimated that the average extreme obliquity of Mars, over the last 4 billion years, has ranged between 37.62° to 41.80° and may tilt as much as 82.035°. At this latter obliquity the poles would be pointed almost directly at the sun causing global temperatures and atmospheric pressure to rise dramatically and the glaciers to melt thereby flooding the planet with oceans of water. However, because changes in obliquity are chaotic and variable, and especially if tilt were to suddenly increase, the resulting floods might even form tsunamis for which there is evidence (Rodriguez et al. 2014; De Blasio 2020). And then, as obliquity declines, these displaced waters would freeze again.

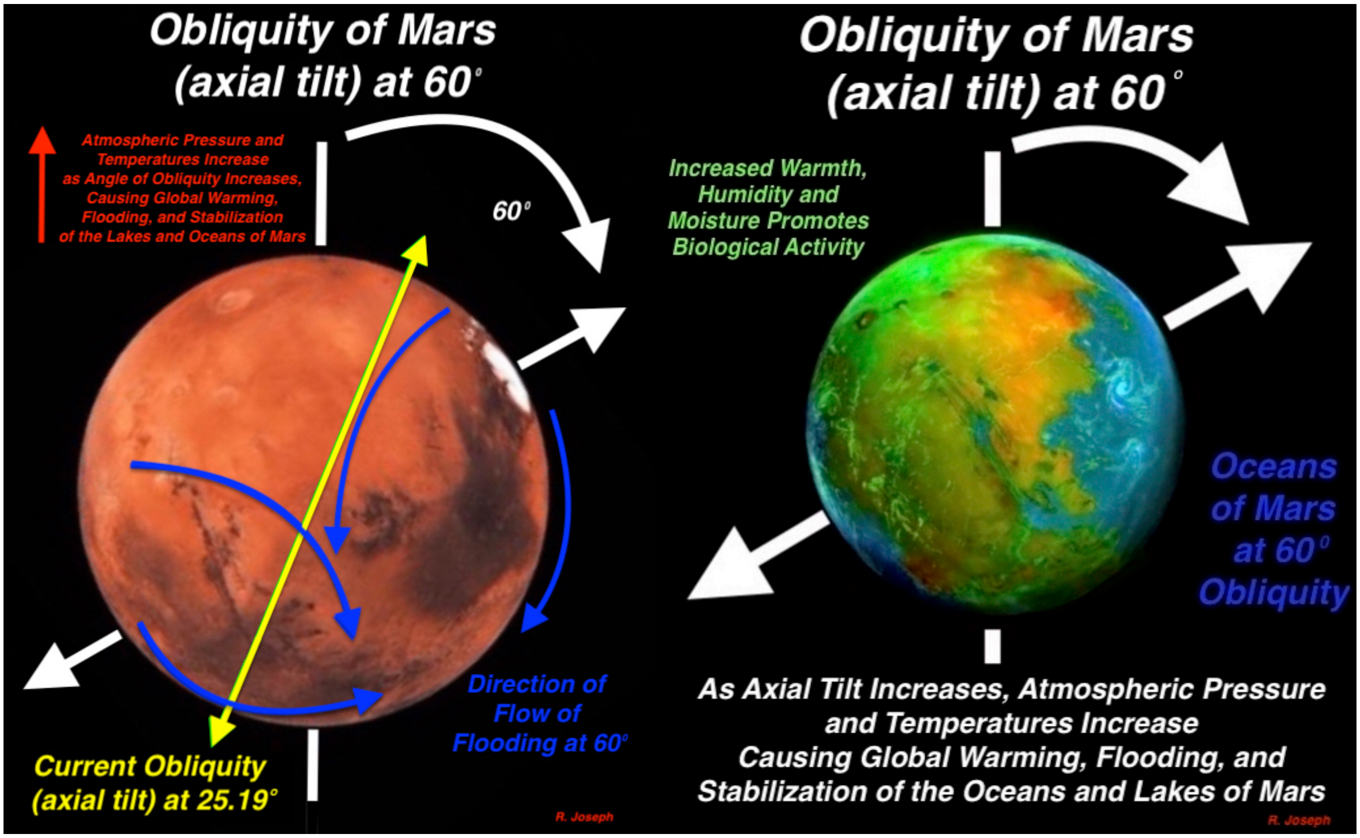


Figure 14: Mars. Obliquity at 60 degrees. Axial tilt increases atmospheric pressure, global warming, causing the melting of glaciers resulting in flooding and the stabilization of the rivers, lakes and oceans of Mars, which promotes the flourishing and evolution of life.

According to Ward, Burns, and Toon (1979) a variety of physical mechanisms can dramatically change the inertia of Mars which would alter secular spin-orbit resonances that can suddenly alter the obliquity of Mars which is in a chaotic state (Schorghofer 2008; Lasker et al. 1993; Touma & Wisdom 1993). Hence, predications about the future and past episodes, duration, and degree of obliquity cannot be estimated or inferred even from direct simulation (Holo, et al. 2919). It is impossible to make accurate predictions about chaotic systems other than to propose a range of possibilities including that obliquity may suddenly and chaotically change direction from 80° to 0° and back again.

Because of this chaotic state, there may have been numerous and relatively sudden waxing and waning episodes of global warming and flooding, then freezing. Based on computerized simulations, Schorghofer (2007) estimates there may have been forty major ice ages over the past five million years. These ice ages would have been preceded and followed by episodes of obliquity induced global warming, flooding, the formation of rivers and lakes, all of which would freeze and become dust and dirt covered glaciers as axial tilting declined. And these chaotic changes in the biosphere would have profoundly affect the survival and evolution of reputed life on Mars.

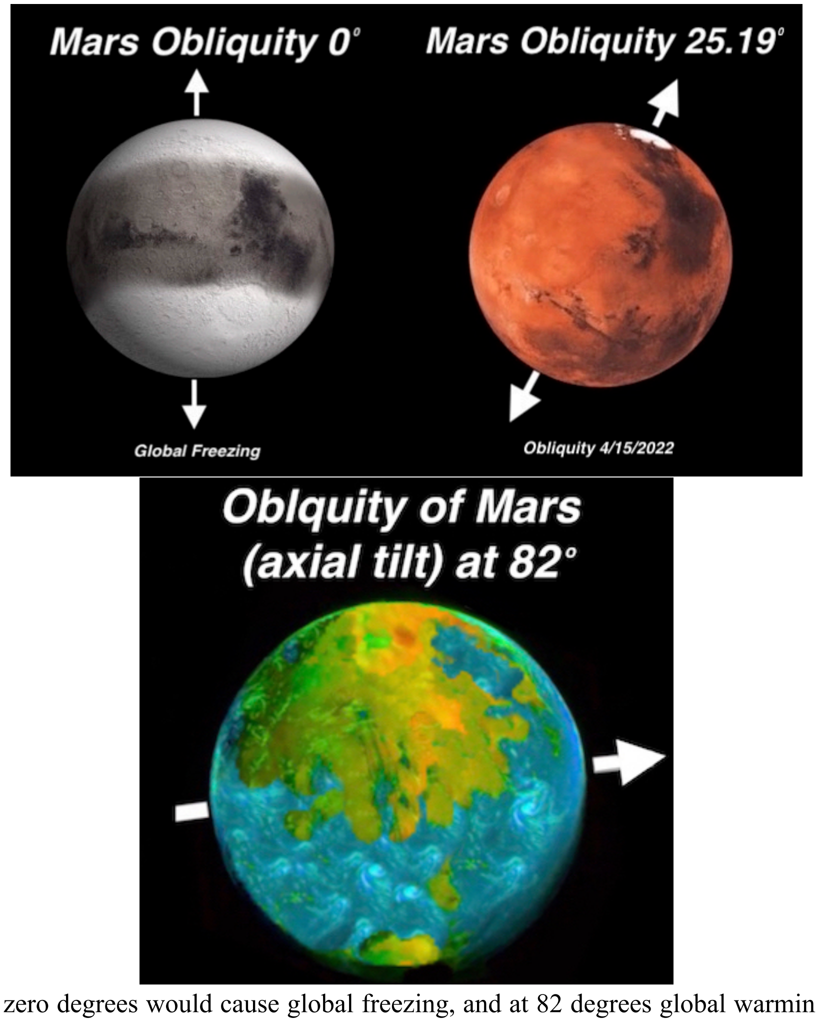


Figure 15: Obliquity at zero degrees would cause global freezing, and at 82 degrees global warming. Given all the evidence of current life on Mars, including what may be vast colonies of fungi, algae and lichens that become biologically active during the Spring and Summer melting of the polar regions, then at 60° to 80° it can be predicted that Red Mars might turn ocean blue and green with life.

Obliquity, Cosmic Dust and 400,000 to 110,000 Year Old Layered Ice Deposits

There are layers of frozen and semi-frozen rivers, lakes, aquifers and glaciers below ground at almost all latitudes on Mars. Dirt, sand, CO_2 covered icy-mantles are often sandwiched one on top of the other, and have been observed in Valles Marineris, Utopia, Elysium Planitia, Cerererus Plains, and surrounding, lowlands; and are indicative of repeated episodes of long-duration stable ponded water that later evaporated or drained and became dust covered and frozen upon or beneath the surface (Kite et al. 2017; Soar et al. 2008; Warner et al. 2014; Treiman 2008; Davis et al. 2018). Cyclic changes in obliquity and global temperatures directly affected the freeze-thaw-freeze cycling of water, such that each episode resulted in layers of sloping ice-rich terrain that are sandwiched above, below and between mixed sediment consisting of wind-blown dirt and cosmic dust. Hence, each cycle of flooding, water stability then freezing, are marked by separate mantled deposits (Jackosky et al. 1995; Soare et al., 2018; Johnsson et al., 2018).

These multiple slabs are indicative of several generations of deposition and removal, including very recent water-carved gullies produced by precipitation, groundwater and meltwater from snowpack during higher obliquity over extended time periods lasting hundreds of thousands of years (Head et al. 2003) to nearly a million years (Kite et al. 2017). Likewise, Soare et al. (2008) argue that superposed depressions indicate a watery origin that is more youthful than the gullies and that some raised-rim landforms superposed on rimless depressions are indicative they were formed by ponded water that remain stable for long periods relatively recently, and then froze.

With the exception of the Martian south pole, the top layers of much of this dusty-mantled-water ice are often buried no more than a meter below the surface. The amount of dust and one meter depth supports the hypothesis that vast bodies of ice had melted and formed surface rivers, lakes and oceans of water that froze relatively recently atop other, older layers of dirt-impacted ice sheets.

It is believed that up to 5,200 tons of cosmic debris falls to Earth each year (Rojas et al 2021). Although Mars is a smaller “target,” its thin atmosphere would not burn up much of that cosmic debris. Nevertheless, the tonnage from space that strikes Mars (which is half the size of Earth) can only be a subject of guess work, e.g. 2,600 tons a year, 26,000,000 tons every ten thousand years. On Earth, one “cubic foot” of soil (1 ft x 1 ft x 1 ft) weighs between 74 - 110 pounds; the equivalent of approximately 35 pounds on Mars. Since the gravity of Mars is 1/3 that of Earth, it can be estimated that over a period of 10,000 years, anywhere up to 8,000,000 tons of debris falls to the surface of the Red Planet which has a total surface area of 144.37×106 km^2 (56 million miles); i.e. at least 14 tons per mile and 0.000027 tons (0.05 pounds) per 12 inches / 30 centimeters of top soil, e.g. a layer at least 3.75 inches (9.5 cm / 0.095 meters) in height per 10,000 years, and approximately 1 meter (3.28 ft) in height over 100,000 years.

Wind blown dirt, dust, and falling cosmic debris striking liquid water would sink, whereas what falls on glaciers would also sink when that water melts; a repeating process due to extreme obliquity: glaciers and the polar ice caps melt, flood, form stable rivers, lakes and inland seas, then freeze and become progressively covered over by debris falling from space and dust blow by powerful Martian winds, thereby forming layers consisting of water-ice-dust-dirt. Thus, over successive periods of high to low obliquity, distinctive spiral bands of terraces and laminae have formed, including top layers less than a meter below the surface (Toon et al. 1980; (Dundas et al. 2018; Putzig et al. 2014; Mitrofanova et al. 2022a). A layer of frozen water one meter below the surface of Mars could indicate that the last freeze cycle began approximately 100,000 years ago and no later than 400,000 years ago; estimates consistent with those provided by Head et al. (2003) and Clifford (2018). Although all the layers in total may be dozens of meters in depth, the fact that many of the ice deposits are only 1 meter (or less) below the surface, indicates a relatively recent freeze cycle.

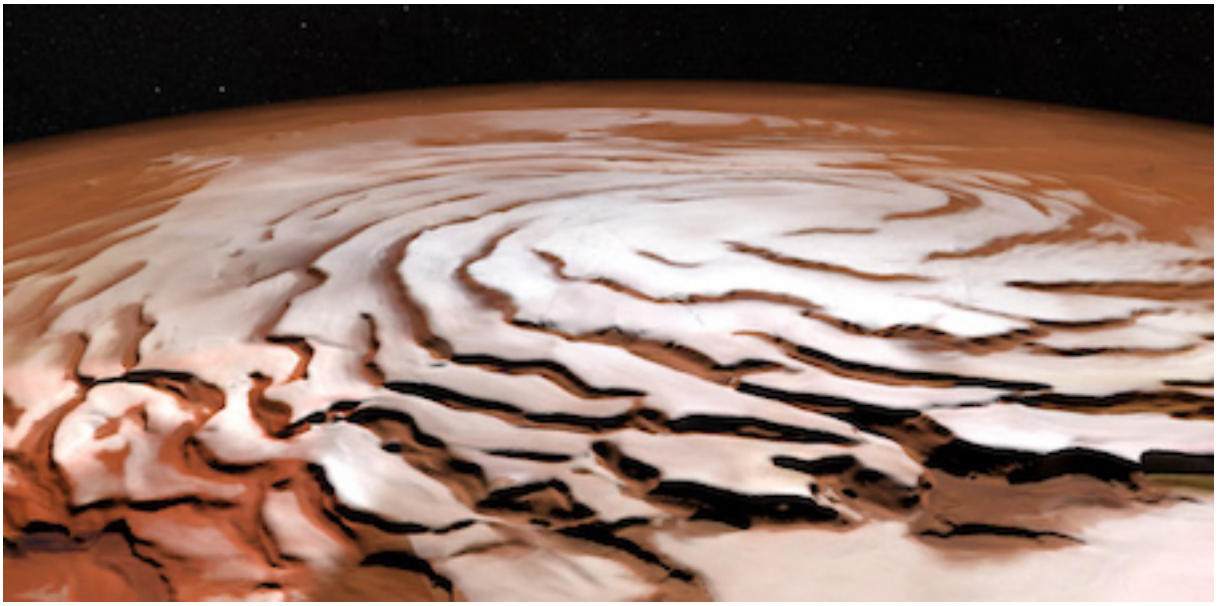


Figure 16: Mars Northern Polar Ice Cap: Mosaic produced via the European Space Agency Mars Express depicting downward directed waves of spiraling layers and troughs; reminiscent of waxing and waning ocean waves and tides, but also shaped by powerful Coriolis winds during high obliquity. An estimated 30% of the planet's atmospheric CO_2 is sequestered, frozen, at the poles during the Winter.

Figure 17: The North Polar layered deposits of dusty water ice that are about 1000 kilometers across, and in total, three kilometers thick. Photographed via the HiRISE camera on NASA's Mars Reconnaissance Orbiter.

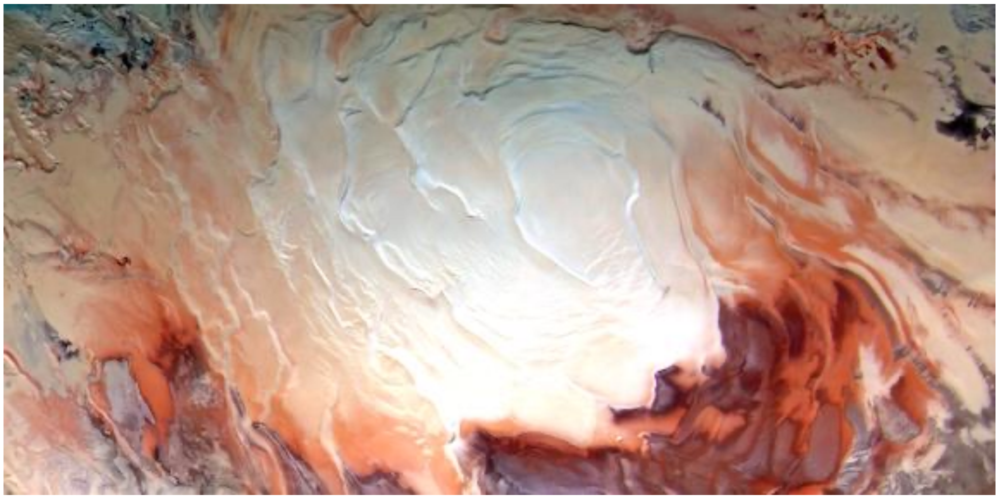


Figure 18: Mars southern polar ice cap on Mars at the beginning of Spring, photographed by the European Space Agency Mars Express, depicting waves of flowing layers. Lakes and oceans of water are sequestered below the ice cap.

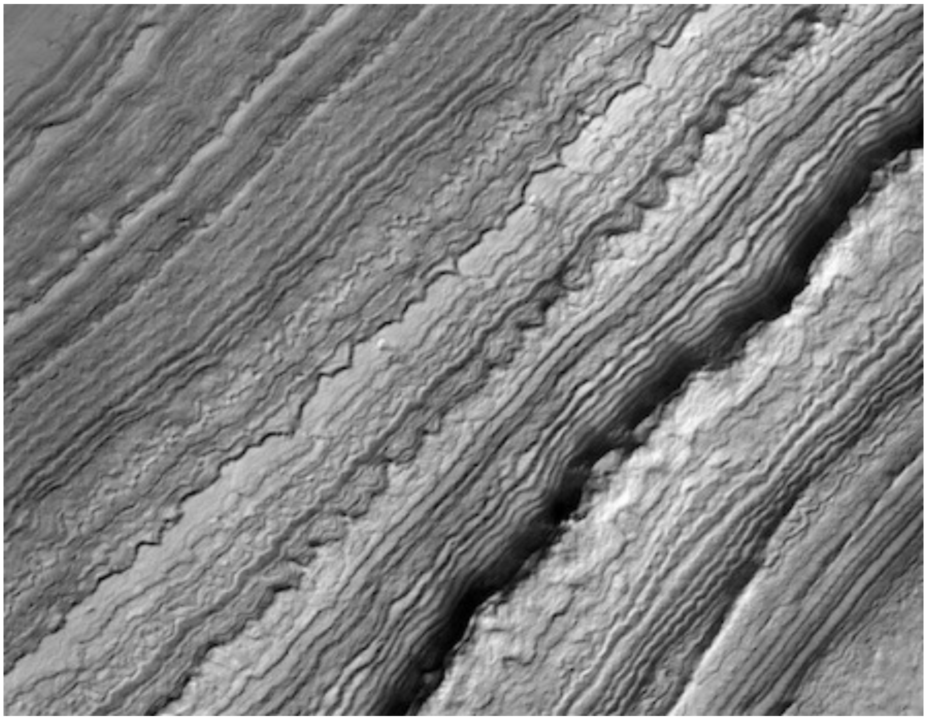


Figure 19: **Mars.** South Polar Layered Deposits. HRISE photograph.

Lakes, Rivers and Catastrophic Flooding of Valles Marineris

Mariner 9, Viking, Mars Express and HiRise observations have revealed that the polar regions are covered with extensive overlapping layered terrain consisting of dark and light colored diagonal stripes and composed of wind-deposited dust and water ice. These patterns are indicative of cyclic melting-freezing polar processes including flow patterns directed south-eastward and downslope toward the lower latitudes during periods of extreme axial tilting (Clifford, 2018; Toon et al. 1980; Jackosky et al. 1995). These flood water later formed ice mantles and dust covered glaciers when the angle of axial tilt diminished (Clifford 2018). However, not all that water froze; some becoming vast deposits of water ice and subsurface aquifers that continually leak upward creating moist soil conditions and clouds of moisture and water ice as have been repeatedly photographed.

Gale Crater resembles a dried lake or inland sea and is located in the equatorial regions and would likely have become flooded with melt water from the arctic and antarctic regions of Mars during high obliquity. Moist soil and mud and frozen white ice has been photographed on the outside and inside of the rover Curiosity's aluminum wheels as it traversed Gale Crater indicating liquid water just beneath the surface (Joseph et al. 2020g).

In 2009, liquid "brines" were discovered at the Phoenix landing site which "splashed on a strut of the Phoenix spacecraft during its landing" and then dripped back down to the surface (Renno et al. 2009). Soft ice ("frozen brine") was also found in shallow (less than 30 cm - 12 inches) trenches carved out by the Phoenix craft's robotic arm (Renno et al. 2009).

On December 15, 2021, the European Space Agency's Roscosmos ExoMars Trace Gas Orbiter discovered a vast river-lake, approximately 16,000 miles (25749504 meters) in size, less than a meter below the soil within the canyons of Valles Marineris (Mitrofanova et al. 2022). As summed up by lead investigator Igor Mitrofanov of the Space Research Institute of the Russian Academy of Sciences: "We found a central part of Valles Marineris to be packed full of water...as much as 40% of the near-surface material in this region appears to be water....This is very much like Earth's permafrost regions." That this vast amount of water is buried at such as a shallow depth (Figure 20) and coupled with observations in Gale Crater and the Phoenix landing site, supports the hypothesis of a relatively recent, albeit massive inundation, due, presumably to high obliquity, as well as evidence of even greater volumes of water at various distances beneath the surface.

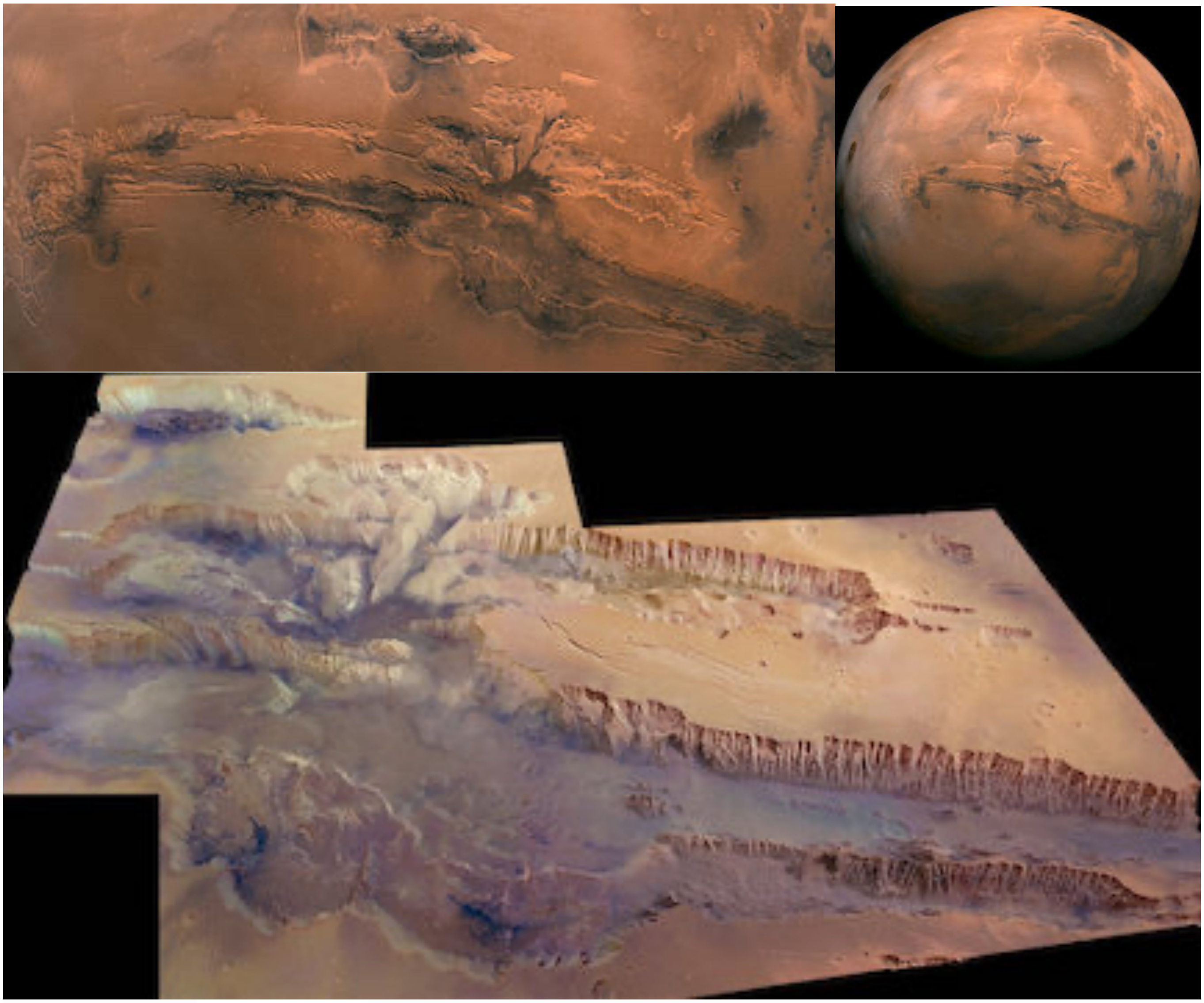
Valles Marineris can be divided into southern and northern subsystems that consists of numerous interconnected canyons that stretch along the Martian equator with some "chasmas" up to 100 km in width and over 200 km in length, and 2 to 8 km in depth. Like the "Grand Canyon" of earth, this Martian equatorial canyon system may have been slowly and repeatedly carved by rivers of flood waters over the course of the last 4 billion years and continuing until the near present (Warner et al., 2014; Davis et al. 2018).

Based on images of the walls and ridges of the Valles Marineris, captured by the Viking, Mars Express, Mars Reconnaissance Orbiter and Mars Odyssey missions, and as indicated by successive layered deposits (Figures 16-19, 24-25), this system of canyons have been repeatedly glaciated (Gourronc et al 2013) and subject to enormous catastrophic floods (Baker 1982, 2009; Robinson & Tanaka 1990; Warner et al., 2014; Davis et al. 2018; Rodríguez et al. 2014, 2016, 2017, 2019) as there are numerous geological formations indicative of chaotic flood channels and inundation by immense volumes of groundwater (Harrison & Chapman 2008).

Channels throughout Valles Marineris are littered with huge blocks of rocky debris that appear to have been propelled vast distances by the high velocity expulsion of catastrophic amounts of water (Komatsu et al., 2000) . Some of that flood water may have been discharged within Valles Marineris from the melting of glaciated dams that hosted and surrounded a deep lake or lakes of water-ice. When these natural glacier barriers broke away, this resulted in the delivery of massive volumes of ice water to downstream outflow channels (Chapman & Tanaka

2002; Harrison & Chapman 2008; Warner et al. 2014) with an estimate discharge greater than 1 km^3·s-^{1} and at velocities ranging from 32 to 75 m·s-^{1} repeatedly creating obliquity-driven flood events surpassing any other flood event in the history of this solar system (Robinson & Tanaka 1990). It has been estimated that the depths of these flood waters may have ranged from 374 m to1280 m (Robinson & Tanaka 1990).

Thus throughout Valles Marineris, there is evidence of repeated flooding episodes (Warner et al. 2014) and multiple wet and dry periods (Davis et al. 2018). Moreover, these surface waters remained liquid, stable and endured for long periods of time (Treiman 2008; Davis et al. 2018) such that the canyons of Valles Marineris have repeatedly hosted a vast inland sea. In support of this hypothesis is the discovery of a vast deposit of water and water ice 1 meter below the surface (Mitrofanova et al. 2022); see Figures 20, 23.



Figures 20: (Top) Valles Marineris. The ESA-Roscosmos ExoMars Trace Gas Orbiter has detected vast amounts of water 1 meter below the surface of Valles Marineris.

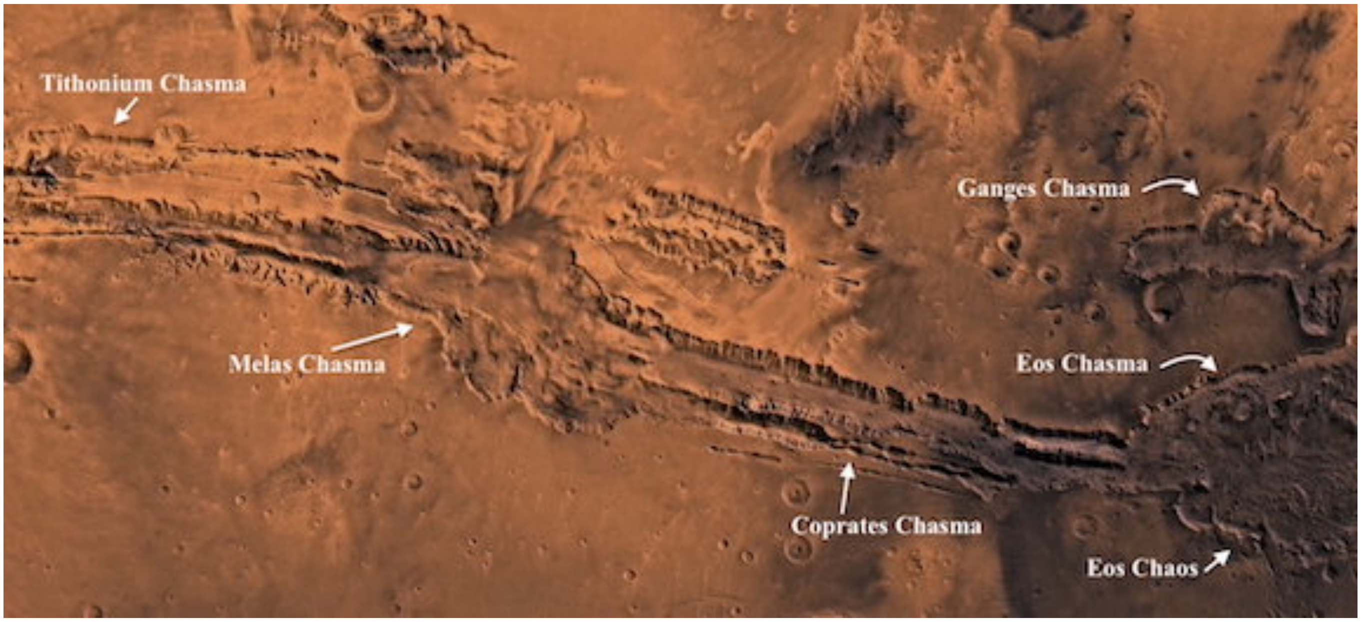


Figure 21: Valles Marineris, major chasmas. HiRise photo labeled by the authors.

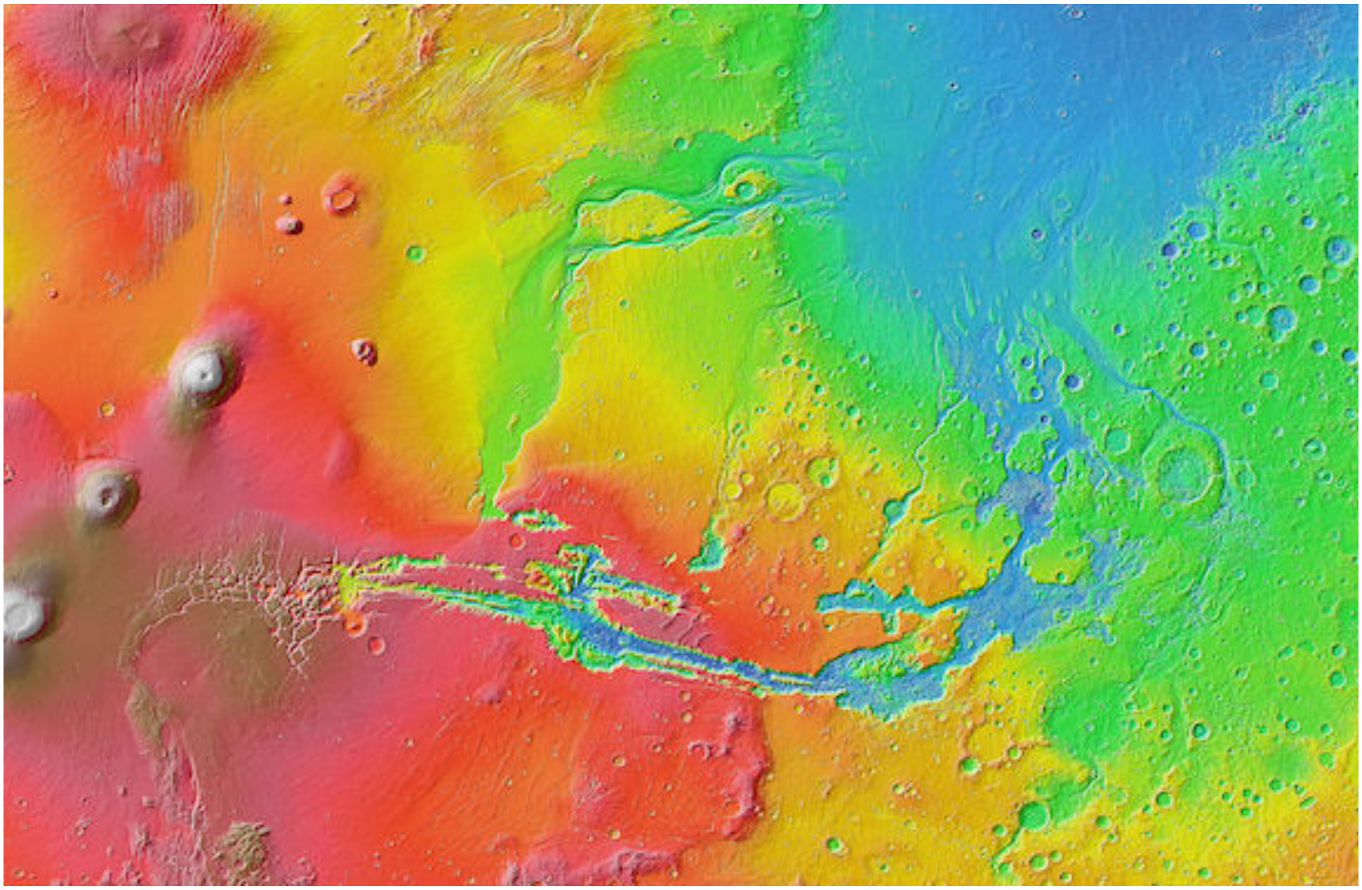


Figure 22: Topographic map of Valles Marineris, and the surroundings including glaciated Tharsis volcanoes. Map depicts past evidence of massive inland seas, lakes, and inflow and outflow channels of flood water; based on MOLA altimetry data.

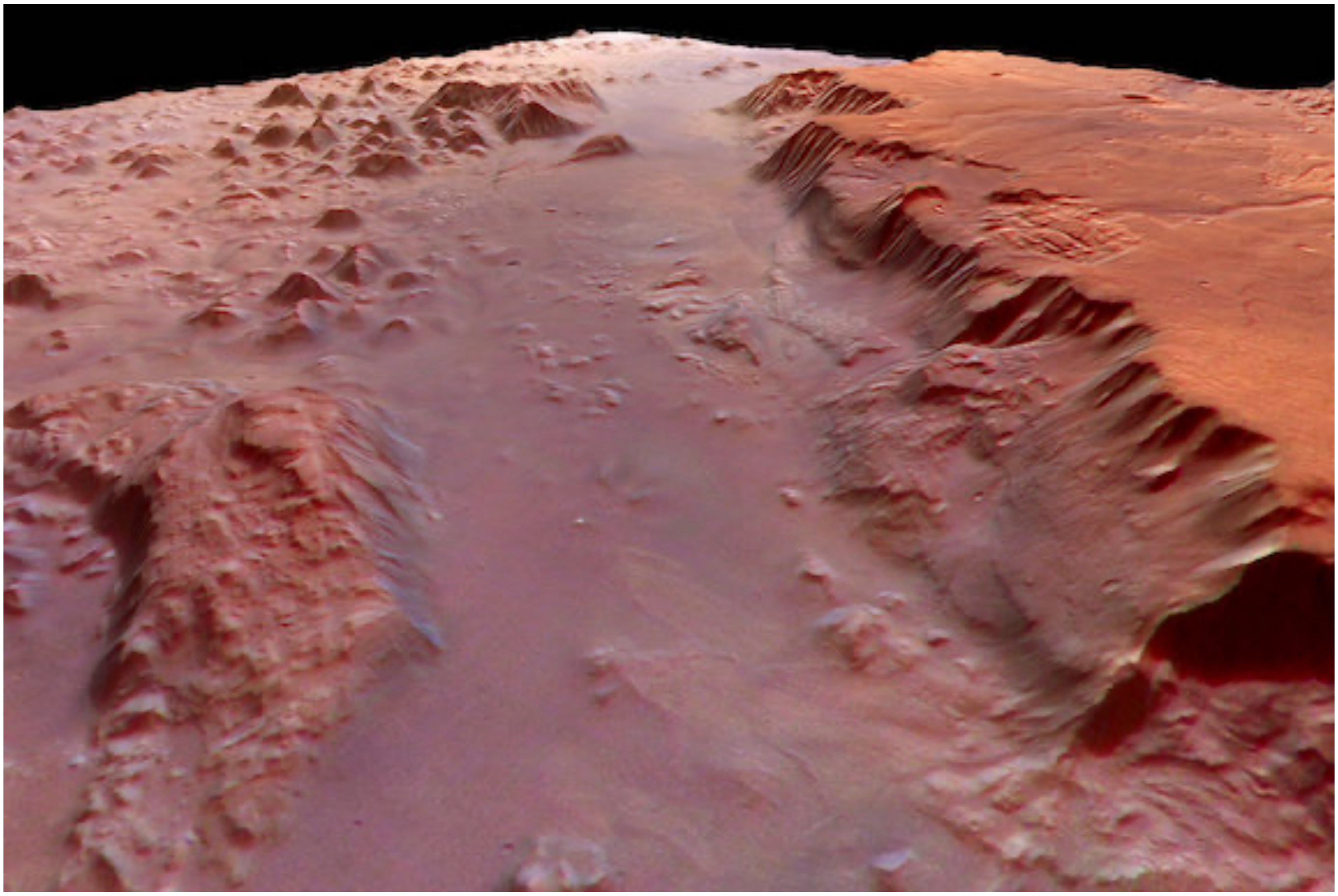


Figure 23: The southern part of Valles Marineris, called Eos Chasma, depicting what may be water just beneath a thin-ice covered river-canyon floor. Photo generated by the High Resolution Stereo Camera on board ESA's Mars Express spacecraft.

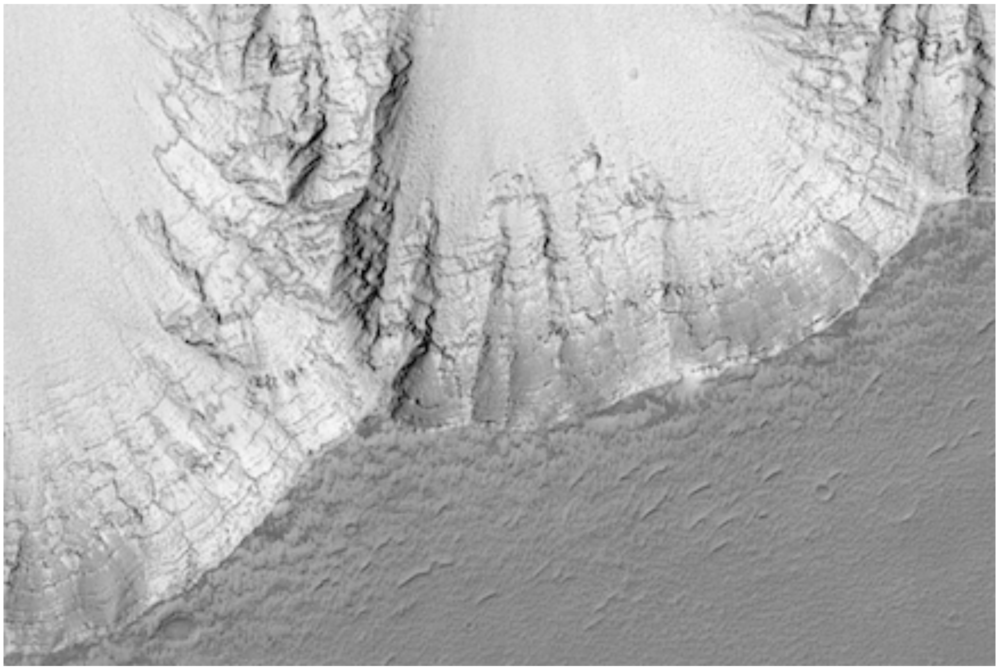


Figure 24: Stacked layers in the icy walls of Noctis Labyrinthus Valles Marinas taken with Mars Global Surveyor. These patterns are similar to those that appear along lake and river banks as water levels recede.

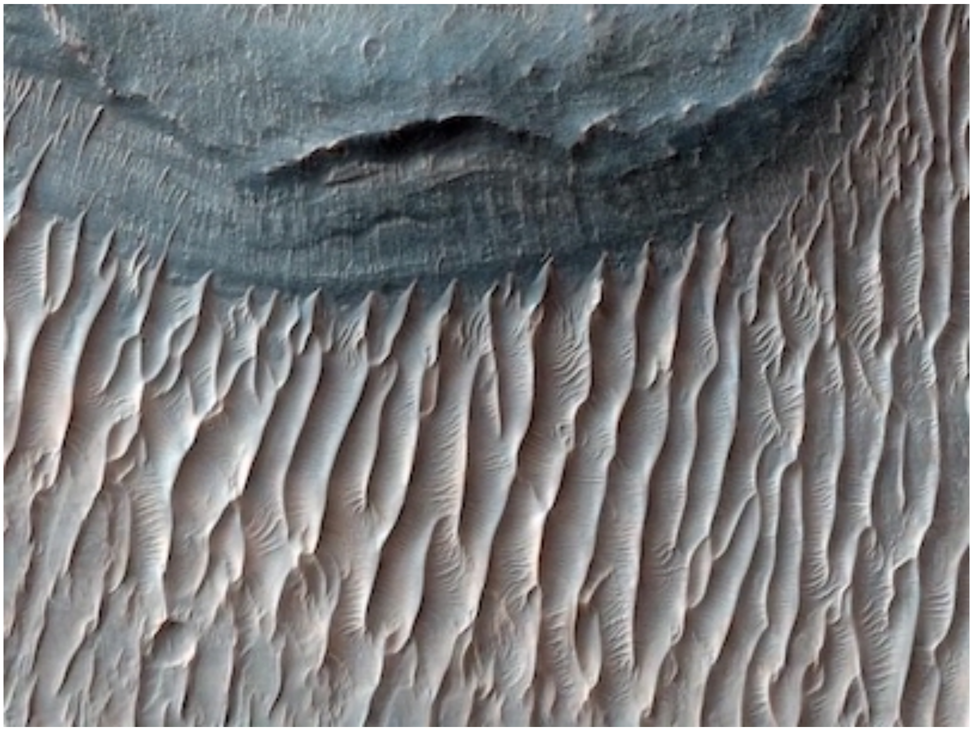


Figure 25: The floor of Ius Chasma, a canyon within Valles Marineris, depicting fine stratigraphic layers modified by successive episodes of inundation by waves of liquid water. Photo by the Mars Reconnaissance Orbiter.

Air Pressure, Obliquity, CO_2, Stable Oceans and Lakes

Air pressure is defined in units called atmospheres (atm). One atmosphere is equal to 1,013 millibars (MB) at sea level and is determined by air temperature and molecular density. On Earth, the weight of air exerts 14.7 pounds per square inch at the surface, and decreases at increasingly higher altitudes. As the number of air molecules increases, air density and pressure and temperature increases. Increased air pressure preserves the stability and duration of surface water and increases global temperatures which increases air pressure. Conversely, as air pressure decreases temperatures decrease, which is why air decreases in temperature as one ascends in the atmosphere.

Jakosky and Carr (1985) have hypothesized that during high obliquity ice will melt causing desorption of CO_2 and producing water vapors and precipitation forming heat trapping clouds and increasing atmospheric pressures. Water vapor is a powerful greenhouse gas and can significantly elevate temperatures and atmospheric pressure (Mischna et al. 2013) and the same is true of methane and CO_2.

The Martian polar regions are extensively layered and appear to be composed mainly of water-ice capped by CO_2 (Toon et al. 1980; Newman et al. 2005). At low obliquities permanent CO_2 ice caps form at both poles, lowering mean atmospheric surface pressures (Newman et al. 2005). Vast deposits of methane are also believed to be sequestered within the ice. During high obliquity the permanent caps will almost disappear due to increased exposure to the sun (Fanale & Salvail 1994). Because frozen CO_2 melts and methane is liberated from the ice as temperatures rise, these gasses increase the molecular density of the atmosphere, thereby increasing air pressure and temperature via the "greenhouse" effect. In addition, melt-water vapors will rise in the air, which also increases atmospheric molecular density such that temperatures continue to rise and atmospheric pressure increases thus stabilizing and preventing the evaporation of the oceans, lakes and rivers that are forming on the surface of Mars due to the melting of surface and subsurface glaciers (Newman et al. 2005). However, air pressure is also variable as not all parts of Mars would be heated equally by the sun, until obliquity approaches 60 degrees.

Kieffer and Zent (1992) have argued that when the "obliquity is at or below its current value, the atmospheric pressure is controlled by the radiative balance of the polar caps; the most important parameter is the CO_2 polar cap albedo, which may vary with intensity of insolation. The major effects anticipated at low obliquity are growth of the polar caps, substantial decreases in surface pressure, cessation of dust storms, and poleward migration of H_2O ground ice. At high obliquity, the mass of the perennial polar caps decreases and permanent CO_2 frost disappears, CO_2 desorbs from the regolith, the air surface pressure will increase to several times its current value, and the atmospheric dust load will increase." This atmospheric dust, along with cosmic debris, will settle upon permafrost and the polar ice-caps reducing albedo and increasing heat absorption; and then settle at the lower depths as snow packs melt. Essentially, high obliquity causes an interactive domino effect that produces oceans, rivers, and lakes that may endure for hundreds of thousands of thousands to millions of years.

By contrast, and as pointed out by Kreslavsky and Head (2005) "at low obliquity, collapse of the atmosphere occurs because insolation of polar regions is very low and the atmospheric pressure is buffered by permanent solid CO_2 deposits at the poles" resulting in "extremely low-pressure conditions." They conclude that atmospheric pressure is dependent on obliquity, and pressure increases as orbital tilt increases.

Jakosky and Carr (1985) estimate that at 35° and 45° obliquity air pressure may exceed 25 mbar and 40 mbar respectively. However, air pressure would dramatically rise exponentially, perhaps as much as 1,000 mbar as obliquity approaches 80 degrees--a function of increased global temperatures, the melting of the poles and all surface and subsurface ice, and the release of water vapor, methane and CO_2 which also increases air pressure, thereby compressing and preventing the evaporation of the rivers, lakes and oceans produced by melt water.

Based on numerical simulations, Nakamura and Tajika (2003) report that atmospheric pressure on Mars is "determined by the equilibrium of three major CO_2 reservoirs: atmospheric CO_2, ice (solid) CO_2, and CO_2 within the regolith" and that permanent ice "disappears when the obliquity is higher than 31.75°..." and these "obliquity changes would result in drastic changes of atmospheric pressure... by runaway sublimation of permanent CO_2 ice... When the atmospheric pressure increases, the greenhouse effect, which lowers the outgoing radiation, increases.... The climatic state will change from the permanent-ice regime to the non-permanent-ice regime" and oceans, lakes, and rivers would form and flow across the surface of Mars and endure and remain stable until obliquity declines.

Likewise, according to Costard et al. (2001), obliquity-induced global warming and associated increases in atmospheric pressure would preserve liquid surface water, whereas Jakosky et al. (1995) estimates that surface water can remain liquid and stable at obliquities of 40° including melt water from the polar caps. Indeed, during high obliquities, oceans of flood water would fill Gale Crater, Meridiani Planum, and the vast equatorial canyons of Valles Marineris forming rivers, lakes and a vast inland sea.

Inter-Glacial Cycles of Obliquity- and Biological- (Oxygen, Methane) Driven Climate Change

Land masses and shallow lakes will become warmer more quickly than deep oceans, because of the fact that soil has a lower volumetric heat capacity vs the mixing of colder-deep with surface ocean water (Berger 2001, Berger & Loutre 1997). However, if, during high obliquity, the lakes and rivers of Mars were relatively shallow, and given that the oceans of Mars may have only had a depth of 50 to 80 meters (Barth 1974; Zhang et al. 2012), then the entire body of water, as well as glaciers, would heat and release moisture into the air thereby contributing to global warming.

In 1930 Milutin Milanković related the collective cyclic effects of alterations in Earth's orbit, precession, and axial tilt to changes in climate, and cyclical variations in solar radiation at the surface; and that orbital forcing has caused episodes of extreme global warming and global freezing over the history of this planet. As refined and defined by Berger (1979) changes in global temperature and climate over thousands of years can be computed from the three classical orbital parameters: the eccentricity of the Earth's orbit around the Sun, its obliquity, and the climatic precession index. Unfortunately, the same predictive calculations cannot be applied to Mars which has an orbit with a semi-major axis of 1.524 astronomical units (228 million km), and an eccentricity of 0.0934 that ranges from 0.079 to 0.105 and with an aphelion and perihelion distances of 1.6660 and 1.3814 AU.

Earth's orbit varies between nearly circular and mildly elliptical; and when the orbit is more elongated the amount of solar radiation is reduced, affecting temperatures. Earth's axial tilt (obliquity) also changes slightly from 22.1° to 24.5°, over a cycle of about 41,000 years. Increases in angle of orbital tilt provides more solar radiation in each hemisphere's summer and less in winter and causes the seasons to become more temperature extreme (Kukla et al., 1997; Berger et al. 2003). However, as already detailed, if the obliquity of Mars increases beyond 40° and approaches and exceeds 60° winter and summer temperatures would dramatically increase and the Red Planet would undergo a period of extreme global warming.

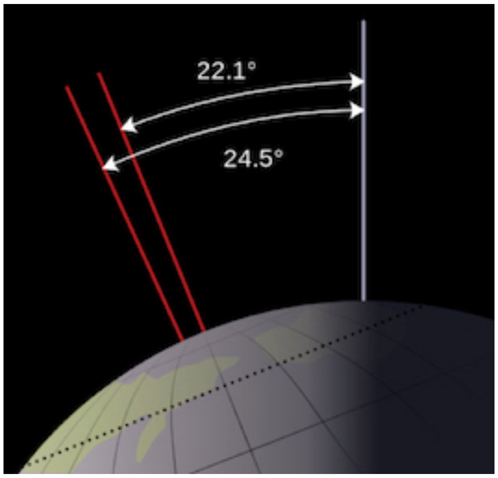


Figure 26. 22.1–24.5° range of Earth's obliquity.

The obliquity of Earth is at present 23.44°, midway between its extreme axial tilts and is now in the decreasing phase of its cycle. Over the ensuing thousands of years reducing obliquity could promote colder summers and an overall reduction in temperatures such that Earth will enter a glacial period (Kukla et al., 1997; Berger et al. 2003). However, biological activity can also alter global temperatures, including increasing atmospheric oxygen which would reduce temperatures vs increases in methane and CO_2 which raise temperatures (Berger et al. 2003; Joseph 2010b). In the history of Earth the waxing and waning of biologically produced oxygen, methane and CO_2, have contributed significantly to cycles of global warming and global freezing (Joseph 2010b).

Due to global warming and surface heat transport, methane, water vapor and CO_2 would be released from the Martian polar ice caps (Francois et al. 1990) thereby causing a dramatic increase in surface air pressure (Manning et al., 2006), all of which are powerful heat-trapping greenhouse gasses, thereby also enhancing the thermal properties of regolith (Newman et al. 2005). Employing numerical simulations, Kite et al. (2017) report that during high obliquity, outgassed methane can build up to atmospheric levels sufficient to create a greenhouse effect that would enable lakes to form and remain stable for up to a million years.

On Mars increases and decreases in oxygen, methane and CO_2, have seasonal cycles (Webster et al. 2018; Trainer et al. 2019) that parallel the seasonal fluctuations in the biological production of these same gasses on Earth (Joseph et al. 2019; 2020a,e). It can be predicted that during high obliquity high levels of methane would be initially released from melting snow packs and permafrost, methanogens would begin decomposing organic matter and releasing yet more methane thereby contributing to atmospheric pressure and global warming and the formation of stable rivers, lakes and oceans. Employing numerical simulations, Kite et al. (2017) report that during high obliquity, outgassed methane can build up to atmospheric levels sufficient to create a greenhouse effect that would enable lakes to form and remain stable for up to a million years.

However, as temperatures and water availability increase, biological-oxygen-production would also increase until reaching levels that counterbalance and reduce the effects of methane on global warming (Joseph 2010b). Biology interacts with obliquity which in turn regulates and affects the biosphere and the biological activity of different organisms. Given evidence of current and past life on Mars, then it can be predicted they would have and will again affect global temperatures during high obliquity.

Currently Earth is believed to be within an interglacial period (Kukla et al., 1997; Kukla & Kukla, 1972). In 2003, and basing their estimates on data from the MGS and Odyssey Mars missions, Head and colleagues proposed Mars is also in an interglacial period that was preceded by a period of global warming.

Stability of the Oceans, Rivers, Lakes of Mars: Obliquity, Thermal Conductivity, Humidity

Head et al. (2003), determined, based on the extent and layering of the polar ice caps, that Mars experiences periods of extreme global warming when obliquity exceeds 30°. Toon et al. (1980) has estimated that at high obliquity (35°) the annual average polar temperature will increase by about 10 K, summer polar ground temperatures will exceed 273 K (31.73°F --0.15°C) and the ice caps will begin to melt and release "green house" heat trapping gasses. As obliquity increases, the magnitude of the annual thermal wave also increases at all latitudes. At an obliquity inclination of 60° the entire planet would become heated and experience global warming. Laska et al. (2004) have estimated that the average high obliquity of Mars ranges from 37.62° to 41.80° and may tilt as much as 82.035°--and in consequence the polar ice caps would be replaced by polar oceans that would be maintained and become stabilized upon the surface; a consequence of global warming, precipitation, the liberation of greenhouse gasses from melting ice and snow, and increased atmospheric pressure and regolith thermal conductivity (Kite et al. 2017; Phillips et al. 2011; Newman et al. 2005).

As regolith-soil temperatures increase, subsurface glaciers and frozen lakes and aquifers would melt and pool upon the surface. The thermal inertia of a planetary surface is a composite interactive function of regolith thermal conductivity, density and specific heat. Thermal conductivity accounts for the amount of liquid, ice and atmospheric gas found in the interstitial pore spaces of regolith. Changes in obliquity modifies surface thermal properties, leading to variations in conductivity (Mischna & Piqueux 2020). Increased heat flow melts ice and releases trapped gasses which increase thermal conductivity. Since the thermal conductivity of Martian dry regolith is dominated by gas filling the pore spaces (Presley & Christensen, 1997), then as these gasses are released this leads to a corresponding increase in thermal conductivity and the transfer of heat.

Due to global warming and the release of water vapor and greenhouse gasses from the polar ice caps (Francois et al. 1990) the thermal properties of regolith would be enhanced (Newman et al. 2005). Hence, increases in the obliquity of Mars alters and increases the distribution of solar heating across its surface which contributes to the melting of ice in the subsurface and polar regions (Head et al. 2003). Also during high obliquities persistent dust storms are likely and can act as condensation nuclei causing clouds and precipitation and atmospheric and surface temperatures to rise (Jakosky & Carr 1985). World wide global warming, coupled with the release of greenhouse gasses and increases in atmospheric pressure, would cause melt-water to flood and rain down upon the surface, creating rivers, lakes, and oceans that would remain stable for up to a million years (Kite et al. 2017). Likewise, according to Colose et al. (2019), “at high obliquity... open ocean can persist even in the winter hemisphere and when global-mean temperatures are well below freezing.”

Therefore, during periods of high obliquity approaching and exceeding 40°, atmospheric pressure, and regolith thermal conductivity increases thereby elevating surface temperatures and atmospheric pressure thereby enabling rivers and lakes to form and remain stable for millions of years (Jenkins 2001; Forget et al. 2013; Mischna & Piqueux 2020; Kite et al. 2017). In addition, regions of ice stability are not only affected by temperature but atmospheric humidity (Schorghofer 2007).

Kang (2019) employing 3D general circulation models, determined that atmospheric humidity and moisture may increase by a magnitude of 300% during high (vs low) obliquity. This is because high obliquity causes extremely high surface temperatures to occur even at the poles, thereby moistening the polar air which is also heated and rises in the atmosphere, thereby increasing atmospheric temperatures and pressure. As water vapors rise the increased moisture increases humidity and atmospheric pressure which increasingly inhibits the evaporation of water thus leading to the buildup of stable, long duration rivers, lakes and oceans even at the winter poles during periods of high obliquity.

Oxygen, Oceans, Martian Meteors, and Life in Gusev Crater Lake?

For over 4 billion years, during high obliquity the surface of Mars was likely repeatedly flooded with rivers, lakes, and oceans of water that, once formed, endured and remained stable for millions of years (Jenkins 2001; Forget et al. 2013; Mischna & Piqueux 2020; Kite et al. 2017); and within these waters life would flourish, diversify, and evolve. Head et al. (2003), estimates that the last period of extreme obliquity and global warming may have come to an end as recently as 400,000 years ago whereas Clifford (2018) proposes 110,000 years. Coupled with the data already reviewed in this report, the one meter depth of numerous massive ice deposits and moisture, and based on the estimates provided by Head et al. (2003) and Clifford (2018), the surface of Mars may have had rivers, lakes, and oceans of liquid water that endured and persisted for almost two millions of years, only to become frozen in the relatively recent past.

Furthermore, as indicated by surrounding wave-like soils and substrates and what appears to be the fossilized Martian metazoan invertebrates atop soil or embedded and extending above mudstone and rocks, these surface waters may have quite suddenly receded Those organisms that did not become extinct include what many experts believe to be cyanobacteria, methanogens, green algae, lichens and fungi which has been photographed emerging from the soil and increasing in size (Joseph et al. 2019, 2021c) whereas any "higher life forms" would have migrated to caves and tunnels beneath the surface, and/or became dormant, and/or formed spores, and/or evolved and adapted to these changing conditions, beginning billions of years ago.

As noted, analysis of ALH 84001 indicates evidence of biological activity, oxygen, and several episodes of waxing and waning aqueous activity (Shaheen et al. 2015; Halevy et al 2011; ; McKay et al. 2009; Thomas-Keprta et al., 2009). These aqueous episodes are most likely due to obliquity-induced climate change: melting and flooding as axial tilt increased; and then rivers, lakes and ocean waters would recede and freeze, beginning billions of years ago when Mars was wet and habitable (Ehlmann et al. 2011; Fairén 2020; McKay, 2010; Vago et al. 2017; Grotzinger et al. 2014; Jaumann et al. 2014), "suitable for biological activity" (Squires et al. 2005) and inhabited by an assortment of bacteria (Macey et al. 2020; McKay et al. 2009; Norland et al. 2010; Thomas-Keprta et al., 2009), possibly including "microscopic eukaryotes" and "filamentous microorganisms" (Squyres et al. 2005).

Because sufficient oxygen was being produced, even billions of years ago, ozone began to form (Farquhar et al., 1998). Upper atmospheric ozone provides a protective shield against gamma and UV rays. Over the ensuing billions of years oxygen continued to be pumped into the atmosphere repeatedly rwater flowed and pooled upon the surface as also documented by analysis of Martian meteorites. In the last 150 years, 227 meteorites that originated on Mars have been found (Meteoritical Bulletin Database, 2022). With the exception of NWA 7533 (Humayun et al. 2013) and NWA 7034 (Agee et al. 2013) which are regolith breccia, most Martian meteors have a basaltic composition and are categorized as orthopyroxenite (ALH 84001) nakhlites (N), chassignites (C), and Shergotty (S) based on texture, chemistry, mineral composition and age (Wang & Hu 2020; Righter et al. 2008; Nyquist et al., 1995).

Analysis of Martian meteorite NWA 7034, which may have originated in Gusev crater, has revealed repeated exposures to water and significant degree of oxygen, as recently as 2 bya (Agee et al. 2013). For billions of years until 120,000 years ago, Gusev crater (Figure 27) may have been repeatedly flooded with water and provided a watery habitat for photosynthesizing-stromatolites-constructing cyanobacteria as indicated by the findings of Ruff and Farmer (2016) who identified “microbially mediated microstromatolites” that they believe may have inhabited a thermally heated body of water. These investigators, and Bianciardi et al (2015), also detected sheaths, biofilms, intertwined microspherule filaments and fenestrae (for the venting of oxygen)—a feature common to all Martian stromatolites (Joseph et al. 2020b)-- as well as features reminiscent of “filamentous and coccoidal biomorphs, diatom frustrules,” and “populations of heavily ensheathed fossil cyanobacteria” (Ruff & Farmer 2016).

The primary source of free oxygen is photosynthesis via the biological activity of green algae and cyanobacteria in particular. Initially, on Mars and Earth, in the absence of significant quantities of free oxygen, photosynthesizing and other organisms likely feasted on and reduced nitrogen, iron, methane and carbon dioxide for energy and releasing nitrates, nitrogen dioxide, ammonia, carbohydrates, and oxygen as waste products. As they flourished and diversified, they left behind their fossilized and geochemical footprints in Earth’s oldest rocks, including evidence of cyanobacteria dated to 3.5 bya (Hoashi et al., 2009). On Mars, these biological footprints include oxygen and organic residue detected in Martian meteorite ALH. It is these ocean and lake-dwelling Martian organisms that likely constructed the microbialites and stromatolites identified by Ruff, Farmer (2016), Bianciardi et al (2015), Rizzo, Cantasano (2009, 2016), Noffke (2015) and Joseph (2014; Joseph et al. 2020b).

Martian meteorite, NWA 7034 has been dated to 2.089 bya (Agee et al. 2013). ALH may be 3.8 to 4.5 billion years in age. The Chassigny (C) Nakhlites (N), Shergottite (S) meteorites have been assigned generalized average ages of 1.3bya, 1.32 to 1.17bya, 465 to 175 mya respectively, and have been extensively analyzed to determine geological history, mineralogy, climate, oxygenation, oxidation and the habitability of Mars (Nyquist et al. 2001). What these meteorites have in common is repeated episodes of exposure to water prior to ejection from Mars and evidence of oxygen (Shaheen et al. 2015; Agee et al. 2013; Nyquist et al. 2001; Clayton and Mayeda, 1983, 1996; Romanek et al. 1998). Thus, there was oxygen and substantial bodies of waxing and waning liquid water on the surface of Mars, from 4.5 to 175 my. As noted, there is current evidence of surface moisture, as well as oxygen in the atmosphere and indications of oceans, lakes and rivers as recently as 110,000 years ago.

Based on an analysis of these meteorites Righter et al. (2008) proposed a "clear progression of oxygen fugacity" from minimal (ALH) to oxidized (Nakhlites) to intermediate (Shergottite) as well as evidence of repeated exposures to water. NWA 7034, however, has been found to have "an order of magnitude of more indigenous water than most SNC meteorites" and contains evidence of "multiple oxygen reservoirs on Mars" (Agee et al. 2013). Agee and colleagues (2013) concluded that NWA 7034 represents the best approximation of surface and atmospheric conditions 2 bya. Thus, this particular area of Mars was repeatedly hydrated, possibly by rivers, lakes, and even oceans of water that were increasingly oxygenated--oxygen most likely produced by photosynthesizing cyanobacteria and eukaryotic algae which flourished and formed vast colonies during periods of high obliquity.

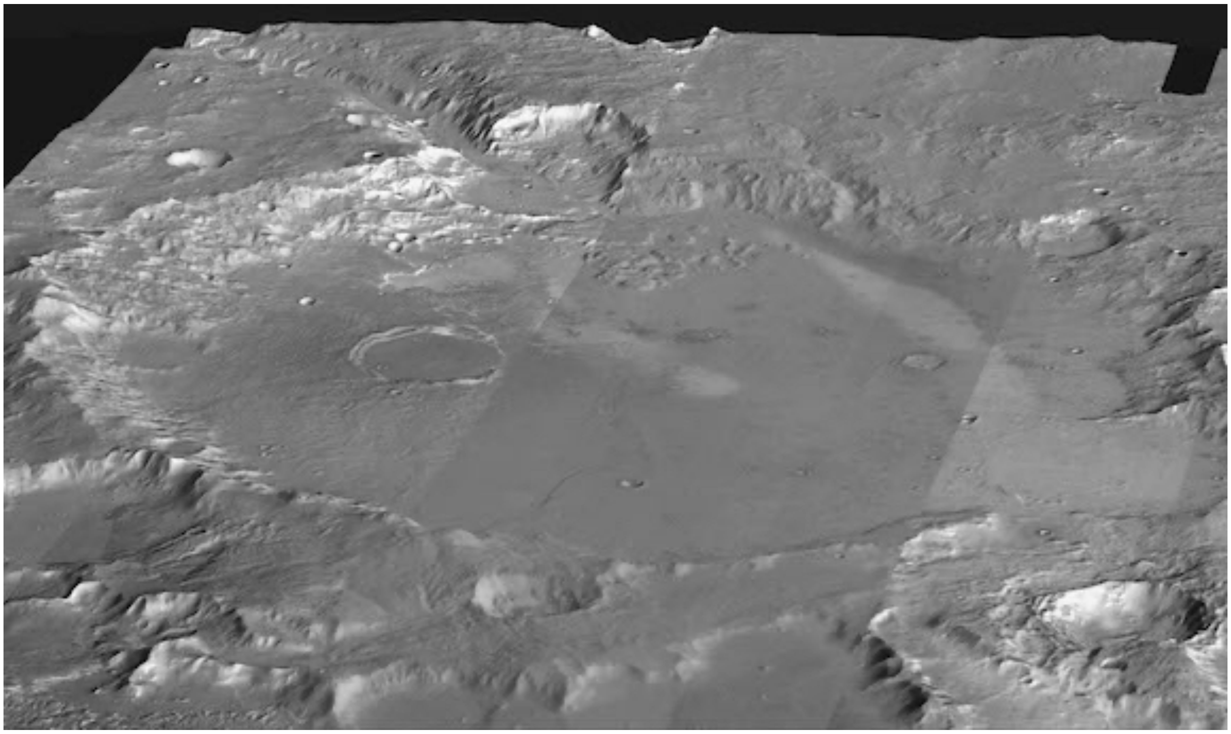


Figure 27: Gusev Crater is approximately 160 km (100 miles) in diameter. Photographed by the Odyssey Orbiter, PIA04260

Life in Gale Crater Lake?

Gale Crater (Aeolis Palus), located in the equatorial and warmest areas of Mars, has a diameter of 154 km (96 mi) and resembles a dried lake or inland sea, at the center of which rises a 5.5 km (18,000 ft) high mountain. There are fluvial valleys rich in potassium salts (Grotzinger et al. 2015), indicative of salty seas; and gullies and channels that appear to have been carved by repeated episodes of flooding that refilled Gale Crater with large volumes of water (Rampe et al. 2020). Chemical and geological analyses of Gale Crater sediments and minerals indicate repeated episodes of hydration (Grotzinger et al., 2014).

The lakes of Gale Crater may have hosted a wide ranging ecosystem that may have been initially based on chemolithoautotrophy (Grotzinger et al., 2014) as well as photosynthesis (Joseph et al. 2020b,f) and within which oxygen producing stromatolite-building cyanobacteria, eukaryotic algae, and then eukaryotic metazoan marine organisms may have eventually evolved (Armstrong 2021a,b, 2022; Joseph 2014; Joseph et al. 2019; 2020; Noffke, 2015; Latif, et al. 2021; Elewa 2021). Specifically, in addition to the stromatolites and microbial mats discovered in Gusev Crater, fossilized mats, domical stromatolites (Figures 30-37, 39- 69) an array of fossils similar to Ediacaran and Cambrian fauna have been tentatively identified in the dried lake beds of Gale Crater (Figures 75-108). These forms resemble the metazoans: *Calymene callicephala, Flexicalymene meeki, Homotelus bromidensis, Isotelus sp., Pseudogygites canadensis, Streptelasma sp.*, Kimberella, *Namacalathus* and *Lophophorates* (Joseph et al. 2020c,d); all of which were embedded adjacent to one another and to specimens that closely resemble each other.

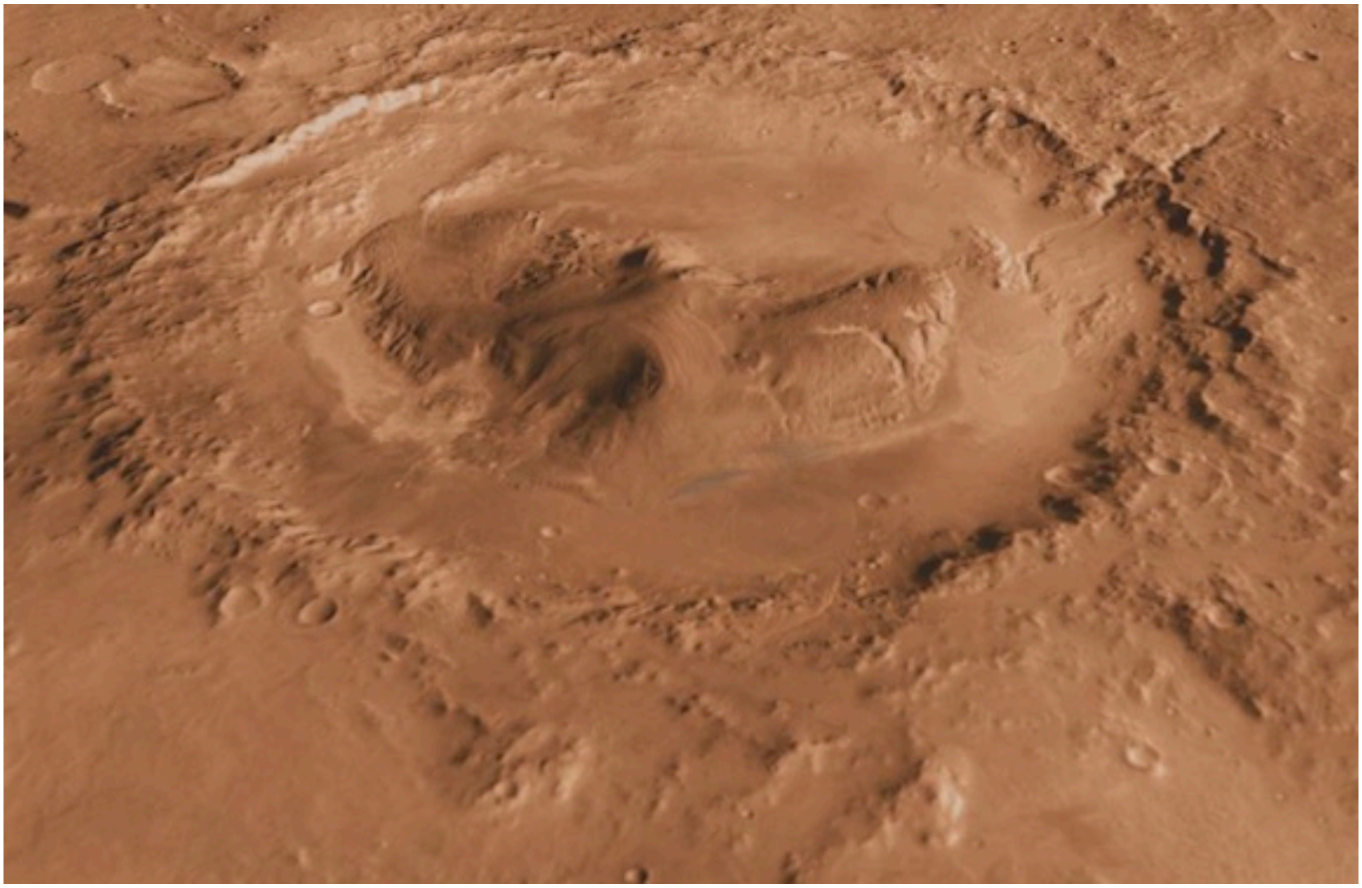


Figure 28: Gale Crater, Mars, today. The crater has a diameter of 154 km (96 miles) and is up to 300 meters (984 ft) deep. Photographed by the Odyssey Orbiter.

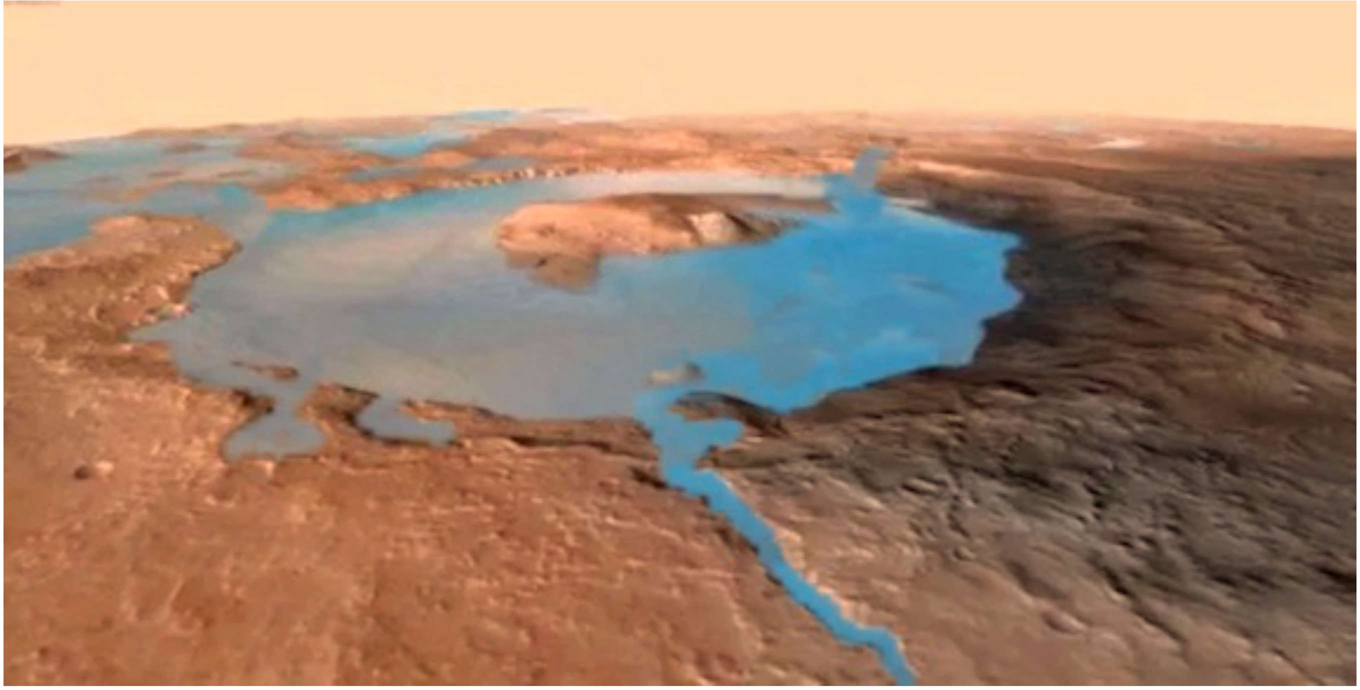


Figure 29: The Gale Crater lakes and inland sea 1 million to 110,000 years ago?

Fossilized Cyanobacteria and Bacterial Mats?

Blue-green algae, also known as ‘Cyanobacteria” (which means “blue”) produce pigments and chlorophyll which enables them to absorb and obtain energy from light. They belong to the phylum of Gram-negative bacteria, and are the only known prokaryote that obtains their energy via photosynthesis and that produce oxygen. They range from 2 to 5 µm in diameter, form vast colonies, and include filamentous species found in extreme environments and which often dominate the upper layers of microbial mats. As there is evidence of oxygen in all Martian meteorites studied, including ALH8004 (dated to between 3.8 to 4.2 bya) it appears they may have colonized Mars over 3.7 bya; and like the cyanobacteria of Earth, began constructing microbial mats and stromatolites (Noffke 2015; Bianciardi et al. 2014). In support of that hypothesis are the published observation of a team that includes internationally known experts in green algae and cyanobacteria (Joseph et al. 2020c) who identified specimens with features similar cyanobacteria with and without filaments, and those resembling fossils of green algae, bacterial mats, and layered and domical stromatolites in areas of Gale Crater. The substrates and/or these specimens also appeared to be variably dry, moist, and possibly covered with thin sheets of ice. These include observations of fossilized biological mats that appear to have formed on the surface of waters that rapidly receded and stromatolites that appear to have been created in the recent and ancient past.

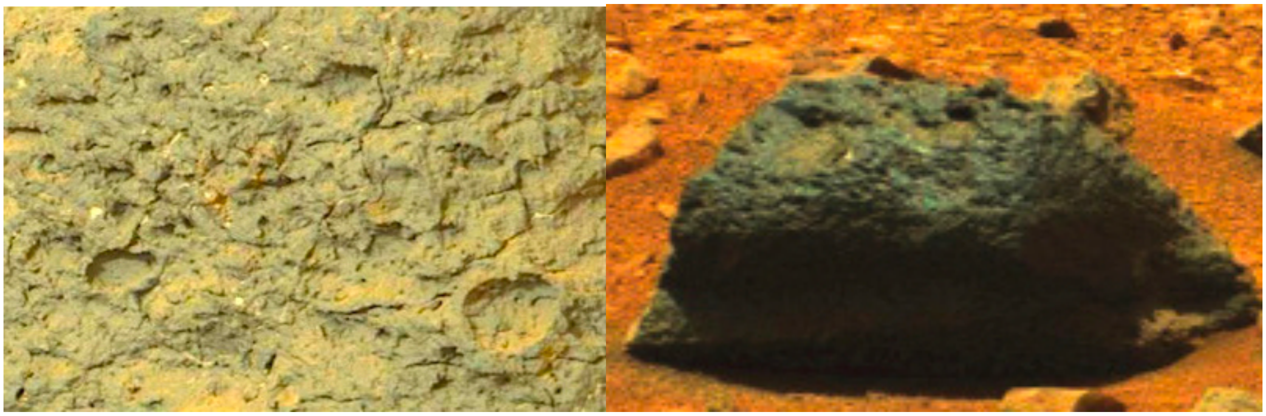


Figure 30: Mars, Gale Crater. (0305MR1262007000E1_DXXX) Mounds of dried blue-green cyanobacteria, microbial mats with erosion pockets?

Figure 31: Earth. Dried microbial mats with erosion pockets: Red Sea coastal plain, south Jeddah, Saudi Arabia (Taj 2014).

Figure 32: Mars, Sol 0322MH0002990020104014C00_DXXX Gale Crater: Elevated patterns created by mat making organisms? These raised patterns are similar to those created by terrestrial mat making organisms in the Negev Desert (Figure 33 below).

Figure 33: (Earth) Elevated patterns created by mat making organisms in the Negev Desert (photographed by Giora Kidron, Negev Desert).

Figure 34: Mars. Microbial mat with vents algae fruiting bodies? 0823MR0036200000500556E01_DXXX

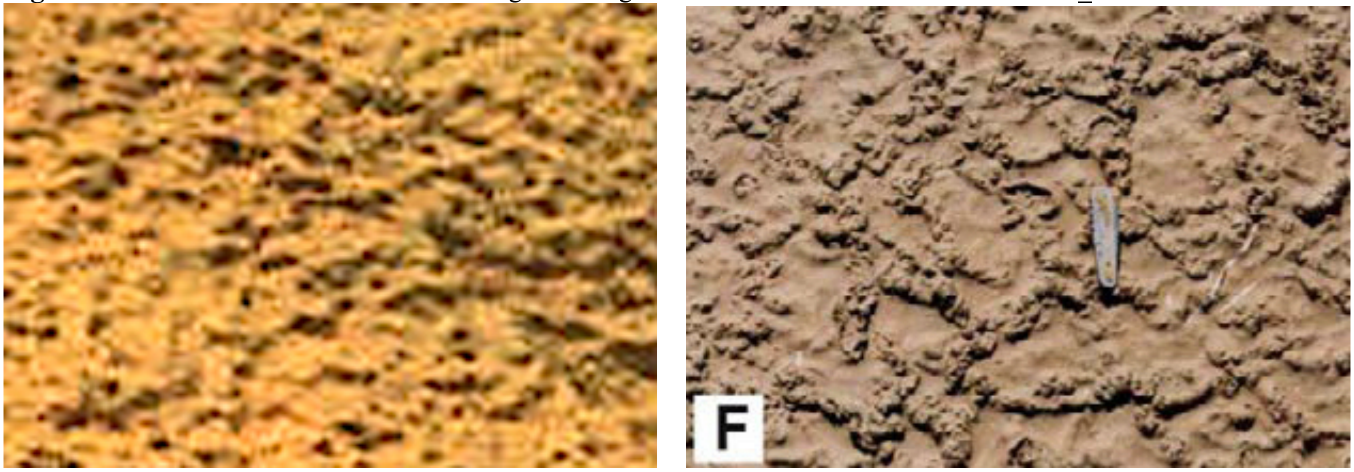


Figure 35: Mars. (Left) Enlarged/Close up view of (Figure 34) microbial mat with algae fruiting bodies? **Earth (Right)** modern microbial mat, Tunisia. Elevated ridges are typical of mat forming organisms including cyanobacteria and algae. The dimpled structures are algae fruiting bodies which are interconnected by networks of mycelium. From Noffke et al. (2001).

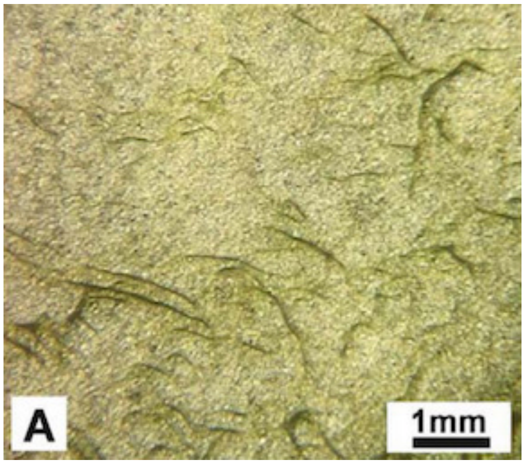
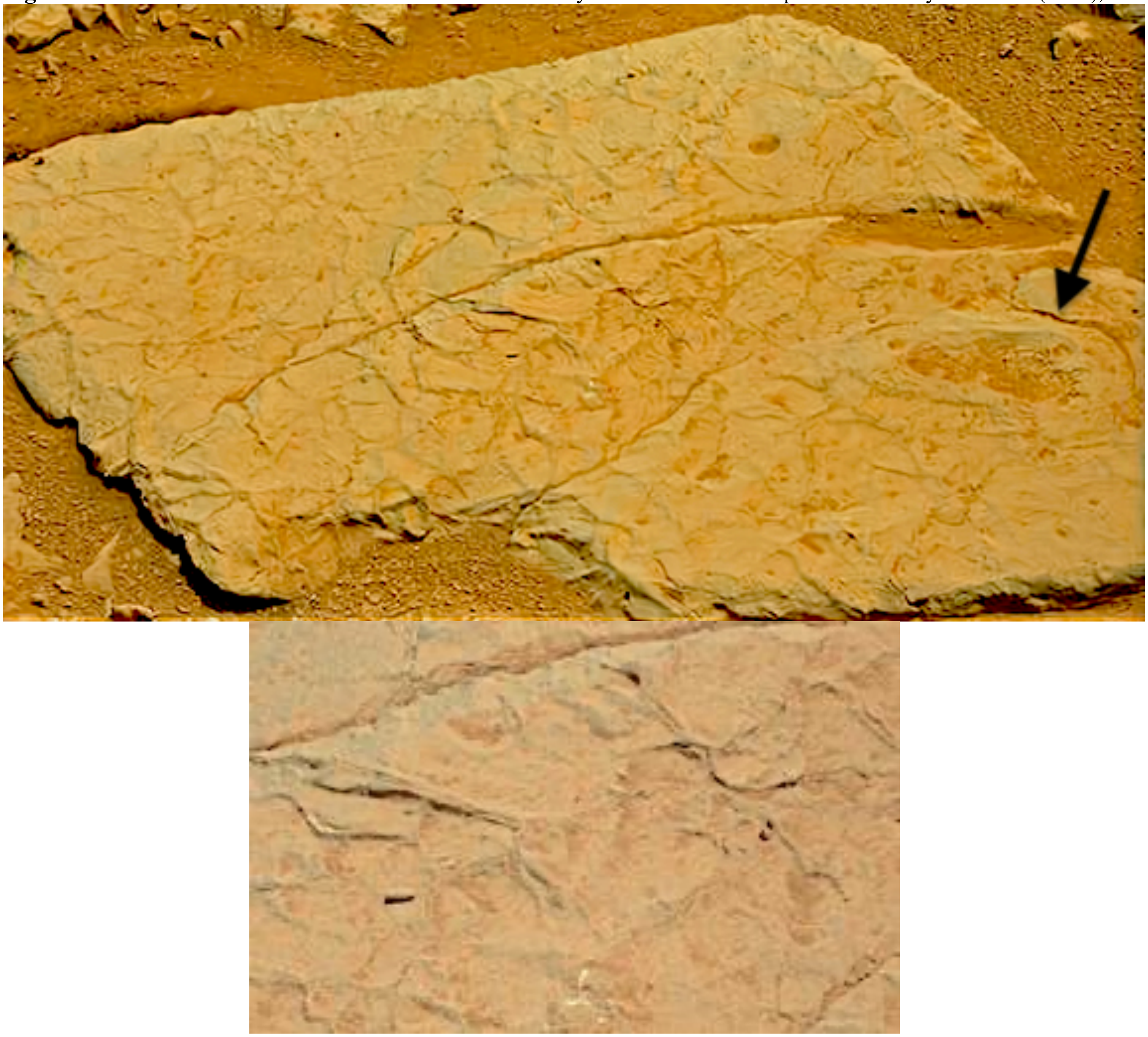


Figure 36: Earth. Earth. Filaments of bacterial mats created by Microcoleus chthonoplastes. Photo by Brohldick (2007),



Figures 37: Mars, Gale Crater. (Center, Enlarged Segment Bottom) Parallel elevated filaments created by mat forming organisms? Black arrow points to what may be a beginning of a concentric stromatolite. 0125ML0007760000103915E01

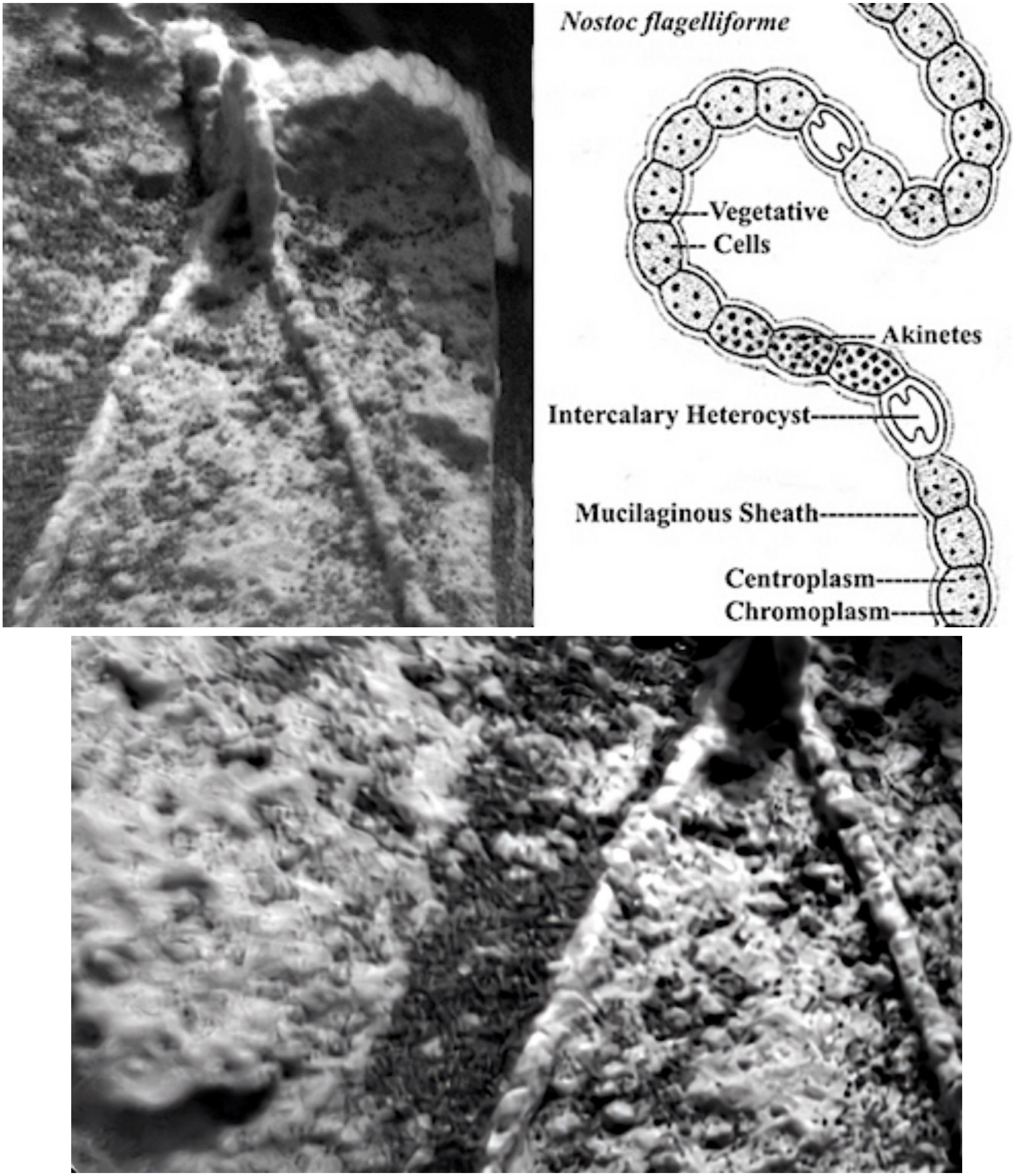


Figure 38: **Mars.** CR0_473216607PRC_F0442414CCAM02853L1. Fossilized Calcium carbonate encrusted cyanobacteria, perhaps similar to *Nostoc flagelliforme, N. parmelioides, N. verrucosum, N. pruniforme,* along with spherical "Nostoc balls," and vesiculous thalli. "*Nostoc* balls" are a calcium encrusted byproduct directly related to the photosynthetic activity of cyanobacteria, formed by the calcification of extracellular polymeric substances making up multiple biofilms and reflect fundamental features of microbial growth calcification These specimens form intracellular Ca-carbonates and which may be scattered and/or arranged in one or several chains within its cells (Joseph et al. 2020c).

Figure 39: Sol 890: A carpet of greenish and yellow covering Martian sand and rock and specimens resembling microbial mats and embedded patterns similar to mat-making filamentous cyanobacteria (Joseph et al. 2020c). 0890MR0038760000501225E01_DXXX

Figure 40: A. Mars. Gale Crater Cyanobacteria and green algae mat? **B & C: Earth:** Cyanobacteria Mats

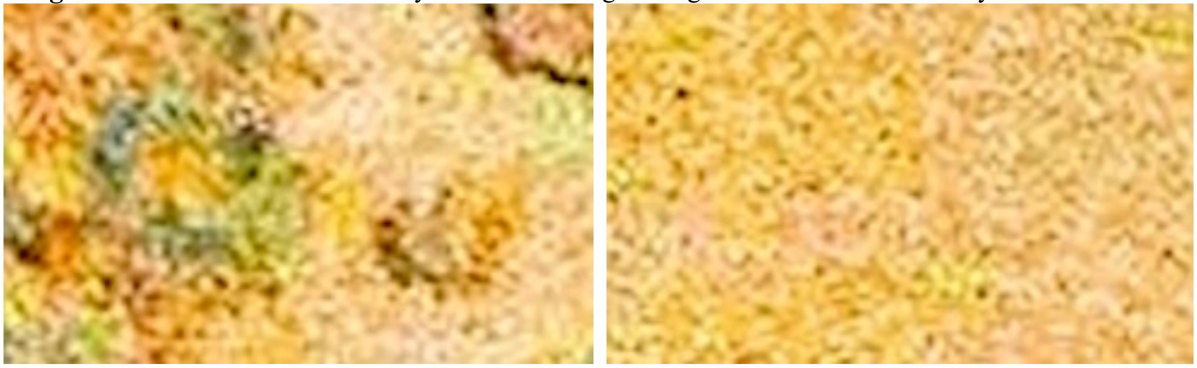
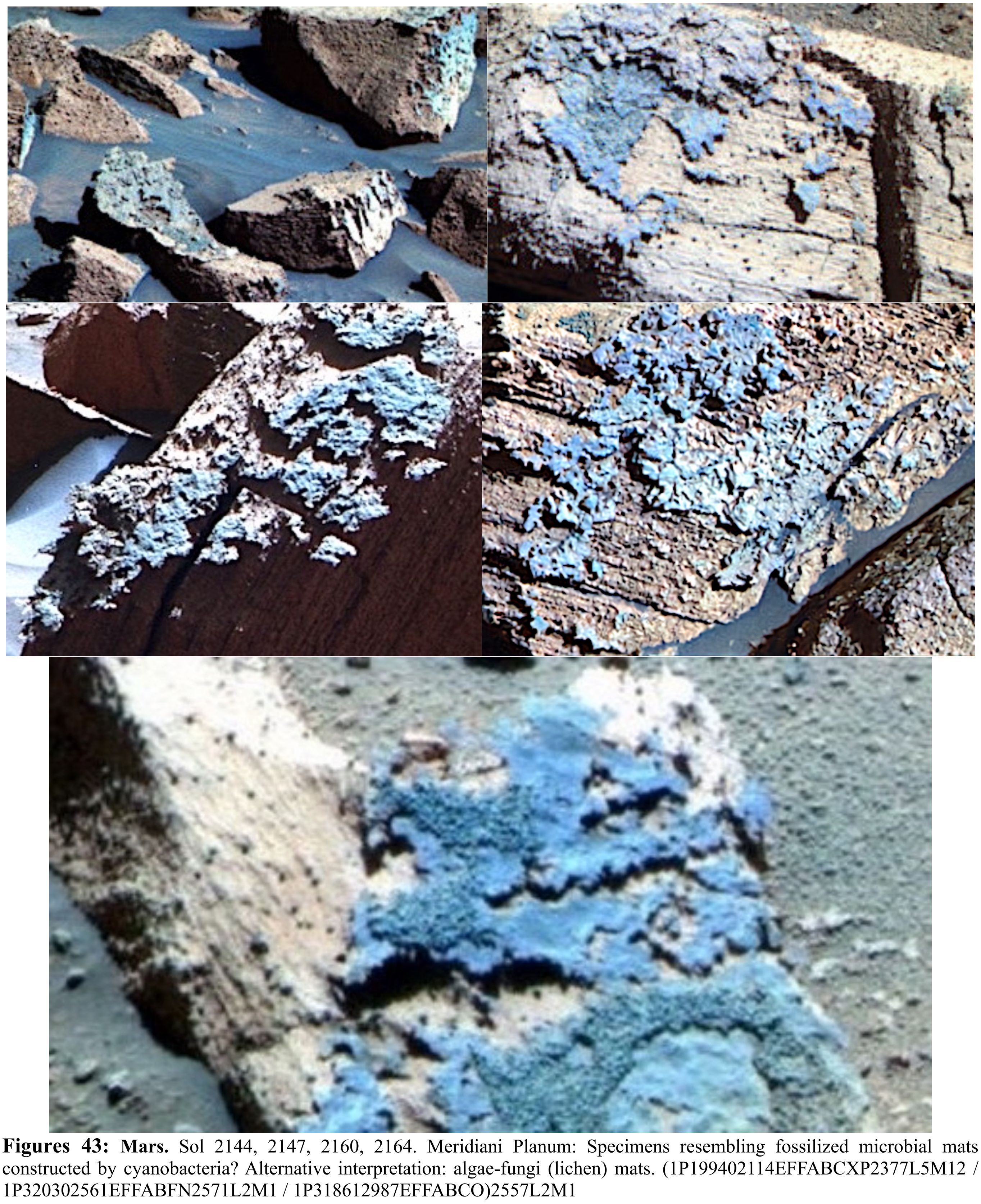


Figure 41: Mars Sol 890: (Left) Concentric stromatolite and (Left/Right) carpet of filamentous cyanobacteria?

Figure 42: (Top). Earth: Algae-Microbial Mat. Image Credit, University of Waterloo. **(Bottom) Mars. Sol 309:** Gale Crater. Formations resembling layers of elevated and possibly fossilized microbial mats which remained elevated due to a sudden and rapid regression of water (Joseph et al. 2020c).



Figures 43: **Mars.** Sol 2144, 2147, 2160, 2164. Meridiani Planum: Specimens resembling fossilized microbial mats constructed by cyanobacteria? Alternative interpretation: algae-fungi (lichen) mats. (1P199402114EFFABCXP2377L5M12 / 1P320302561EFFABFN2571L2M1 / 1P318612987EFFABCO)2557L2M1

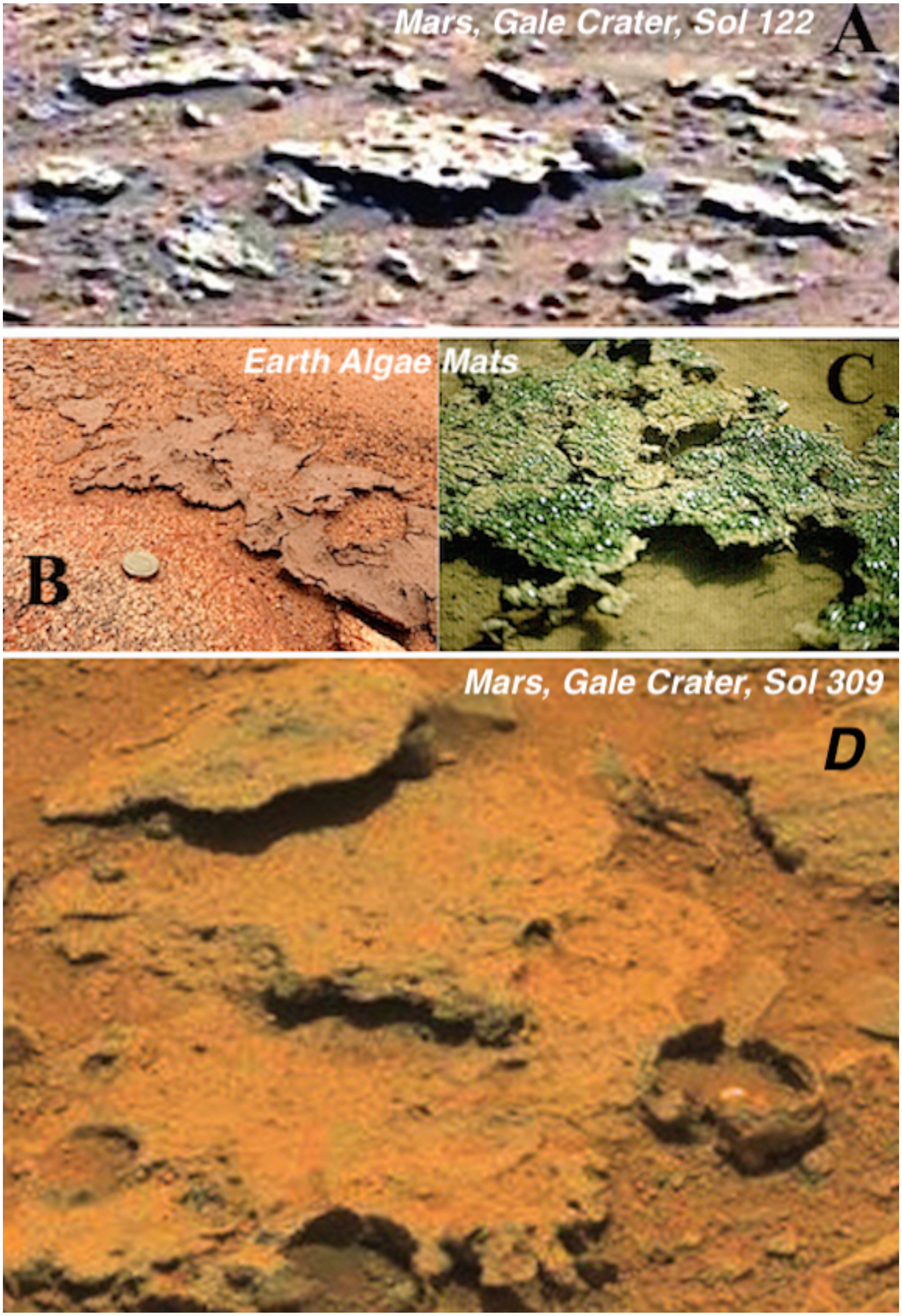


Figure 44: Mars (**A Top**). Sol 122. Gale Crater. Fossilized specimens resembling algae-constructed microbial mats formed in regressive bodies of water? (**D Bottom**) **Mars**: Sol 309. Gale Crater. Domical-concentric-shaped specimen (center right), adjacent to three overlapping fossilized specimens resembling algae-constructed bacterial mats formed in regressive bodies of water? **(B) Earth:** Terrestrial microbial Mat from Damer (2016) **(C) Earth:** Bacterial mat. (Photo Credit, University of Waterloo).

Domical and Layered Stromatolites? Gale Crater & Lake Thetis Australia

That Mars may have had rivers and oceans was recognized by several prominent astronomer in 1784, 1882 and 1895, based on ground-based telescopic observations (Herschel 1784, Schiaparelli 1882, Lowell 1895); findings later supported by the Mariner, Viking, and Mars Global Surveyor missions (Carr 2007; Duxbury 2000; Malin & Edgett 1999; Parker et al. 1986, Head et al. 1999, Sagan & Mullen 1972). These observations led to suggestions, beginning in the 1970s, that water-dwelling cyanobacteria may have constructed stromatolites billions of years ago on the Red Planet (Sagan & Mullen 1972; Twari 1998; McKay & Stocker 1989) and that a "search for stromatolites on Mars" should be undertaken (Walter 1988).

In 2002, and based on the detailed analysis of images from the Viking landers photographed at Utopia Planitia and Chryse Planitia indicative of an ancient paleolake, DiGregorio reported what he believed to be biosignatures compatible with stromatolite-building cyanobacteria. Subsequently, other investigative teams upon examining Martian sedimentary structures also reported evidence of microbial mats, microbialites, and stromatolites that may have been fashioned in ancient and recent lakes and ocean shorelines (Bianciardi et al. 2014, 2015; Joseph, 2014, Joseph et al. 2019, 2020b,c; Noffke, 2015; Ruff & Farmer 2016; Rizzo & Cantasano, 2009, 2016; Small 2015), including those repeatedly exposed to receding bodies of water (Noffke, 2015). The analysis of Rizzo, Cantasano (2009, 2016) and Bianciardi et al. (2014, 2015) are notable: Performing complex micro- and statistical analysis, they determined that these microbialite-like sediments consist of coalescing structures, whose basilar elements are micro-spherules producing oriented concretions and that aggregate in films, laminae, filaments and spherules that began their growth at a microscopic scale until reaching macroscopic structures similar to stromatolites.

Stromatolites are constructed by algae/cyanobacteria in association with sulfate reducing and purple bacteria which form bacterial communities that collectively precipitate $CaCO_3$ in shallow waters which in turn enables them to cement together sand and sedimentary grains via their mucous and biofilm secretions (Stal, 2012; Mobberley et al., 2013, 2015; Louyakis et al., 2017, 2018; Riding 2007). Stromatolites may form stratified and layered mounds that are conical, domical, stratiform, or branching—and similar sedimentary structures have been observed on Mars (Joseph 2014; Joseph et al. 2019, 2020b, 2022; Rizzo 2020; Rizzo et al 2021).

On Earth, living stromatolites are formed along seashores and reefs, freshwater lakes, including Lake Thetis of Western Australia which is host to fossilized and living domical conical concentric stromatolites and thrombolites (Figures 45-55). On Mars, in Gale Crater, domical stromatolites closely resembling the concentric stromatolites of Lake Thetis have been observed (Joseph et al. 2020b). Some of the domical stromatolites of Gale Crater appear to be living or recent constructions, whereas others are clearly fossilized and quite ancient (Figures 52, 54-55). In addition, faint concentric outlines are also visible in areas adjacent to these domical stromatolites (Figure 54). The implications are that Martian stromatolites have been repeatedly fashioned at different epochs of time, in response to episodes of global warming and the replenishment of waters that have repeatedly formed an inland sea within Gale Crater; water that later receded.

Figure 45: Earth, Lake Thetis and submerged stromatolites and thrombolite mats in the Winter and (right) exposed during the Summer (Joseph et al. 2020b).

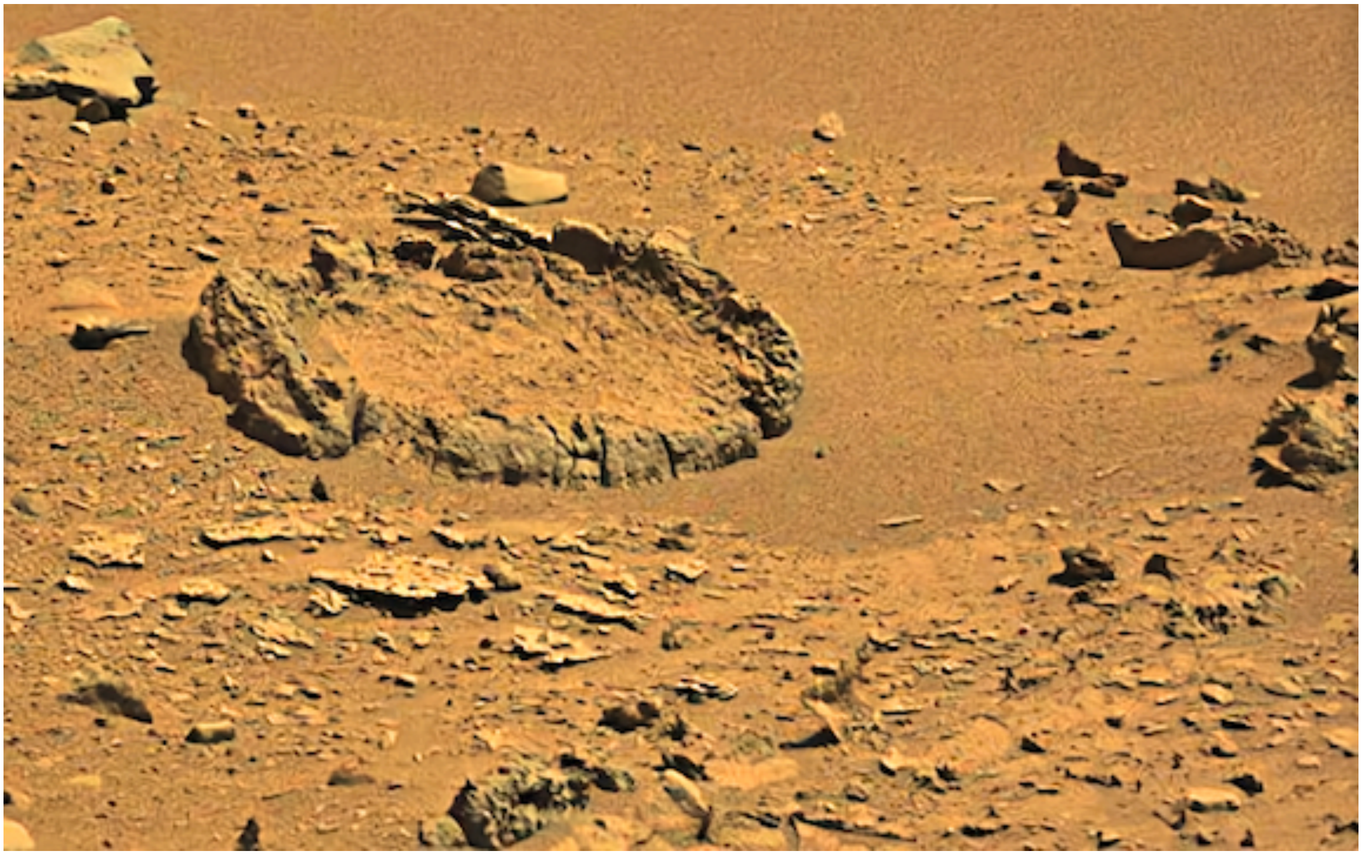
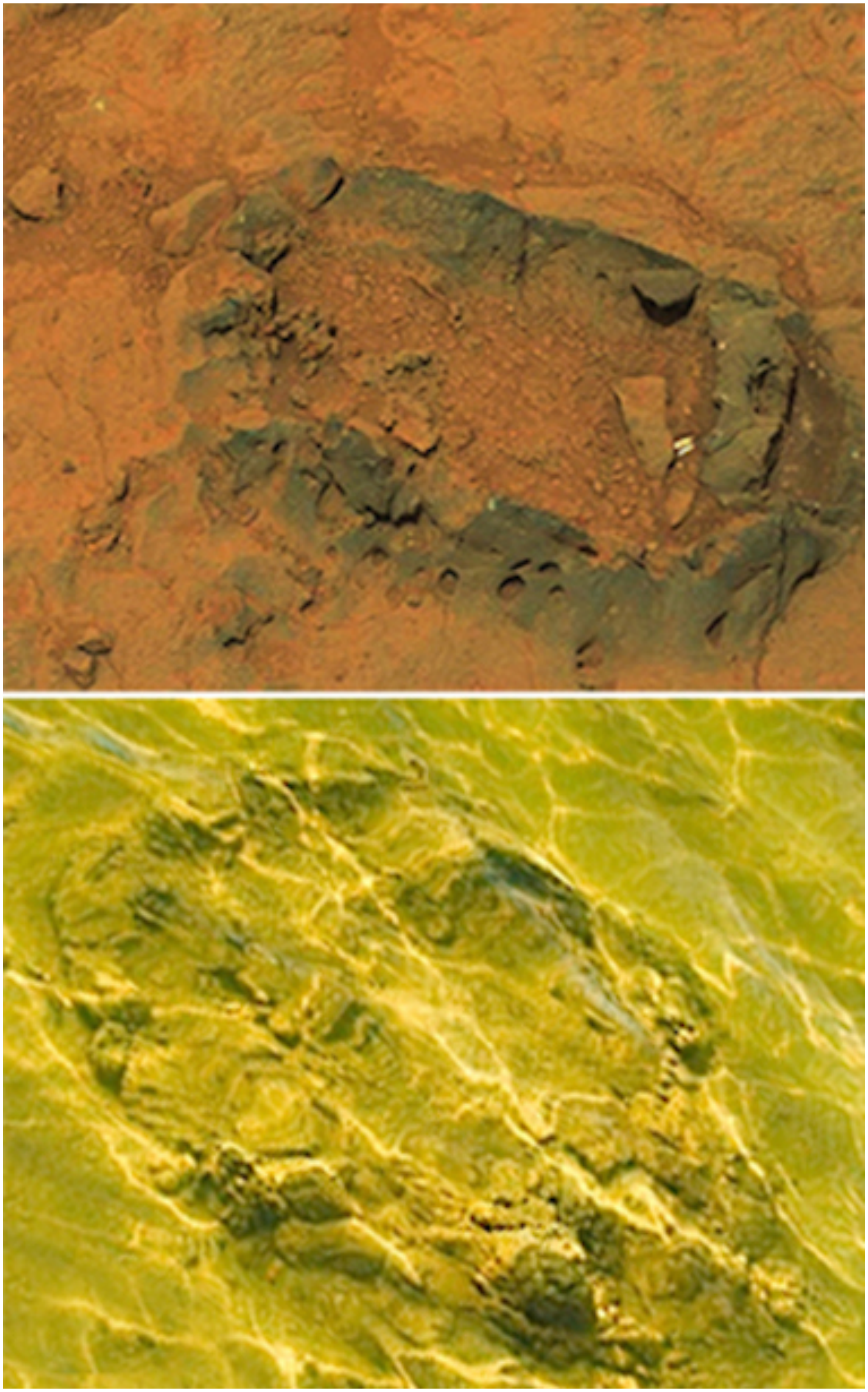
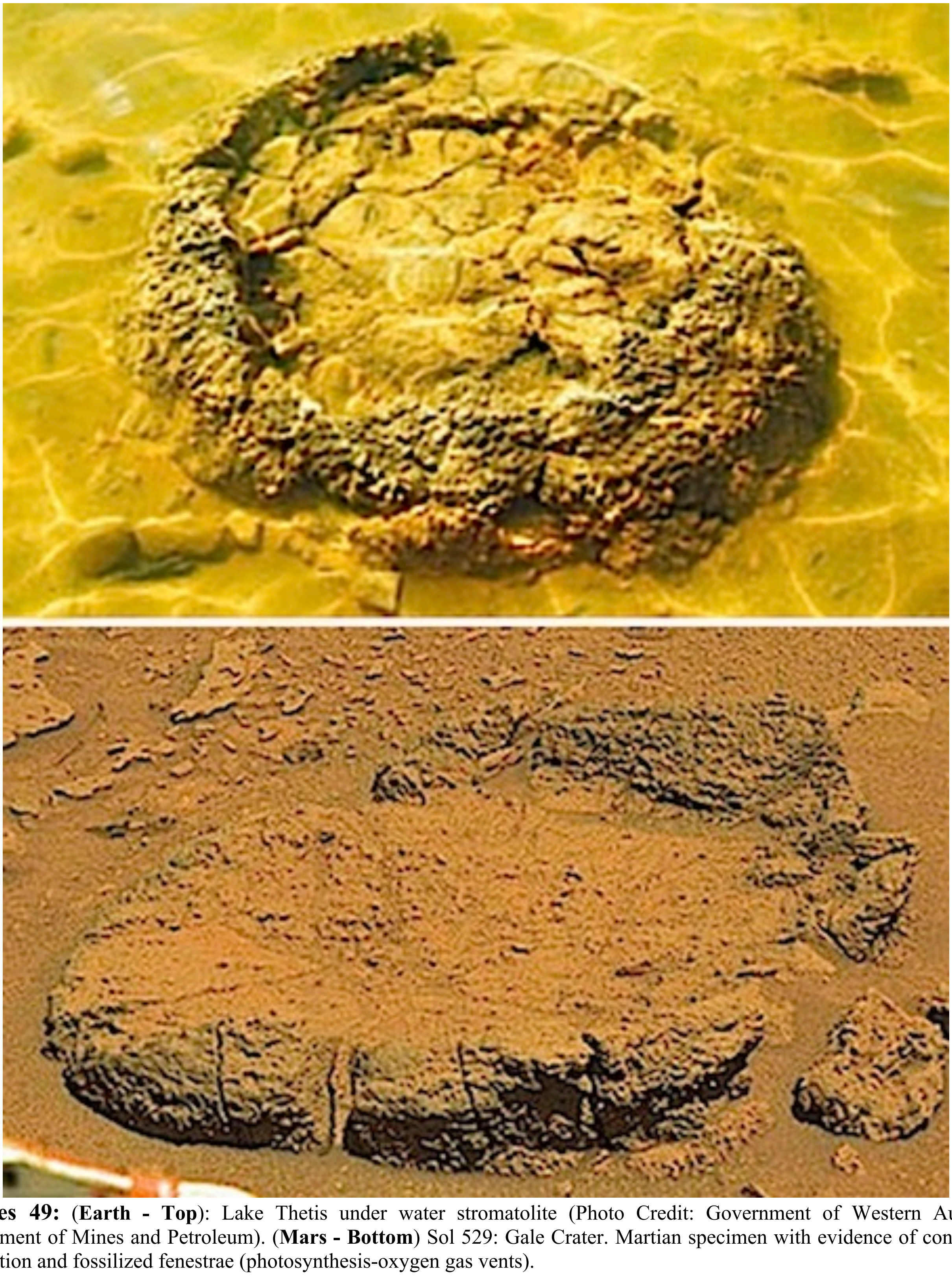


Figure 46: Mars. Sol 122: Gale Crater. Martian concentric specimen, located in within a shallow depression; and appears to be fossilized (see Figure 47). “Peanut brittle” specimens in the foreground resembling algae-constructed mats and appear to be elevated above the surface as if suddenly exposed to a receding body of water (0528ML0020830000203201E01_DXXX).

Figure 47: Mars Sol 122: Portion of Martian concentric specimen (see Figure 46) with evidence of fenestrae (photosynthesis oxygen gas vents) within the upper portion of the walls. This specimen appears to be fossilized and displays the upward and inward orientation typically caused by upward-migrating microbial colonies at the sediment-water interface. This stromatolite-like structure and its central interior is also covered with mat-like and algae-like specimens that may be living and dead. (528MR0020830010303294E01_DXXX)



Figures 48: (**Mars - Top**) Sol 308: Gale Crater. Water pathways leading down and curving around a Martian Specimen resembling a fossilized concentric stromatolite. (**Earth - Bottom**): A Lake Thetis underwater fossilized stromatolite (Photo Credit: Government of Western Australia Department of Mines and Petroleum).



Figures 49: (**Earth - Top**): Lake Thetis under water stromatolite (Photo Credit: Government of Western Australia Department of Mines and Petroleum). (**Mars - Bottom**) Sol 529: Gale Crater. Martian specimen with evidence of concentric lamination and fossilized fenestrae (photosynthesis-oxygen gas vents).

Figures 50: Mars (Top Sol 122) vs **Earth:** Lake Thetis: Collapsed concentric stromatolites,

Figures 51: Mars, Gale Crater. Sols 122, 309, 654. Concentric formations that resemble fossilized concentric stromatolites (Joseph et al. 2020c).

Figures 52: Mars. (Sol 308) Gale Crater. Spectra removed from NASA original photo. Green colors were not added. Blue arrows indicate water pathways and ponding. White arrows indicate bacterial mats. Black arrows point to holes typically associated with water wave and embedded marine organism erosion (0308ML0012730520106657E02_DXXX).

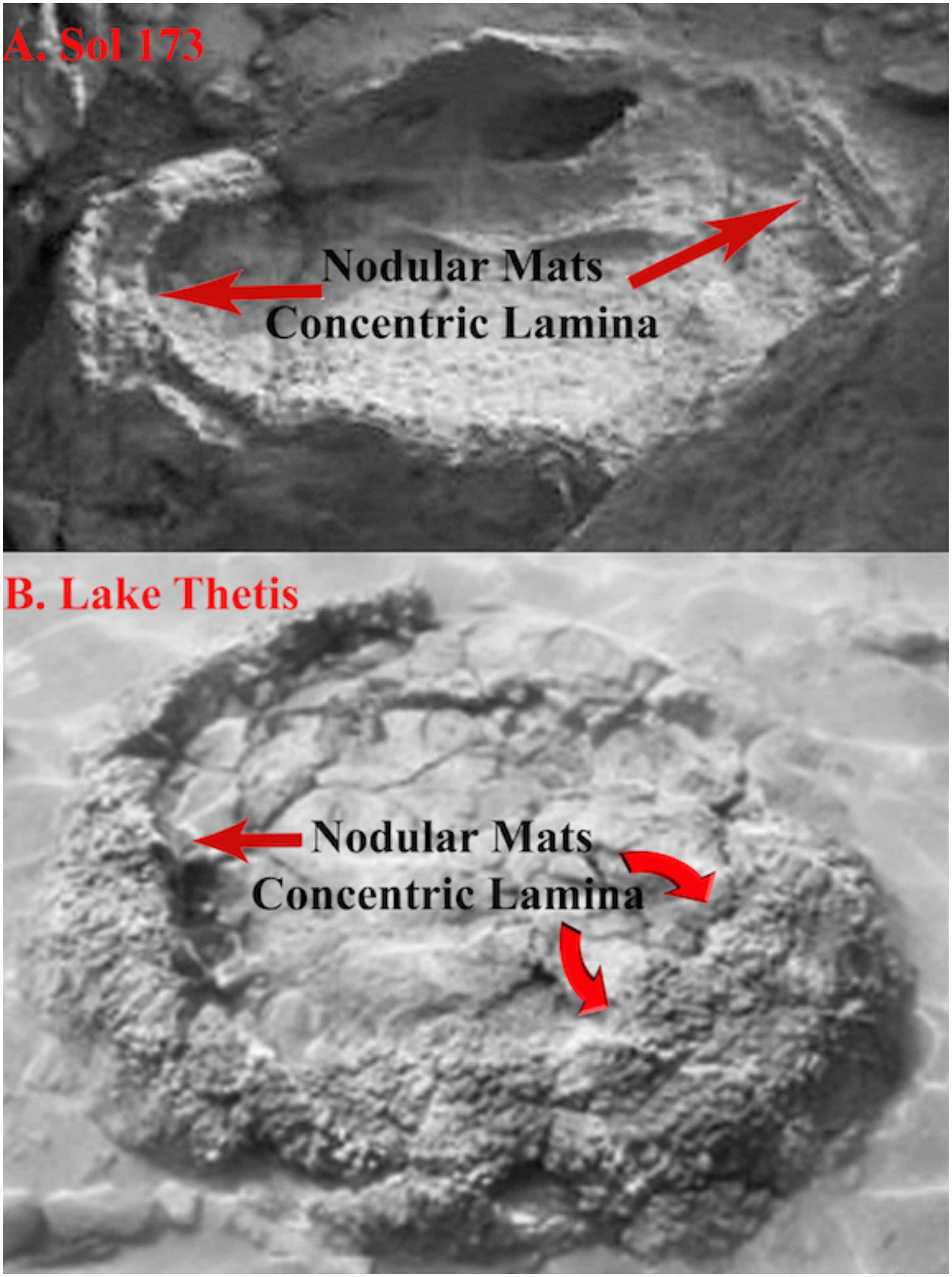


Figure 53: Mars. (**A - Top**): A-Sol 173 This specimens has all the features of a terrestrial stromatolite from **(B - Bottom)** Lake Thetis, including microbialites with concentric lamina, nodular bacterial mats and thrombolites which have a non-laminated clotted "peanut brittle" structure, as well as what appears to be numerous fenestrae/gas bubbles produced by oxygen released via photosynthesis.

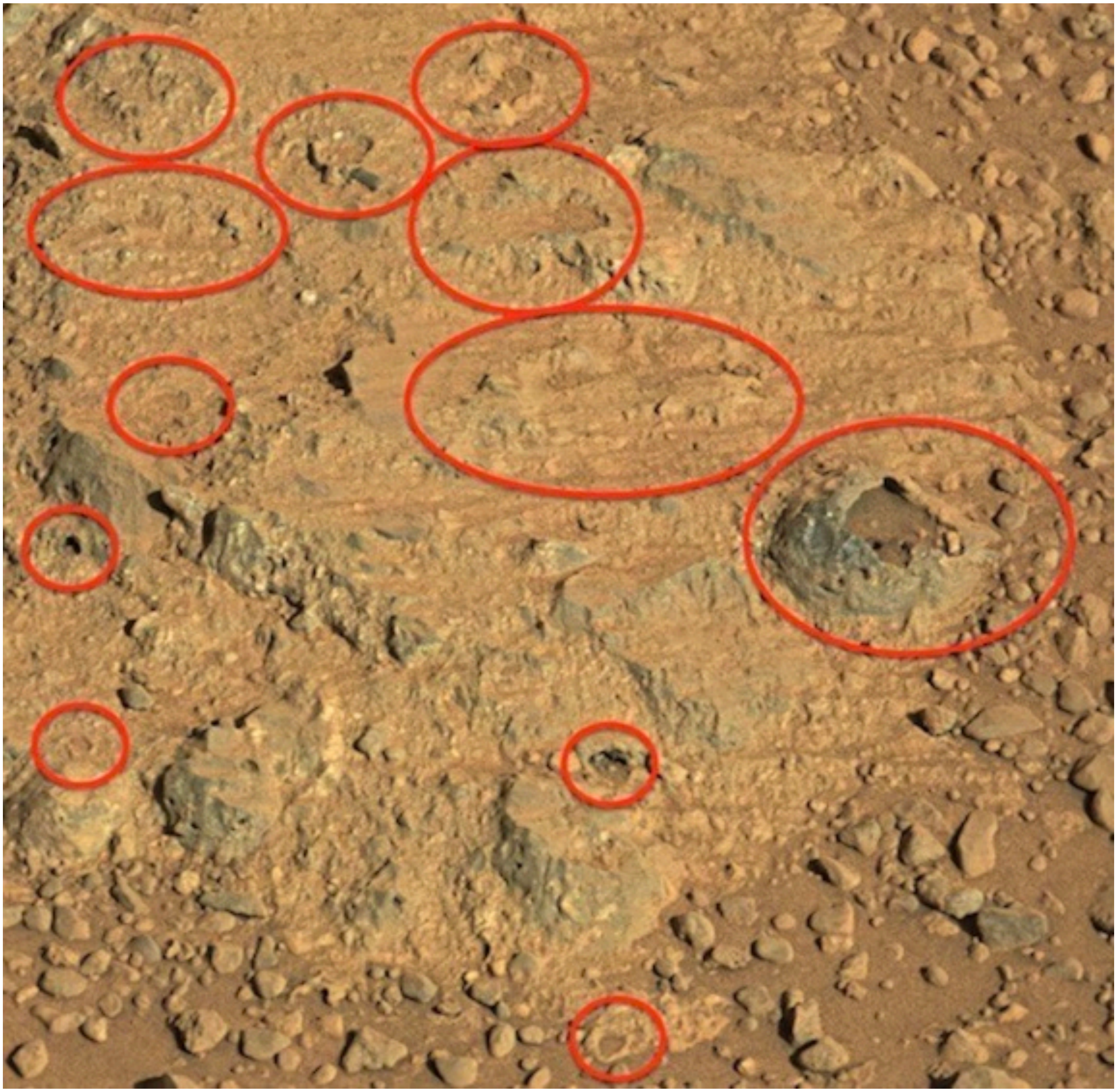


Figure 54: Mars. Sol 654. Gale Crater. Faint concentric impressions on the surface of Gale Crater, Mars: a series of stromatolites constructed during repeated episodes of extreme obliquity and flooding? (0654MR0027730000401977E01).

Figure 55: Mars. (top) Sol 105. Fossilized remnants of a Martian concentric stromatolite? Photographed by rover Spirit (Sol 105) **Earth (bottom):** Lake Thetis fossilized remnants of a concentric domical stromatolite.

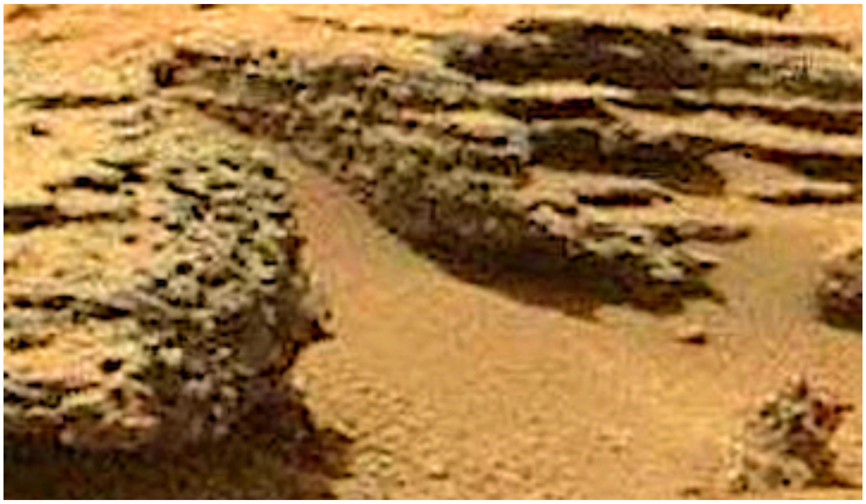


Figure 56: (**Mars. Sol 744**). Gale Crater. Clumps and rows of what resembles networks of hyphae and algae-fruiting bodies with fenestrae attached to sediments similar to terrestrial stromatolites (0744MR0031940350403360E01_DXXX)

Figures 57: Earth. Fossilized stromatolites composed of networks of hyphae/mycelium and algae fruiting bodies (photographed by Dr. Alexey Sergeev in south-western Qatar (https://www.asergeev.com/pictures/archives/compress/2016/1799/02.htm). The central cavity within these hyphae networks of algae fruiting bodies may have served as a vent to release oxygen during photosynthesis.

Figure 58: Mars, Sol 840. Gale Crater. (0840MR0037360290500864E01_DXX). Layered bacterial mats creating a stromatolite tower?

Figure 59: **Earth**. Archaen stromatolite, Pilbara region constructed by benthic microbial communities including sulphate-reducing bacteria, and microalgae, dominated by filamentous and spherical cyanobacteria with fenestra (photographed by Ken McNamara, the Geological Society, https://www.geolsoc.org.uk/Geoscientist/Archive/December-2009/Stromatolites-great-survivors-under-threat). The central cavity within each mico-symmetrical hyphae / mycelium network vented the release of oxygen during photosynthesis.

Figure 60: Mars. (Sol 744). Gale Crater. Symmetrical and fenestrate like formations embedded in mat-and stromatolite-like layers (0744MR0031940270403352E01_DXX).

Figure 61: Mars. (Sol 0744). Gale Crater. Note numerous oval, symmetrical, networks of algae fruiting bodies aligned in rows and layers. False color spectra have been reduced and green hues that had been hidden within the spectra can now be viewed. No green colors were added to the photo (0744MR0031940240403349E01_DXXX).

Figure 62: **Mars**. (Sol 840). Gale Crater. Toppled layered, columnar stromatolite with clumps of algae? .

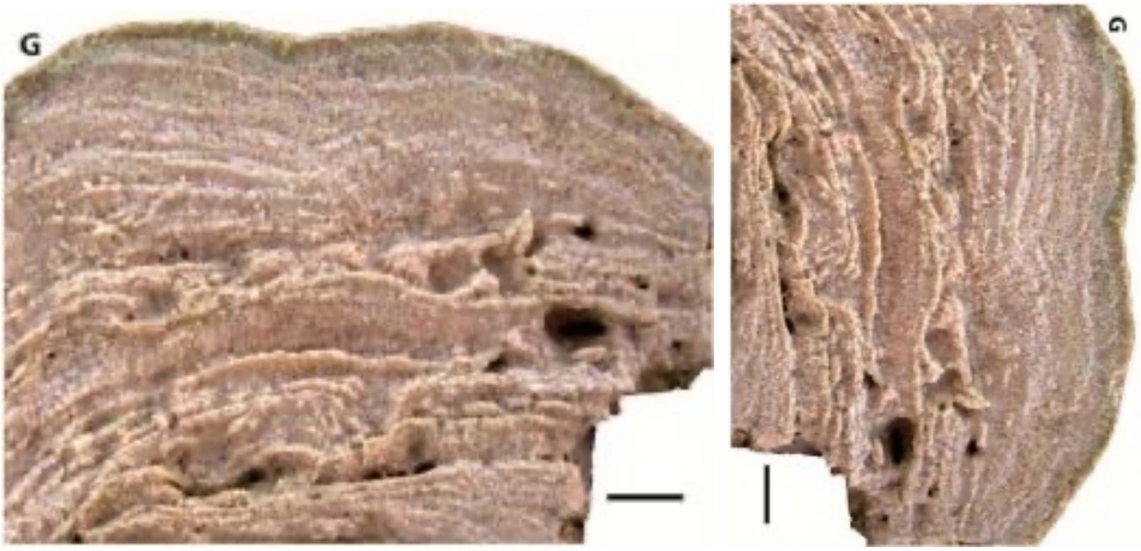
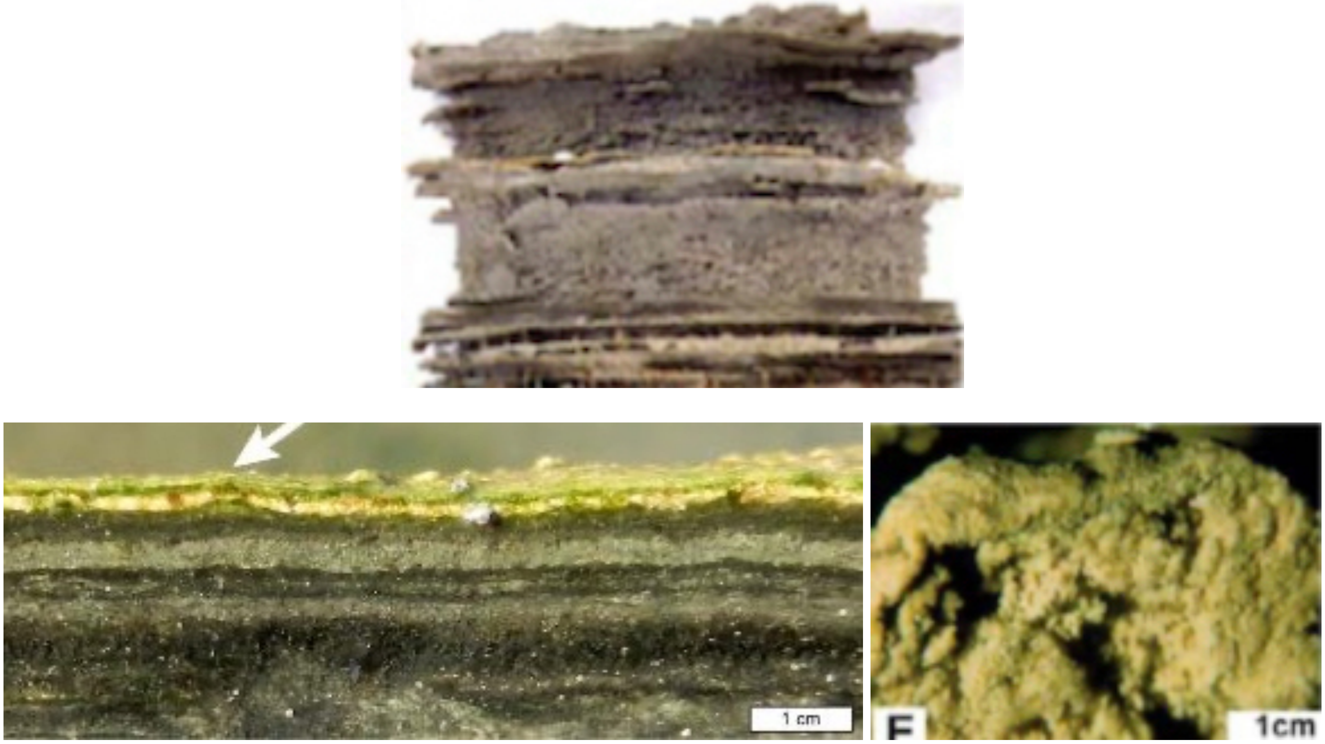


Figure 63: **Earth**. Cross-section of a columnar stromatolite showing well-developed lamination. The scale bar is 1 cm. From Bourillot et al. 2020.

Figure 64: **Mars.** Sol 840. Gale Crater. Microbial-algae mat stacks with clumps of algae on the top?



Figures 65: **Earth.** (Top center): Modern mats from the coast of Tunisia. Note that the upper green layers of these mats are formed by cyanobacteria (arrow), while in the lower parts anaerobic bacterial communities dominate. Martin Homann, 2018. (Left bottom) Earth: Cross-section of a gas dome atop thin green mat on top. Photo: Nora Noffke. (Bottom Right) Earth. Terrestrial stacks of microbial mats underlain and overlain by cross-stratified sediments (relief cast 30 cm high). Photo: Gisela Gerdes; modified after photo published in Gerdes and Krumbein (1987). Photo: H.-E. Reineck. In Gisela Gerdes (2007), Structures left by modern microbial mats in their host sediments. In Atlas of microbial mat features preserved within the clastic rock record, Shieber, J., et al. (2007).

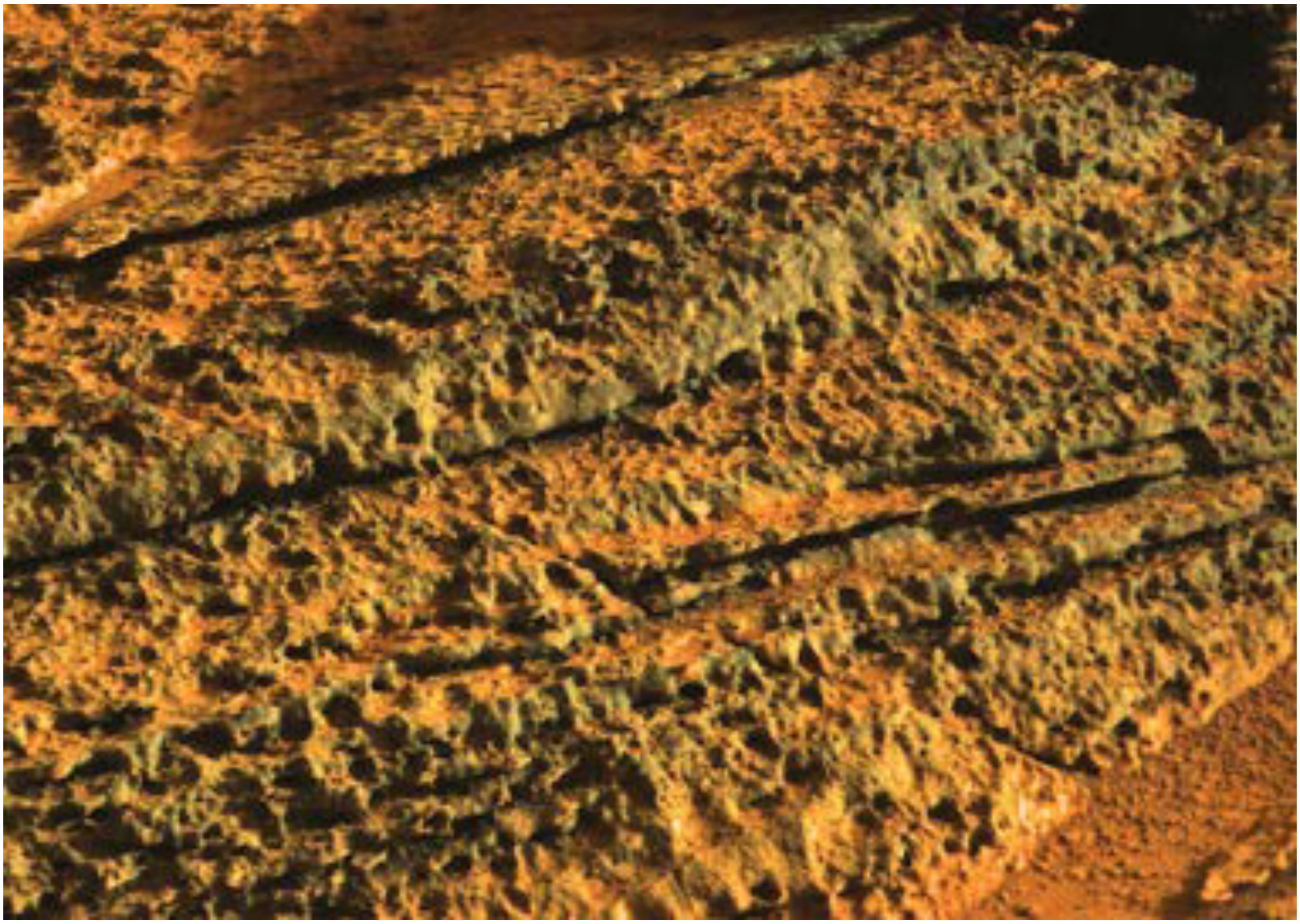


Figure 66: Mars. Gale Crater. Layered stromatolite and dried algae?

Figure 67: Earth. Terrestrial stacks of microbial mats underlain and overlain by crossstratified sediments (relief cast 30 cm high). Photo: Gisela Gerdes; modified after photo published in Gerdes and Krumbein (1987). Photo: H.-E. Reineck.

Fossilized Arcritarchs (Planktonic Micro-algae)?

Water-dwelling acritarchs are a diverse class of unicellular eukaryotes that evolved around 1.8 bya (Evitt, 1963; Martin, 1993). Microfossils of acritarchs are similar to planktonic microalgae and consist of a central cavity. They've been found in association with dormant green algae, may have evolved from alga prokaryotes, and are the ancestors of dinoflagellates (Evitt, 1963; Colbath & Grenfell, 1995).

Specimens resembling fossilized micro-algae and arcitarchs have been identified on Mars (Kazmierczak 2016, 2020; Bianciardi et al. 2021; Joseph et al. 2020c). In 2016, Jozef Kazmierczak, of the Institute of Paleobiology, Polish Academy of Sciences, and an expert in acritarchs, reported the discovery of fossilized biomorphs, photographed by the Rover Opportunity (MER-B) on the western rim of Endeavour Crater, Mars. Kazmierczak (2016, 2020) reports, that these Martian fossils are morphologically strikingly similar to terrestrial microfossils of unicellular "acritarchs" and colonial planktonic microalgae that accumulated in shallow lagoons of Late Devonian seas. Ruff and Farmer (2016) have also reported evidence of filamentous, coccoidal biomorphs and diatoms (microalgae) in Gusev Crater where Bianciardi et al. (2021) found similar specimens in Gale Crater.

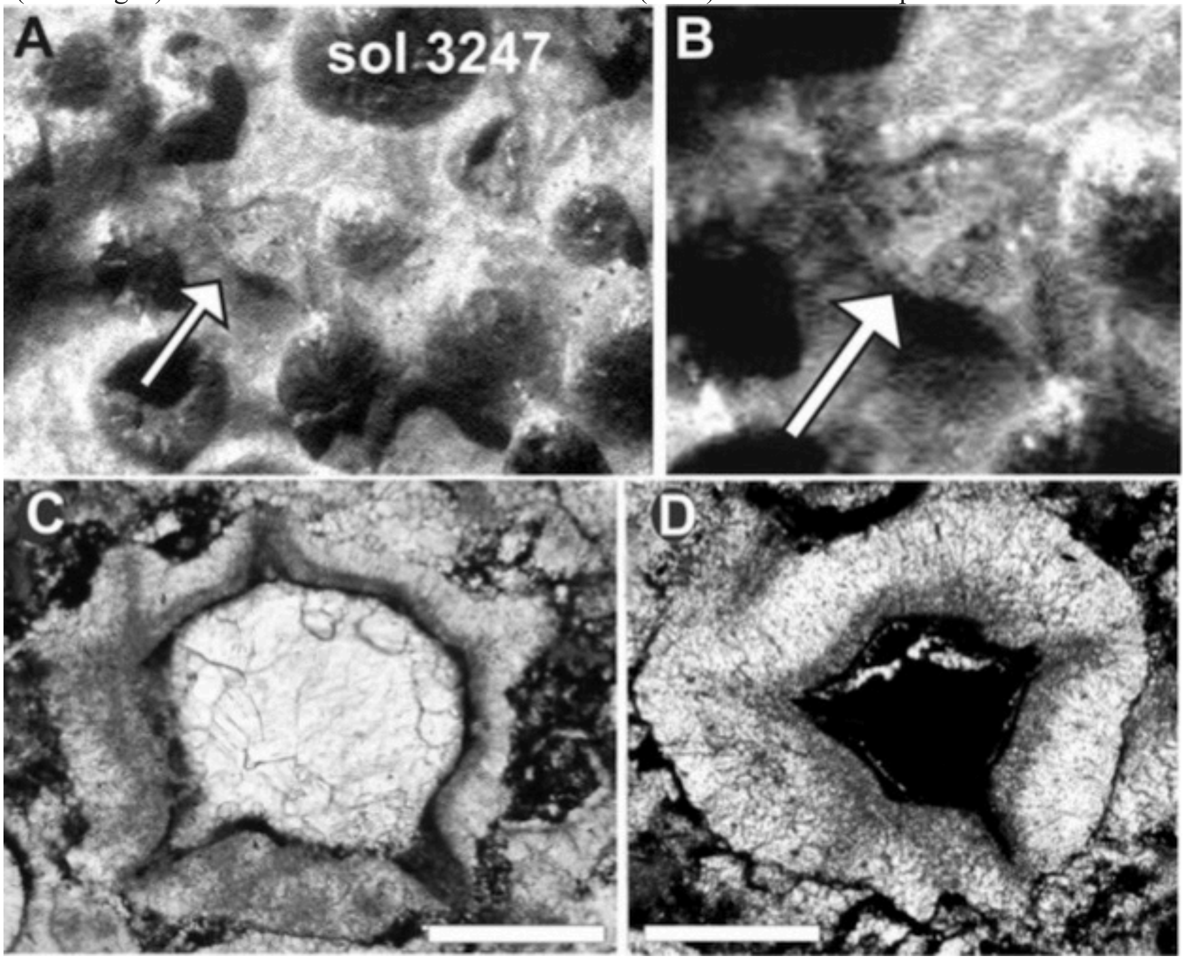


Figure 68: Mars, Endeavor Crater. **Top, A.B.** Sol 3247 / 1M416437725EFFBXSIP2956M2M4-BR). Martian biomorph located on a weathered rock surface outcrop, Endeavor Crater, Mars. The fossilized biomorph has been subject to erosion which reveals its interior cavity filled with granular material. The diameter of the Martian acanthomorph is approximately 2.5 mm. This specimen is similar to terrestrial acritarch fossils. (**Earth, Bottom, C.D.**). Optical micrographs of terrestrial acanthomorph microfossils, i.e. typical acritarchs. Thick calcium carbonate coatings excreted by these organisms can be viewed. Scale bars: for (C) and (D) - 100 μm. (Reproduced with permission from Kazmierczak 2016).

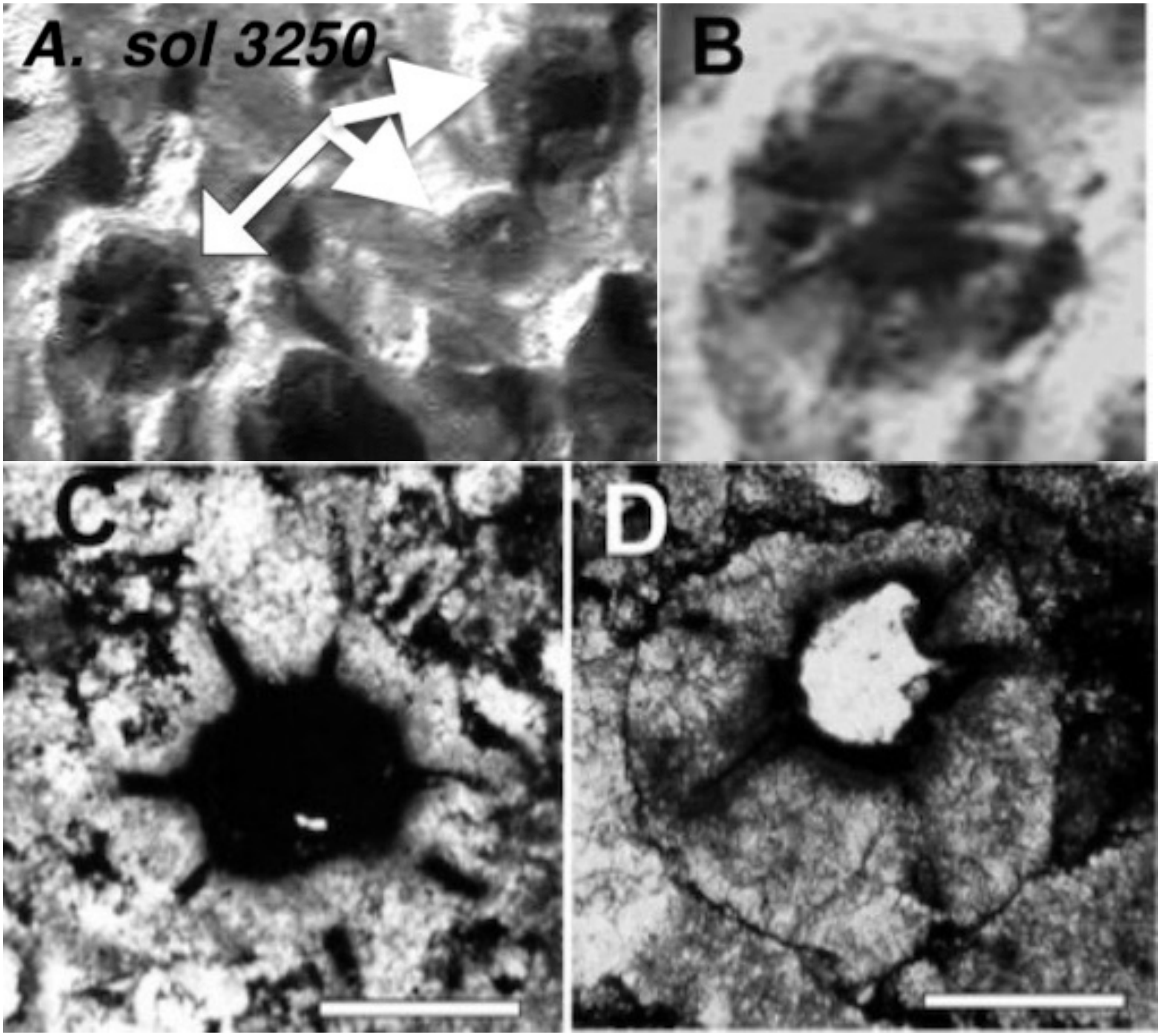


Figure 69: (**Mars, Top, A.B.)** Endeavor Crater. Sol 3250 / 1M416713255EFFBXSIP2955M2M1). Martian biomorph, approximately 1.5-2 mm in size) located on a weathered rock surface outcrop, Endeavor Crater, Mars. Note (arrows) spherical central bodies with radially extended spiny processes. (B) Magnification of biomorph (A--left). (**Earth, Bottom, C.D.**) Optical micrographs of morphologically similar microfossils of Baltisphaeridium; typical acritarchs / unicellular algae from the Late Devonian, Upper Silesia. Scale bars for C and D = 100 µm. (Reproduced with permission from Kazmierczak 2016).

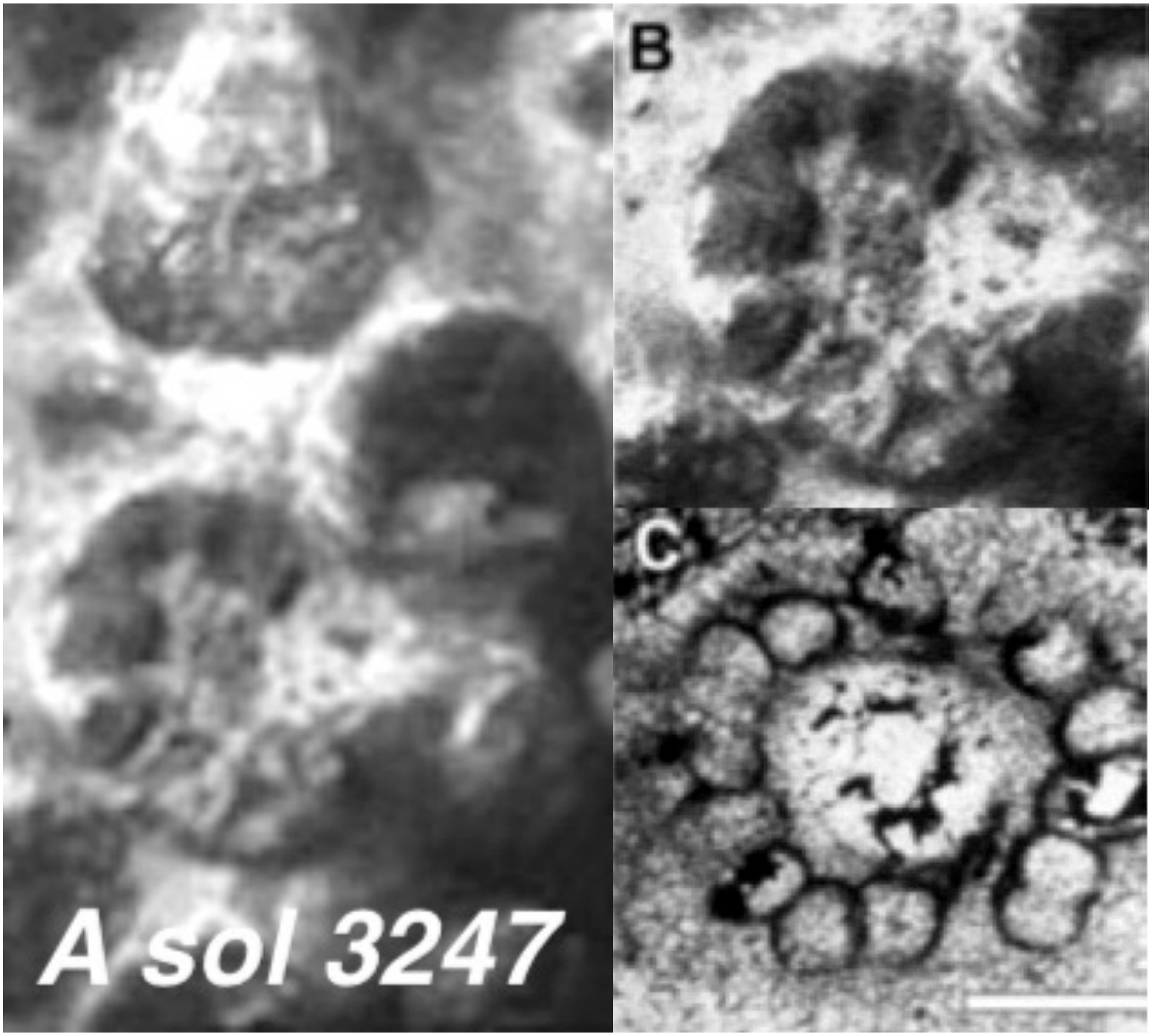


Figure 70: (**Mars, Left/Right Top, A.B.**) Endeavor Crater. Sol 3247 / M416437725EFFBXSIP2956M2M4-BR). Martian biomorph, approximately 1.5-2 mm in size) located on a weathered rock surface outcrop, Endeavor Crater, Mars. Note: Spherical shape with well-delineated, ring-like external cellular wall composed of tightly adhering subglobular bodies surrounding a hollow central chamber. (**Earth, Bottom, C.**) Optical micrograph of a thin section of a Late Devonian volvocalean alga. Scale bars for C = 100 µm. (Reproduced with permission from Kazmierczak 2016).

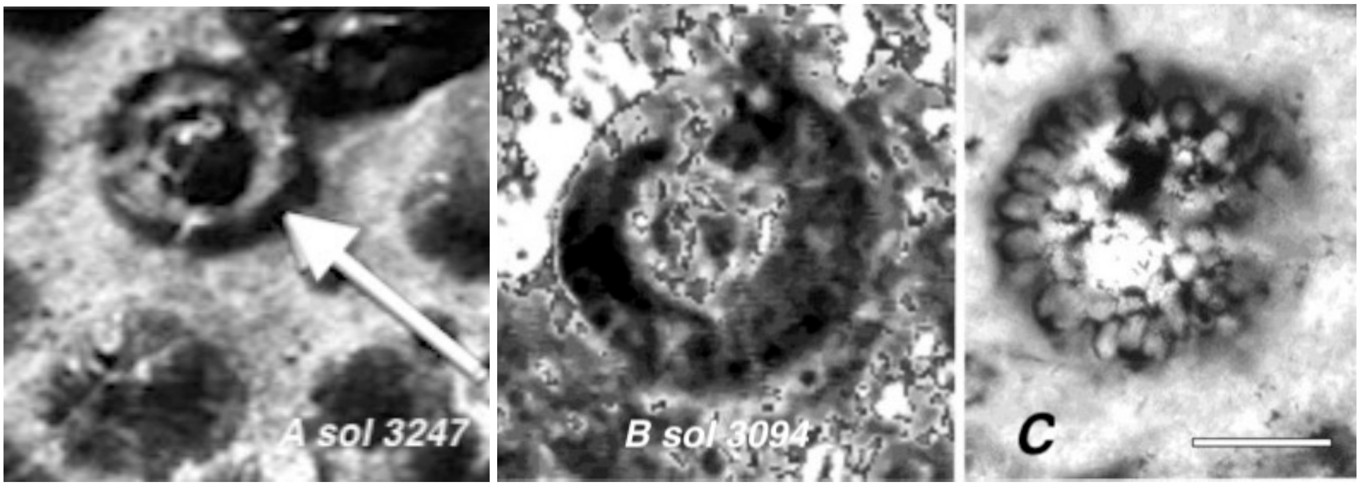


Figure 71: (**Mars, Top, A** Sol 3247 / **B**. Sol 3094). Endeavor Crater. Martian biomorph, approximately 1.5-2 mm in size) located on a weathered rock surface outcrop, Endeavor Crater, Mars. Note: Spherical shape with well-delineated, ring-like external cellular wall composed of tightly adhering subglobular bodies surrounding a hollow central chamber. (**Earth, C.**) Optical micrograph of a thin section of a Late Devonian volvocalean alga. Scale bars for C = 100 μm. (Reproduced with permission from Kazmierczak 2016).

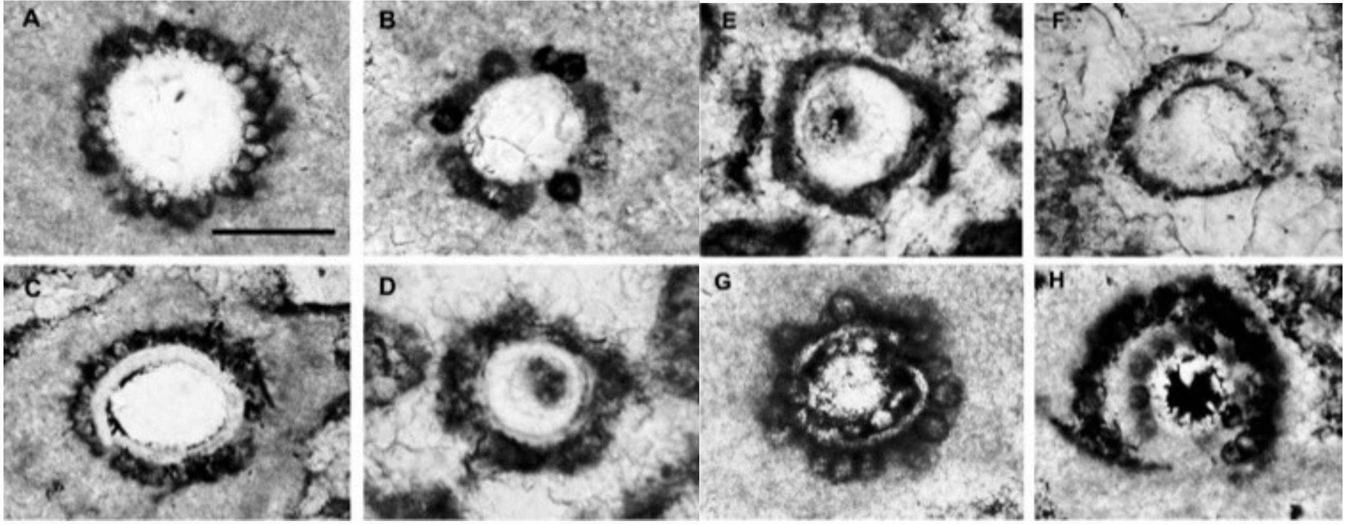
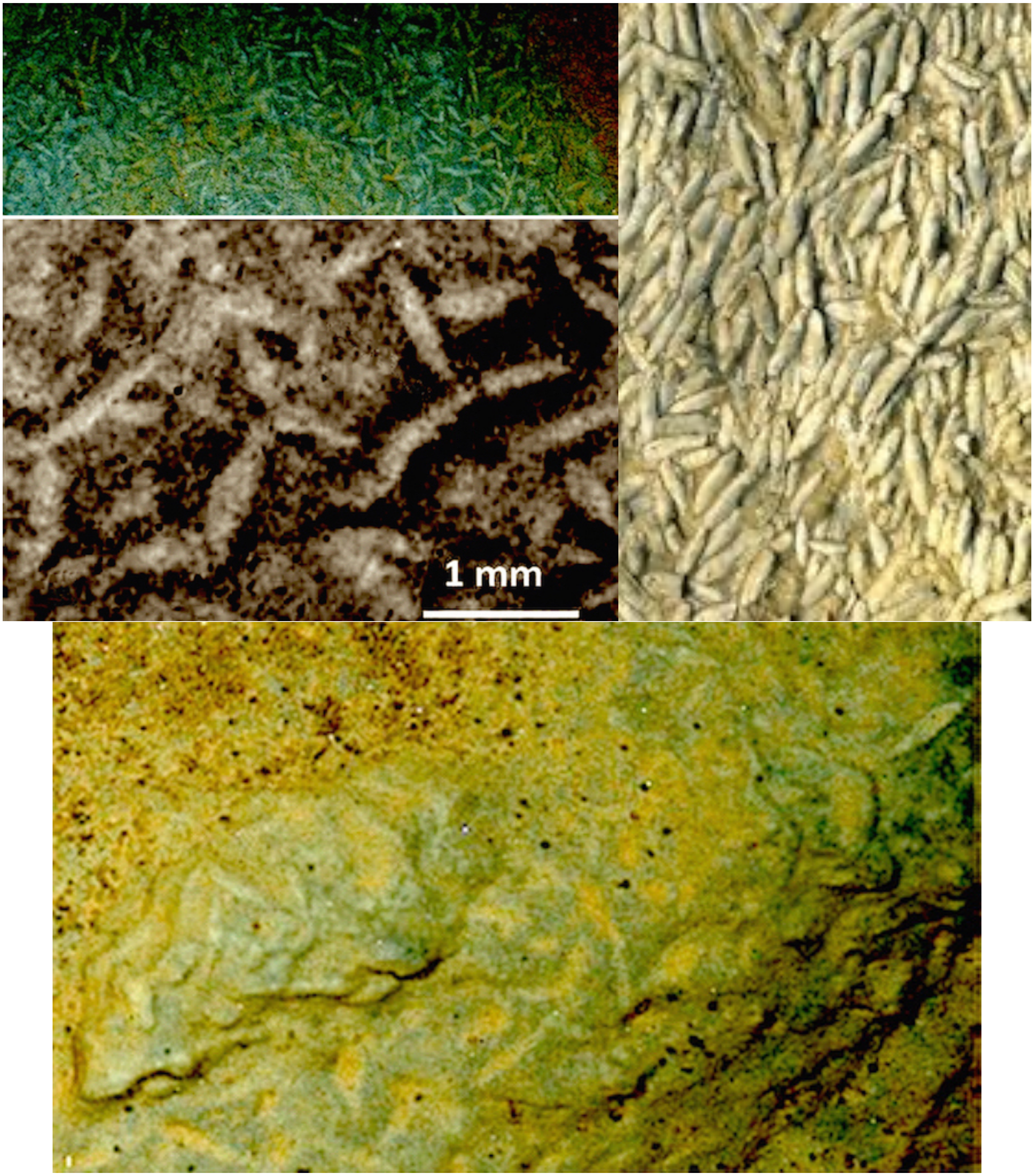


Figure 72: **Earth,** A=H: Optical micrographs of Late Devonian fossilized volvocalean alga / acritarchs. Scale bar for A = 100 μm. (Reproduced with permission from Kazmierczak 2016).

Fossilized Eukaryotic Foraminifera (Algae / Protozoa with Flagella)?

Foraminifera are eukaryotic single-celled organisms that likely evolved between 900 and 650 million years ago. They are members of a phylum that includes amoeboid protists and are composed of microgranular calcite and/or chitlin. Protists are also directly related to and include multi-cellular eukaryotic algae. Fossilized formations that resemble vast colonies of fossilized Foraminifera were discovered in Gale Crater (Joseph et al. 2020c) as depicted in the following photos.



Figures 73: (**Mars.** Sol 809, **Left: Top/Center,** Sol 869 **Bottom**): Gale Crater. Fossilized Impressions of biomorphs, photographed attached to mud stone, in Gale Crater Mars, and that have been identified as similar to foraminifera; their fossilization made possible via their calcite and/or chitlin composition. From Joseph et al. 2020, and top-left figure also appears and is discussed in Bianciardi et al. 2021. (**Earth, Top Right**): Fossilized Foraminifera (Fusulinid) in limestone.

Seaweed? Plant Roots?

Seaweeds evolved from algae around 1.1 bya, and both are the ancestors of the earliest plants that developed 450 million years ago (Tang et al. 2020). Specimens that resemble seaweeds, filamentous cyanobacteria/algae and plant roots, surrounded by what may be algae fruiting bodies entangled in mycelium, have been photographed in Gale Crater (Joseph et al. 2020c).

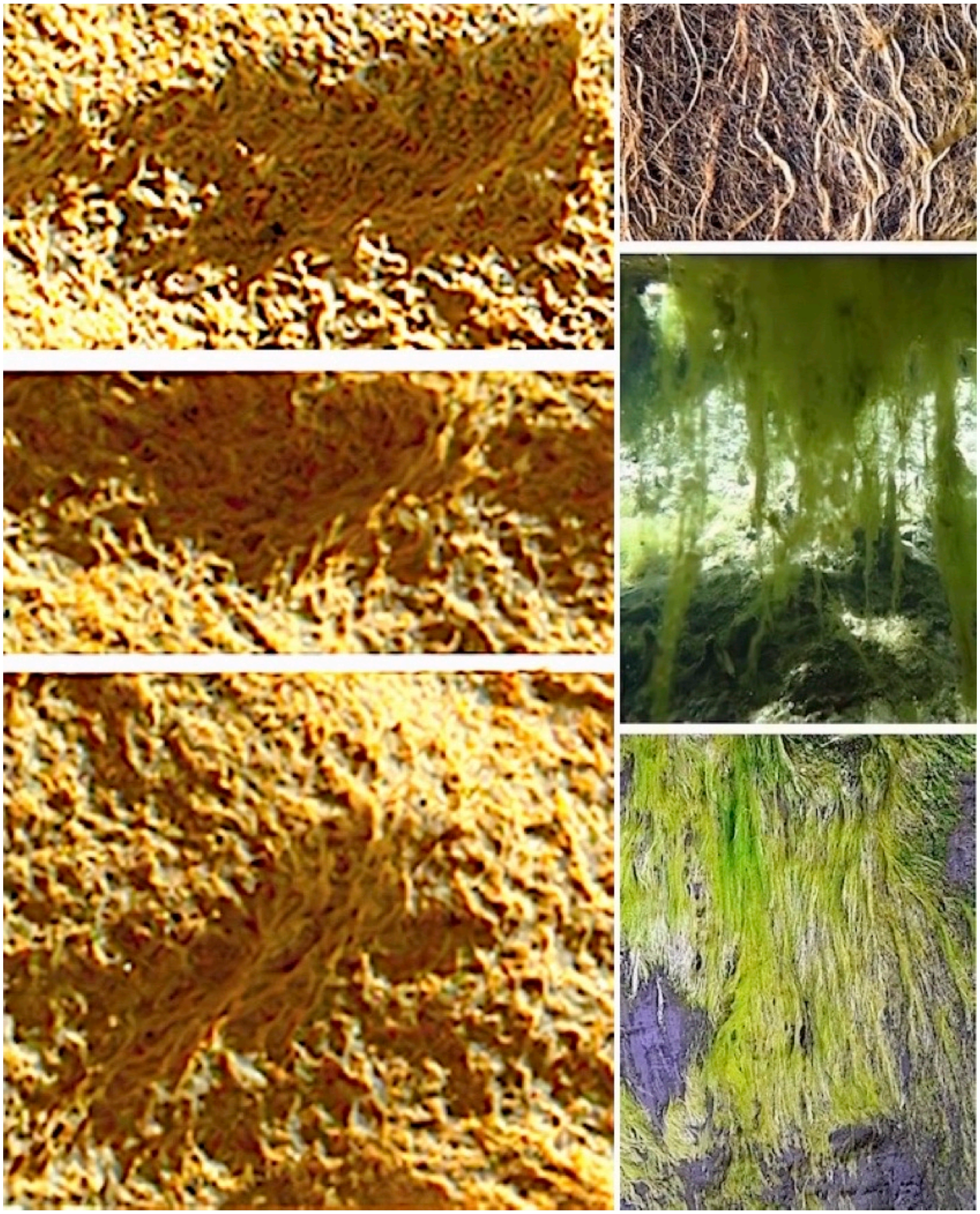


Figure 74: (**Mars,** Sol 322 Left column): Gale Crater. Possible flowing tangles of dried seaweed consisting of and surrounded by filamentous cyanobacteria/algae fruiting bodies, Also, similar to Pseudoparenchymatous plant roots pressed tightly to rock surfaces marked by porosity; photographed in the dried lake beds of Gale Crater. The filamentous algae Klebsormidium and Oedogonium are comparable to the specimens seen here from Gale Crater (From Joseph et al. 2020c). 0322MH0002990020104014C00_DXXX (**Earth,** Right column): Seaweed.

Corals and Sponges?

Formations resembling fossilized siliceous filamentous sponges have been photographed on Sol 809 in the dried lake beds of Gale Crater (Joseph et al. 2020c). These sponge-like structures resemble opaline-calacite-mineralized trace fossils and are similar to those that were fossilized during the late Cambrian era within sediment surfaces of seashores in northern China. Ruff and Farmer (2016) have also identified what they believe to be opaline silica "sponge-like" specimens in an ancient volcanic hydrothermal lake (Ruff et al. 2011) that meets the criteria for biology, including evidence of porosity.

As shown in Figures 75-78, 80-82. unusual intertwined upward directed tubular-conical structures were photographed in Gale Crater, on Sols 3396, 3397, with features, including porosity, similar to sponges and corals (Armstrong 2022). It is not possible these are mineral-salt formations that somehow rose up above the surface like a stalagmite. Stalagmites form in limestone caves and caverns and grow upward due to the accumulation of hydrated and dissolved sediments, minerals and calcium carbonate dripping down from above (Forest 1950; Fairchild & Baker 2012). There is no evidence these multi-tubular-conical structures were formed in a cave or cavern and there are no other means for salts and minerals to fashion upward growing intertwined tubes in this area of Mars. It is also not possible these are entwined lava tubes as there is no evidence of volcanic activity or lava in the surrounding areas of Gale Crater. Moreover, a close examination of these photos reveals wave-like rows and layers of sand similar to that produced by receding waves of water (Figures 78-81). Given that Gale Crater hosted a vast lake (or inland sea) in which stromatolite-constructing organisms, tube worms and marine-metazoan invertebrates may have dwelled (Armstrong 2021a; Elewa 2021; Latif et al. 2021; Joseph et al. 2020b,c, 2021a,b; Suamanarathna et al. 2021a) and evidence of rock-boring mollusks, it should not be surprising that formations resembling coral and sponges may have also flourished. Thus, the most likely explanation is that these enigmatic multi-tubular-conical and adjacent formations photographed on sol 3396, 3397 are also remnants of marine organisms, e.g. fossilized corals, sponges, or sea plants that long ago flourished in the lakes of Gale Crater (Armstrong 2022) and then became fossilized when lake waters suddenly receded as indicated by Figures 78-81.

Sponges: Richard Armstrong (2022), who was the first to report and to identify the likely biology of the formations photographed on sol 3396, 3397 (Figures 75-78, 80-82), believes they closely resemble fossilized sponges (e.g., Phylum Porifera) which, in the oceans of Earth, are attached to the substratum and form a crust, clump or small tree-like structure growing either individually, in colonies, or on branched stems. Sponges in deep water often grow into branched forms, whereas in receding bodies of water and surf they form simple clumps; and both forms can be viewed in sol 3396, 3397 (Figures 75-78, 80-82). As explained by Armstrong (2022): In its simplest form, the sponge comprises a tube, sealed at the bottom and open at the top (operculum), the walls being perforated by several closable pores (porocytes) that enable them to draw in water and extract nutrients.

As noted, stromatolites are constructed via the secretion of calcium. The incorporation of calcium or silica into the body of the sponge would have also contributed to its fossilization. Thus, what appear to be sponges may have flourished in Gale Crater that once hosted a stable, long duration inland sea that suddenly and rapidly receded as indicated by the wave-like striations in the surroundings (Figures 78-81).

Corals: Armstrong (2022) also raised the possibility the specimens photographed on sol 3396, 3397 may be corals (e.g. Phylum Cnidaria, class Anthozoa). Corals are composed of reef-forming polyps and are more evolutionarily advanced than sponges (De Haas & Knorr 1966). Polyps are generally anchored to a single location and may form colonies that are cemented together as a skeleton of calcium carbonate. Their body is cylindrical with tentacles arranged around a 'mouth"--similar to the formations photographed Sol 3396, 3397.

Structures that resemble tabulata corals have been tentatively identified in other areas of Gale Crater (Joseph et al. 2022) and upon which are attached symmetrical multi-tentacled star-shaped formations that appear biological (Figure 118). And there is a coral-like similarity to the specimens of Sol 3396, 3397, as can be seen in Figure 77. Nevertheless, according to Armstrong (2022), the morphology of the sol 3396, 3397 specimens closely resemble the fossilized sponges that long ago flourished within the inland sea that once filled Gale Crater.

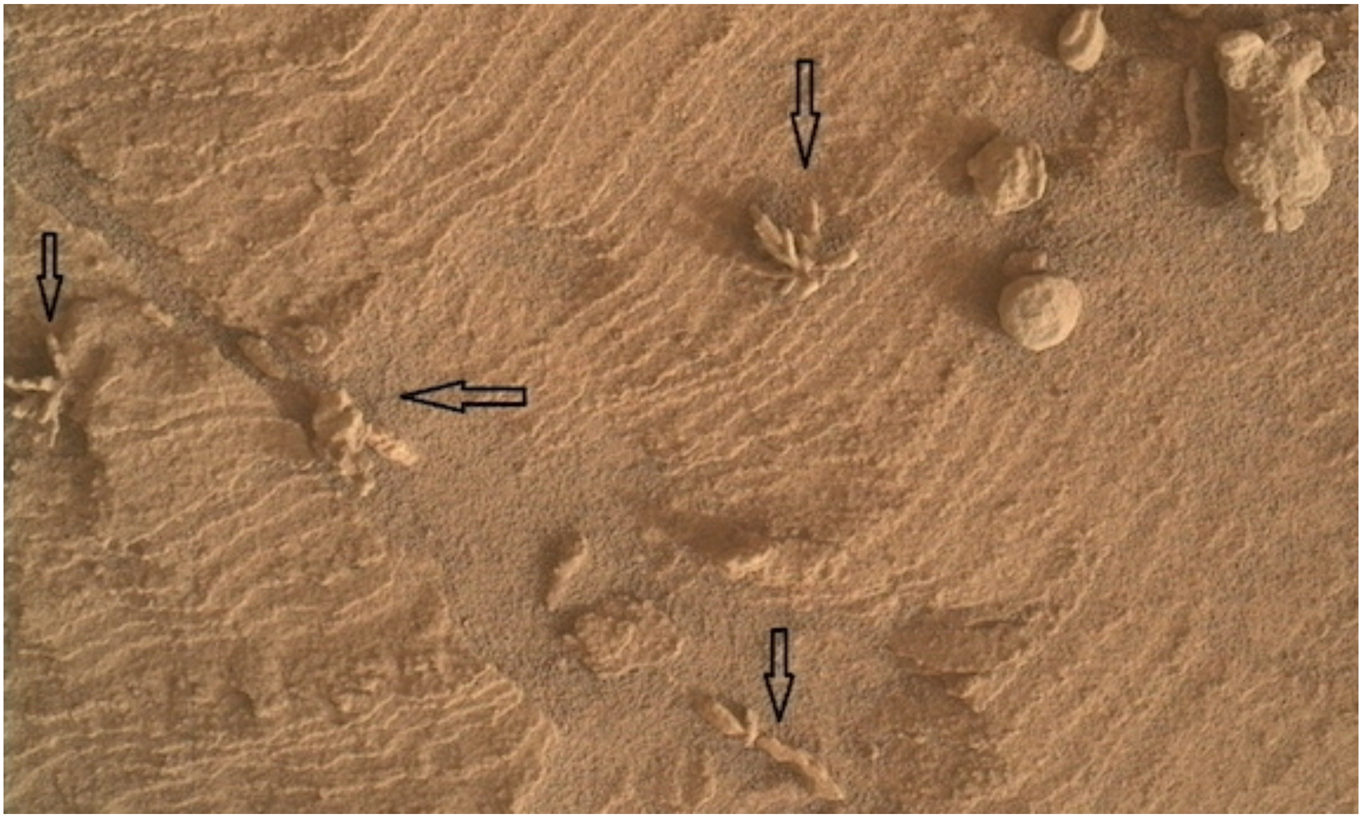


Figure 75: **(Mars,** Gale Crater, Sol 3396): Sponge / Coral-like specimens photographed in Gale crater by the rover Curiosity. Note wave patterns on surface and the tubular branches attached by a single point to the substratum, the variation in width of the tubes, and the slightly rounded or flattened tips.

Figure 76: (**Left - Mars**, Gale Crater, Sol 3396) (**Right Earth**): Fossilized Spongers (top right) Fossil sponge, *Peronidella furcata*, Photo Credit: Martin Land / Science Photo Library. (bottom right) Sponge, “Venus basket” AKA “sea orange.”

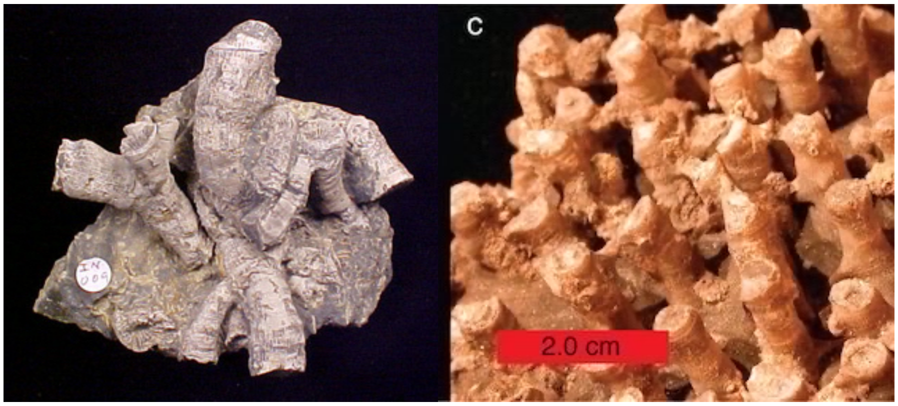


Figure 77: **(Earth)** Fossilized Carboniferous Coral attached to a Brachiopod Carboniferous reef system, (Right) Tabulate Syringopora corals (Photo Mark A. Wilson Dept. of Geology, College of Wooster).

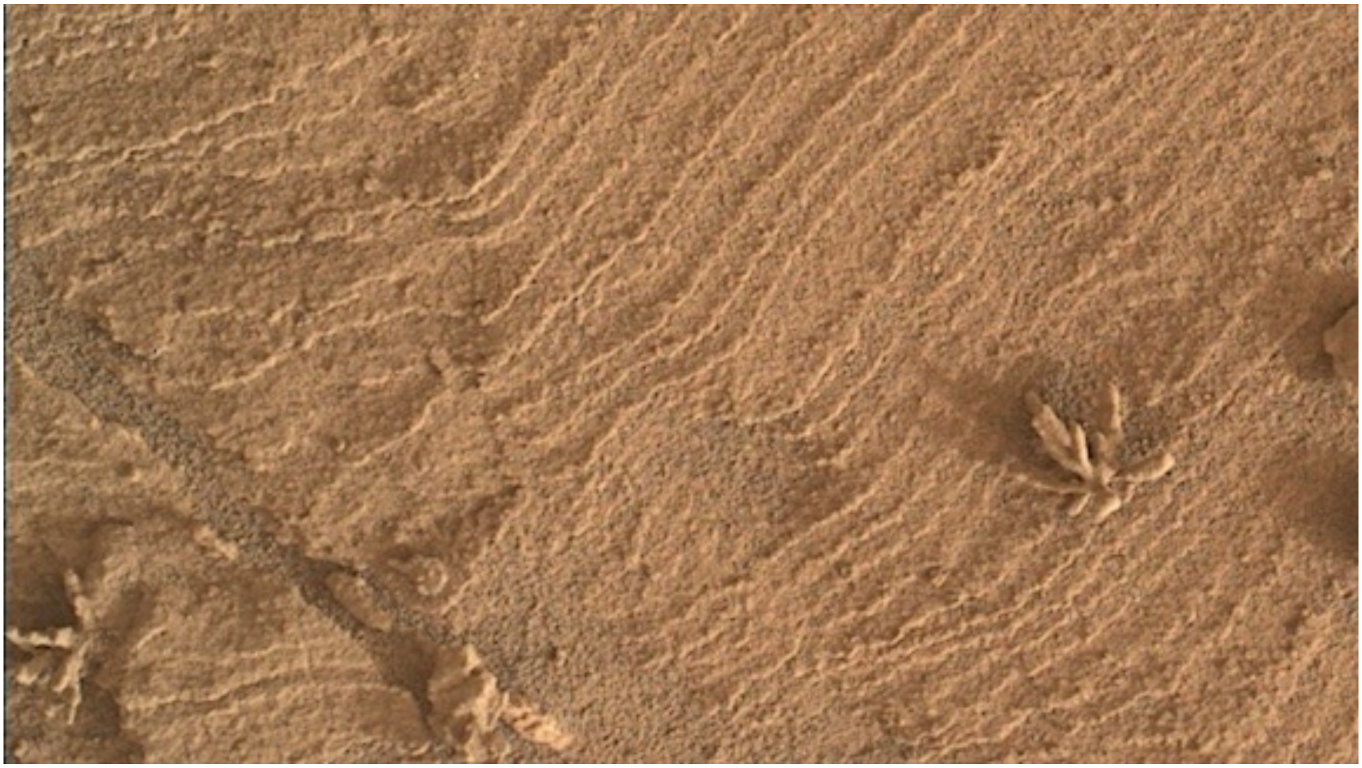


Figure 78: **Mars.** Sponge / Coral-like specimens photographed in the dried lake beds of Gale Crater (Sol 3396) Note the waves and ripples across the substratum from top left toward bottom right and which may be evidence of waves of receding water.

Figure 79: **Earth.** Seabright / Boardwalk Beach, Santa Cruz, CA, USA. Note the wave and ripple patterns.

Figure 80: **Earth.** Receding waves, Seabright Beach, Santa Cruz, CA.

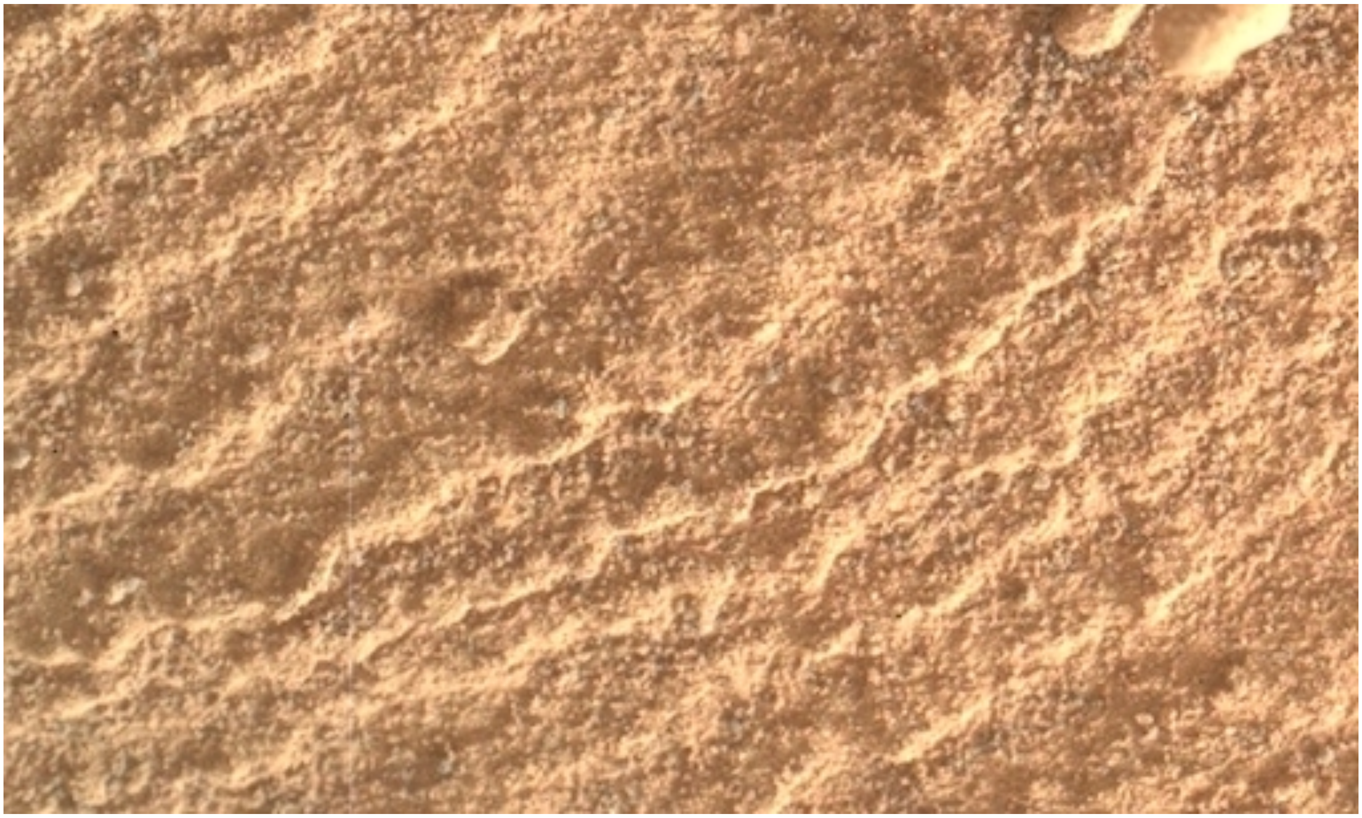


Figure 81: **Mars.** Gale Crater. Portion of photograph in which sponge/coral-like formations can be viewed (see Figures 75, 78). Note receding wave-like patterns in the sand. (3396MH0002240011201009C00_DXXX).

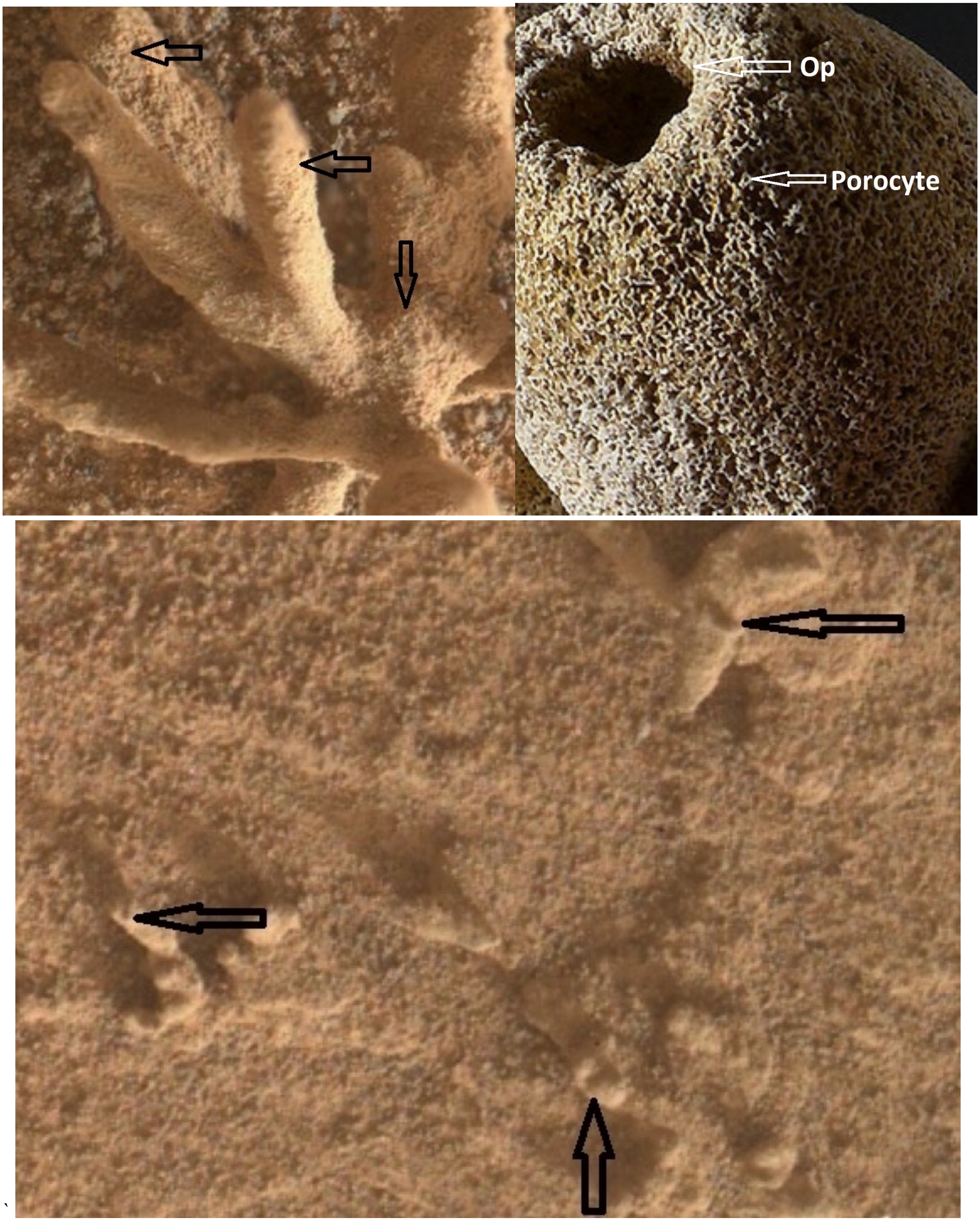


Figure 82: Gale Crater. Sponge-like specimens photographed by Curiosity on sol 3396 showing possible opercula (arrows) at the tips of the tubes (Armstrong 2022).

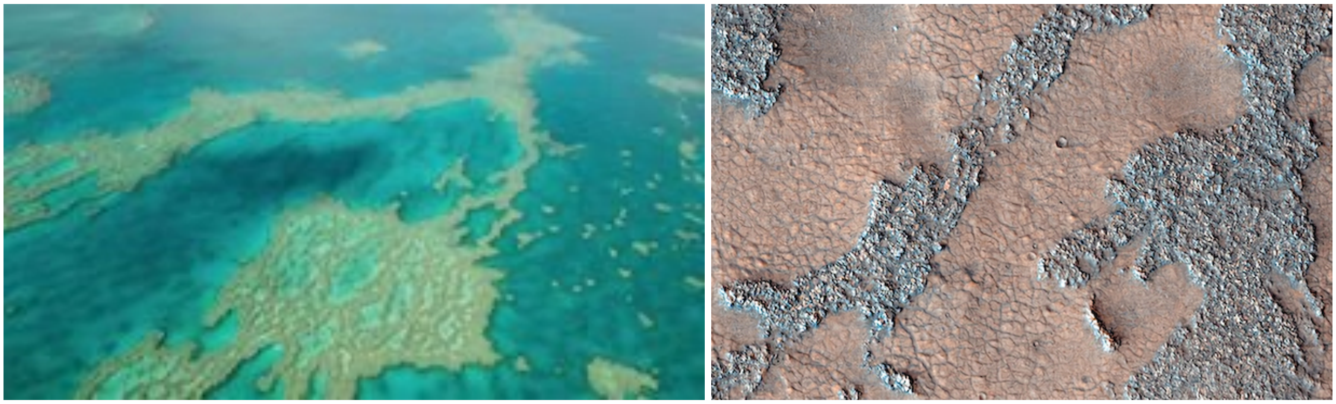
Coral Reefs of Antoniadi Crater Basin?

Figure 83: Mars. Coral Reefs of Antoniadi Crater Basin? Antoniadi basin is approximately 330 km in diameter. This photo is fragment of Figures 1, 2. (760_ESP_012435_2015). The hard pixilated-rubble rocky material is estimated to have a height of 1 m to 5 m or more. The fracture patterns in the surrounding soils are similar to soil that cracked as it dried and shrank. This indicates that a vast body of water may have filled this basin, most likely forming an inland sea.

Elevated Networks of Ridges in Antoniadi Crater Basin. NASA (2009) speculates that the miles wide and long branched features on the floor of Antoniadi Crater are composed of rough erosion resistant rocky materials that somehow filled river channels. That this basin held a vast volume of water is evident from the fracture patterns in the surrounding soils that strongly resemble watery soil that shrank as it dried. ESA--the European Space Agency-- (2020) describes these elevated rocky structures as evidence of ancient river networks that protrude from the surface, but are unlike channels which are usually sunken in the surface. Like NASA, the ESA argues these are river channels that filled with hard material, and speculates this elevated material may be lava from an unknown source.

Nicolas et al. (2021) and Mangold et al. (2021) note that these branched ridges are between 1-5 m high and up to 10 km long and from 10 to 200 m wide without obvious organization in width and lack any evidence of layering. They note there is no indication of exhumation of these ridges from material in the surrounding surface such that the origin is unknown. These ridges are not only above the surface but are distinct from inverted channels as observed elsewhere on Mars and do not resemble ancient river channels as there is no increase in width in any apparent direction as expected for channels with increasing discharge rates downstream. The slopes toward the south are also contrary to the inferred flow direction to the north assuming a tributary network, whereas subglacial drainages rarely display a dendritic pattern. Like NASA and the ESA, they speculate that somehow lava or mud, from an unknown source, formed these raised ridges.

The Coral Reefs of Mars? There is only one terrestrial analog to the ridges in the basin of Antoniadi Crater: The Coral reefs of Australia (Figures 1, 2, 84). Given evidence of oceans, lakes, rivers, and marine life reviewed in this monograph, and the hole-bored rocks in Jezero Crater (Figure 3) that were likely fashioned by marine organisms (Figure 4), it is our hypothesis that these elevated ridges are fossilized coral reefs that were constructed by Martian organisms similar to stony corals (scleractinian polyps) who flourished when this area was covered by a shallow ocean or inland sea. A close examination of Figure 83, reveals whitish residue that may be calcium carbonate skeletal remains of vast colonies of stony coral organisms. On Earth, these colonies consist of millions of polyps that grow on top of former colonies, eventually forming massive reefs in shallow water in both warm and cold climates. The Great Barrier Reefs in Australia are the largest of these coral reefs on Earth; and if surrounding seas were to vanish, the seabed would dry and assume a fractured appearance surrounded by vast coral reefs that we believe would closely resemble the networks of elevated ridges throughout Antoniadi Crater Basin.



Figures 84: **Mars (Right)**, Antoniadi Basin. HiRISE photograph of a1 km (0.6 mile) section of Antoniadi Crater (330 km / 230 mi) diameter and hosted an inland sea. The branched ridges are approximate 1 to 5 meters in height. **Earth** (Left), the Great Barrier Reefs of Australia, orbital view. .

Metazoans in the Seas of Mars?

Namacalathus and *Kimberella* are believed to have first evolved, on Earth, during the close of the Ediacaran epoch and prior to or at the onset of the Cambrian Explosion (Vannier et al. 2010; Vickers-Rich & Komarower, 2007; Yu et al. 2010). *Lophophorates,* may have evolved later, during the Cambrian era (Taylor et al. 2010). In 2020, Joseph and colleagues (2020c) published evidence of an assemblage of formations resembling fossilized metazoan invertebrates embedded on and protruding from the surface of mudstone on the floor of Gale Crater; many nearly identical to and located in close proximity to one another including those with an ice-cream-cone shape similar to "*Namacalathus*" and "*Lophophorates.*" Like their putative counterparts from Earth, the Martian *Lophophorates* and *Namacalathu* have a distinct morphology including a spheroidal 'head' and a 'tail' or 'stem' of variable length, as well as an open orifice at one end (Figures 85-88). Yet others have an ovoid-proboscis-shape coupled with pleopod-zipper-like appendages on the outer-body similar to "*Kimberella*" (Figure 89).

Pleopods enable movement and food gathering.

Ovoid specimens with pleopod-like appendages have also been photographed within Endurance crater (Figures 91, 106, 108), adjacent to what closely resemble fossilized tube worm, worm tubes, crustaceans, and vents in the surface that may lead to underground aquifers (Joseph et al. 2021a,b). In addition, as based on sequential photos, an ovoid specimen with forward facing pleopods appears in front of a hole that had been occluded hours earlier (Figure 118). Moreover, these latter specimens and the shrimp- and salamander- like specimens adjacent to the "tube worms" photographed in the dried lake beds of Endurance Crater appear to have eyes (Figures 101-102).

Subsequent investigation of this general vicinity (photographed on Sols 809, 869, 880, and 905) revealed the presence of dozens of formations that resemble "*Namacalathus*," and "*Lophophorates*," and "*Kimberella*." These specimens were subjected to a computerized quantitative morphological analysis comparing them with analog fossils from Earth and were found to be statistically indistinguishable on all measures (Armstrong 2021a; Joseph et al. 2020d). Feature analysis of (1) the "ice-cream-cone" shaped *Namacalathus*" and "*Lophophorates*, included evidence of a 'head' and 'tail' that resembles terrestrial *lophophorates* and the Ediacaran fossil *Namacalathus*. (2) Comparisons of the ovoid+proboscis-shaped Martian structures similar to the Ediacaran fossil *Kimberella* also confirmed a close morphological similarity (Armstrong 2021a).

It is noteworthy that all these specimens were embedded yet protruded from the surface. If they are in fact fossils, this indicates they may have only recently died in a rapidly receding body of water that had been stable and had endured for an unknown length of time.

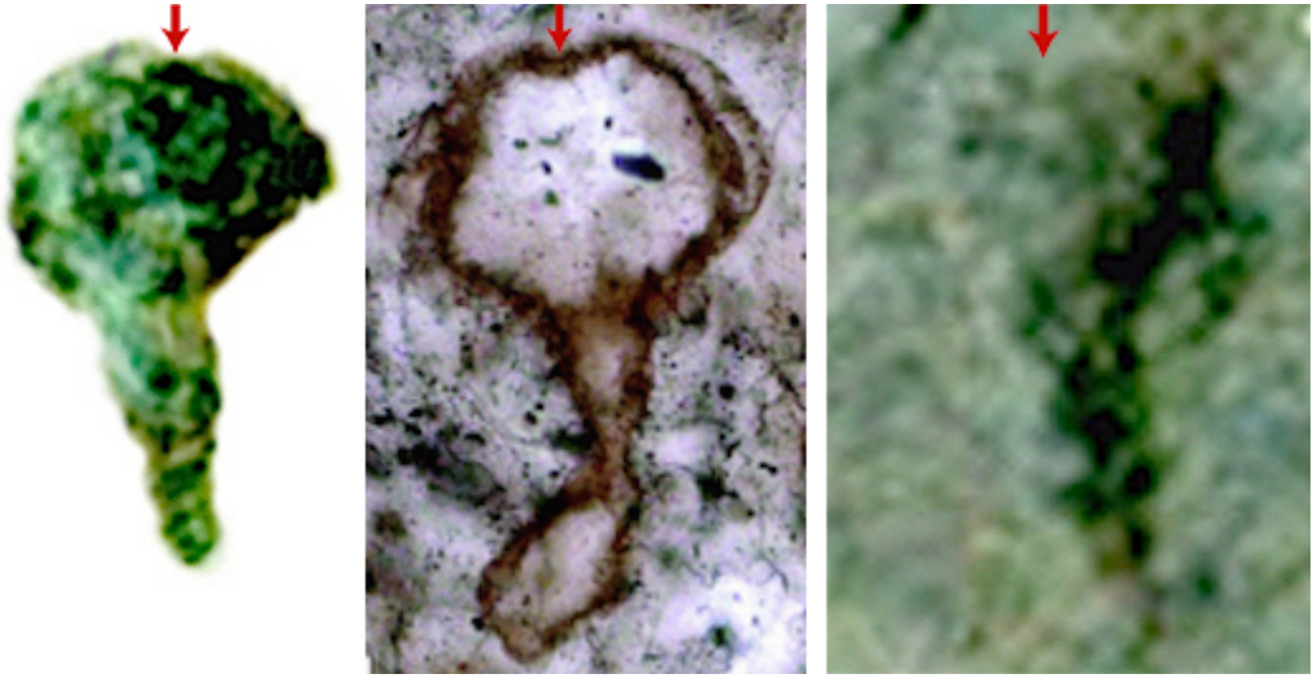


Figure 85: (**Mars left**): Gale Crater. Sol 809. (**Earth center**): Namacalathus. (**Mars right**): Sol 869). Gale Crater. Arrows indicate open apertures (from Joseph et al. 2020c)

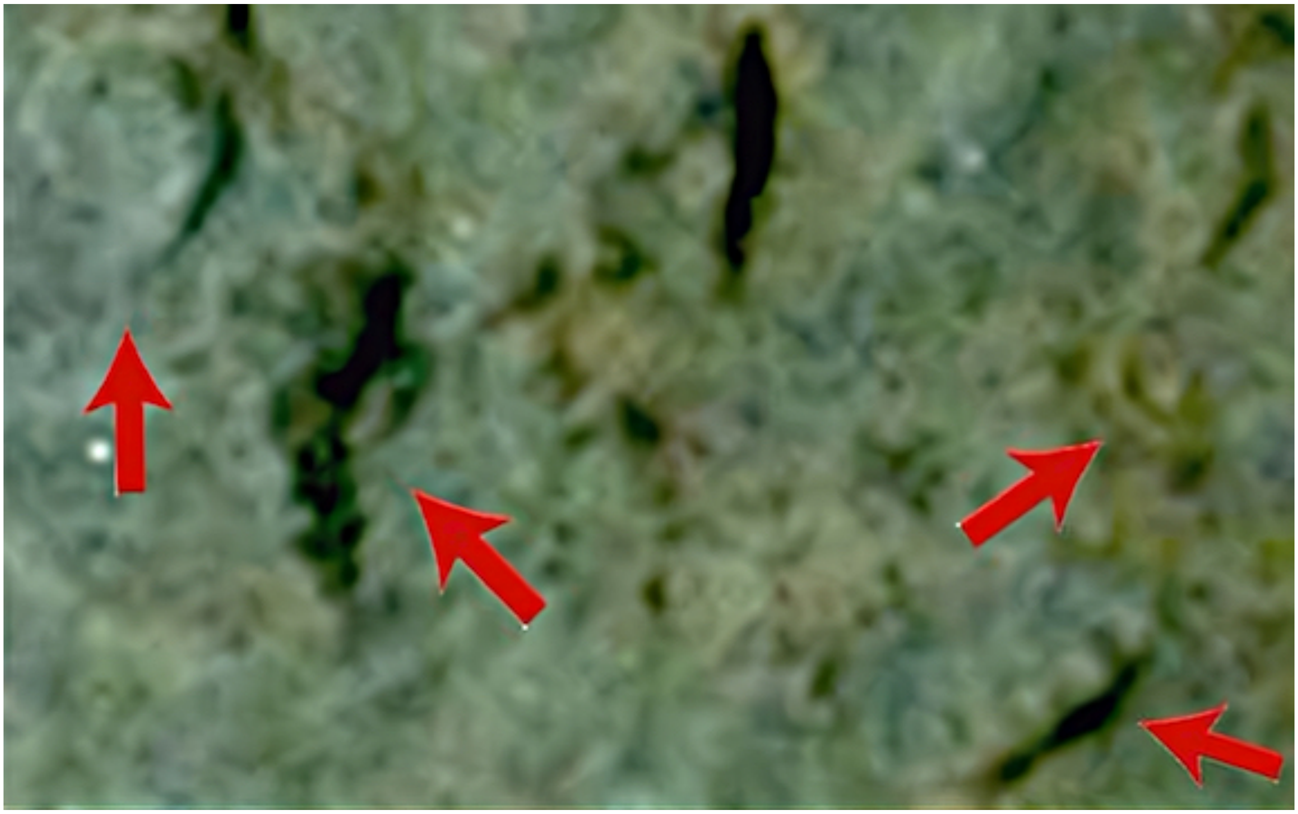


Figure 86: Mars, Gale Crater. Sol 809. An assemblage of specimens which resemble variety of metazoans (From Joseph et al. 2020c).

Figure 87: Mars, Gale Crater. Sol 809. An array of fossil-like specimens which resemble a variety of Ediacaran and Early Cambrian fossils: "*Namacalathus,*" "*Lophophorates*." (From Joseph et al. 2020d).

Figure 88: **Mars,** Gale Crater. (First row): Sol 809 and Sol 869. (Second row) Sol 905 and Sol 905. Specimens photographed in Gale Crater and that are quantitatively and statistically significantly similar to Ediacaran fossils of *Namacalathus* (**Earth, Bottom Row)** Cambrian fossils of Lophotrochozoa (three bottom right). Photos of Namacalathus reproduced from and courtesy of Kontorovich, A. E. et al. 2008. Photos of Lophotrochozoa reproduced from and courtesy of Zhang Z-F. et al. 2014.

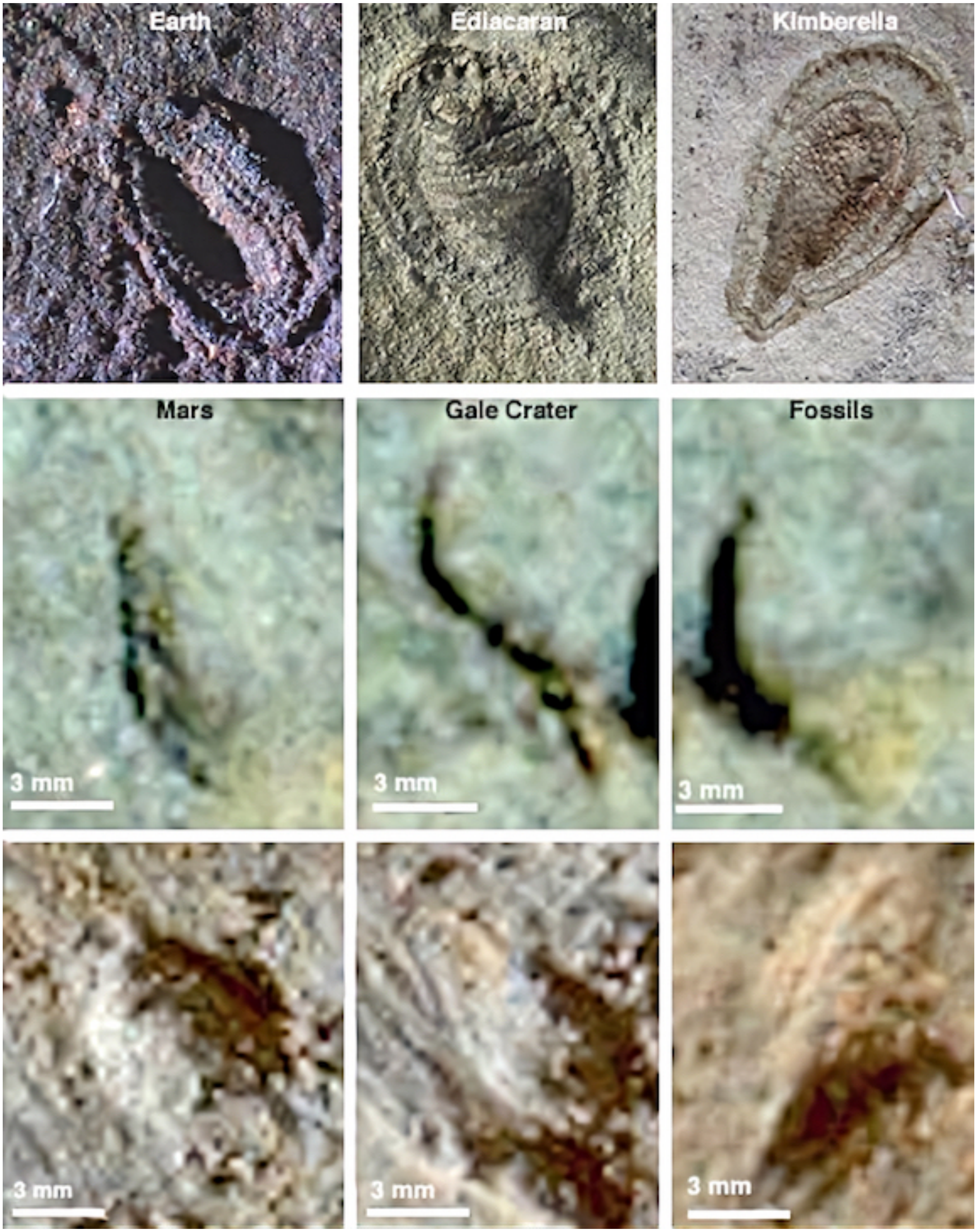


Figure 89: **Earth** (First row) fossilized remains of Ediacaran *Kimberella.* (**Mars, Bottom two rows**): Specimens photographed in Gale Crater, quantitatively and statistically indistinguishable from Ediacaran fossils of *Kimberella.* Sol 809, Sol 809, Sol 809; Sol 880, Sol 905, Sol 905. Note proboscis and pleopod appendages (Joseph et al., 2020d).

Martian Tube Worms & Hydrothermal Vents?

In 2021 hundreds of tubular and spiral specimens resembling terrestrial tube worms and worm tubes were discovered in the soil and atop and protruding from "rocks" on Sols 177, 199 and 299 within Endurance Crater, Meridiani Planum (Joseph et al. 2021a,b). Dozens of these putative "worms" and tubes are up to 3 mm in size and display twisting, bending, and curving typical of biology (Figures 90-107).

Morphological comparisons with living and fossilized tube worms and worm tubes also supports the hypothesis that the Martian tubular structures may be biological as they are similar and often nearly identical to their terrestrial counterparts (Armstrong, 2021a; Joseph et al. 2021a,b; Suamanarathna et al. 2021a). In addition, larger "anomalous" oval-specimens ranging from 3 mm to 5 mm in diameter were photographed and observed to have web-like appendages reminiscent of crustacean pleopods (Joseph et al. 2021a). Yet others resemble coiled worms. Some are similar to "shrimp" and "salamanders" with forward facing eyes (Figures 101-102).

A detailed comparative, quantitative and morphological analysis of these Endurance Crater "tube like" specimens was performed by Armstrong (2021a) and Suamanarathna et al (2021). These scientist confirmed what appear to be tube worm operculas and similarities to fossils of *Spirobranchus* and *Coprinisphaera* in the process of borrowing as well as circular to subcircular holes, or paraboloid external pits, in the walls of almost all chamber-like substrates. Armstrong (2021a) also determined these specimens were statistically indistinguishable from terrestrial tube worms based on comparative morphological features, and completely unlike pseudo-fossils.

That marine organisms may have evolved and flourished in the vicinity of Endurance Crater, Meridiani Planum, was originally predicted by NASA's rover Opportunity crew in 2004, 2005, and 2006. This area is believed to have hosted a briny body of water that was heated by hydrothermal vents which are also the favored habitats of tube worms. Further, all these specimens were photographed adjacent to vents in the surface. The mineralogy of Endurance Crater is also similar to that produced by hydrothermal vents and tube worms and their symbiotes (Joseph et al. 2021a; Suamanarathna et al. 2021a). However, if any of these specimens are alive, fossilized, mineralized or dormant is unknown.

That Endurance Crater may host an aquifer that is thermally heated would not be unusual. Ruff et al (2011; Ruff & Farmer 2016) have found evidence of an ancient hydrothermal lake, possibly volcanically heated, and indications of marine biology in Gusev crater, i.e. filamentous and coccoidal biomorphs. They also raised the possibility these hydrothermal waters had been propelled to the surface (Ruff et al. 2011) along with its inhabitants.

A number of investigators have reported evidence of multiple subglacial lakes that may contain liquid water and water-ice that are heated by unknown thermal anomalies (Arnold et al. 2019; Sori et al. 2019). Thus it is possible that during high obliquity and coupled with flooding, that heated water was and is propelled to the surface, forming a stable lake within Endurance Crater in which tube worms, crustaceans and other marine organisms evolved and dwelled. And, like other areas of Mars, it appears that the waters that filled Endurance Crater recently rapidly receded, leaving evidence of crustaceans, amphibians, and tube-like organisms, some of which appear to be dormant, or which only recently died.

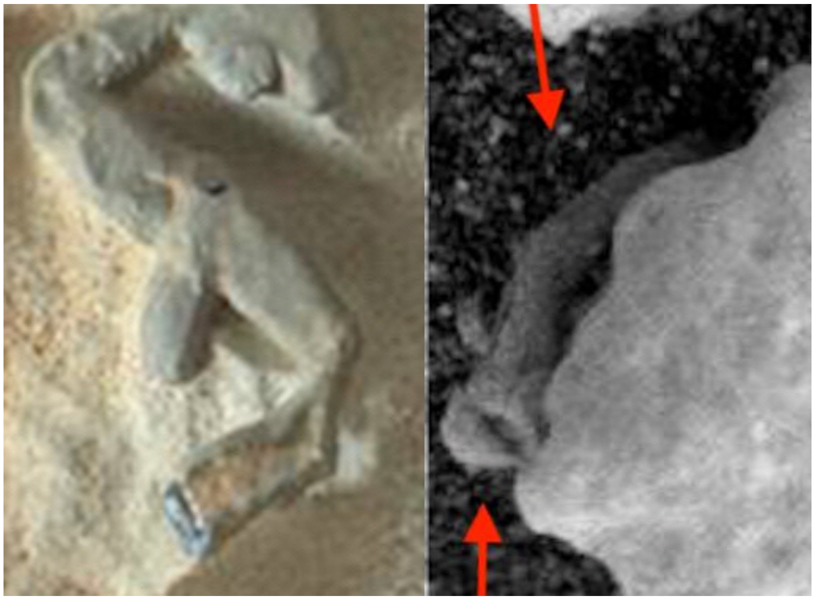


Figure 90: **Mars**. Fossil-like tubular formations from (left) Gale Crater and (right) Meridiani Planum (Joseph et al. 2021a).

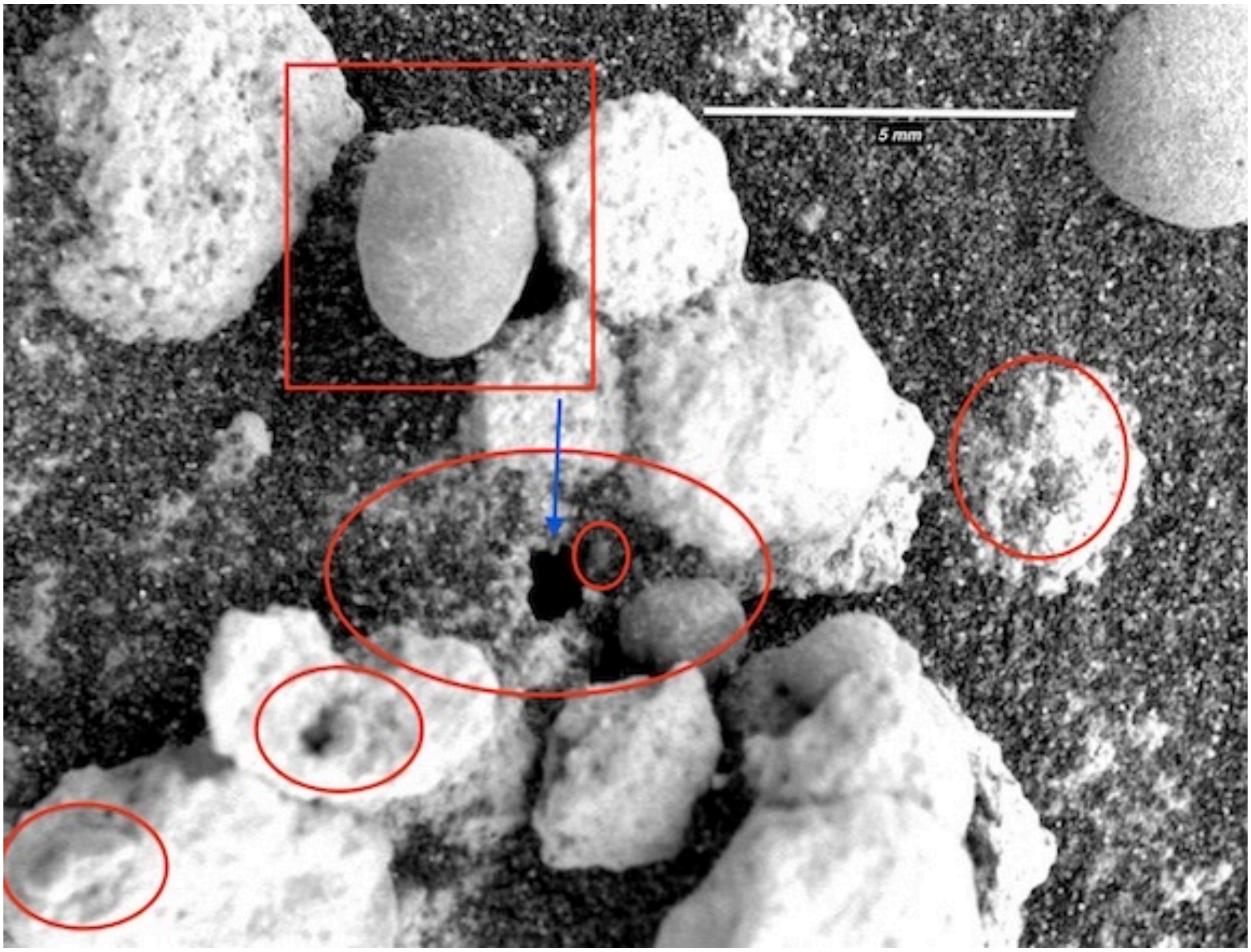


Figure 91: **Mars**. Endurance Crater (1M145849709EFF3505P2976M2M1). Blue arrow points to a hole/vent. Numerous spiral and tubular shaped "worm-like" formations are circled in red. The red box frames an oval-specimen with web-like appendages reminiscent of crustacean pleopods (Joseph et al. 2021a).

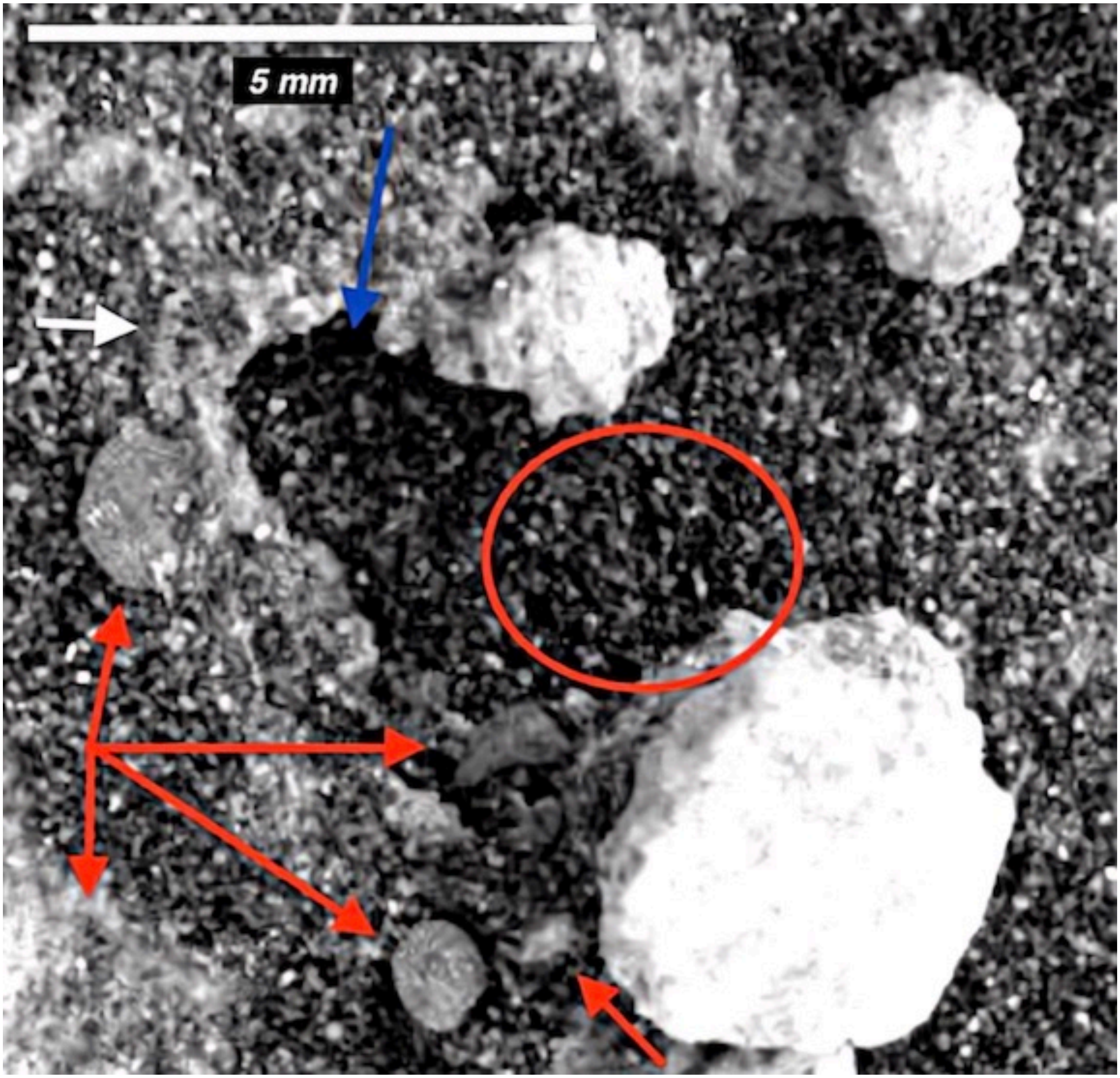


Figure 92: **Mars**. Endurance Crater (M145852935EFF3505P2906M2M1). Blue arrow points to a hole/vent. Note fossilized/mineralized tubular specimens on either side of arrows. Red arrows point to tubular specimens. Numerous spiral shaped "worm-like" specimens can be viewed circled in red at the entrance to the hole. Note "twisted" snail-like specimen at center bottom center with appendages. White arrow points to a elongated structure that may be a fossilized/mineralized worm that had occupied the "worm tube" directly beneath it (from Joseph et al. 2021a). A detailed morphological analysis of these Endurance Crater "tube like" specimens was performed by Armstrong (2021a) and Suamanarathna et al (2021a).

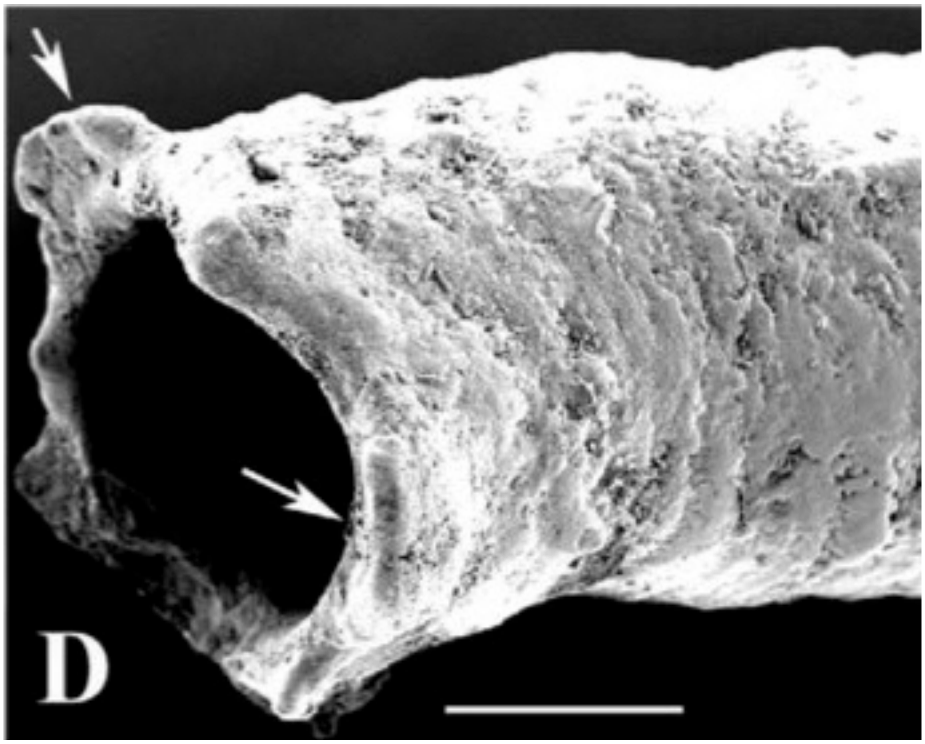


Figure 93: Earth. D—0.5 mm. Open tube of Annelida, Serpulidae with animal removed.

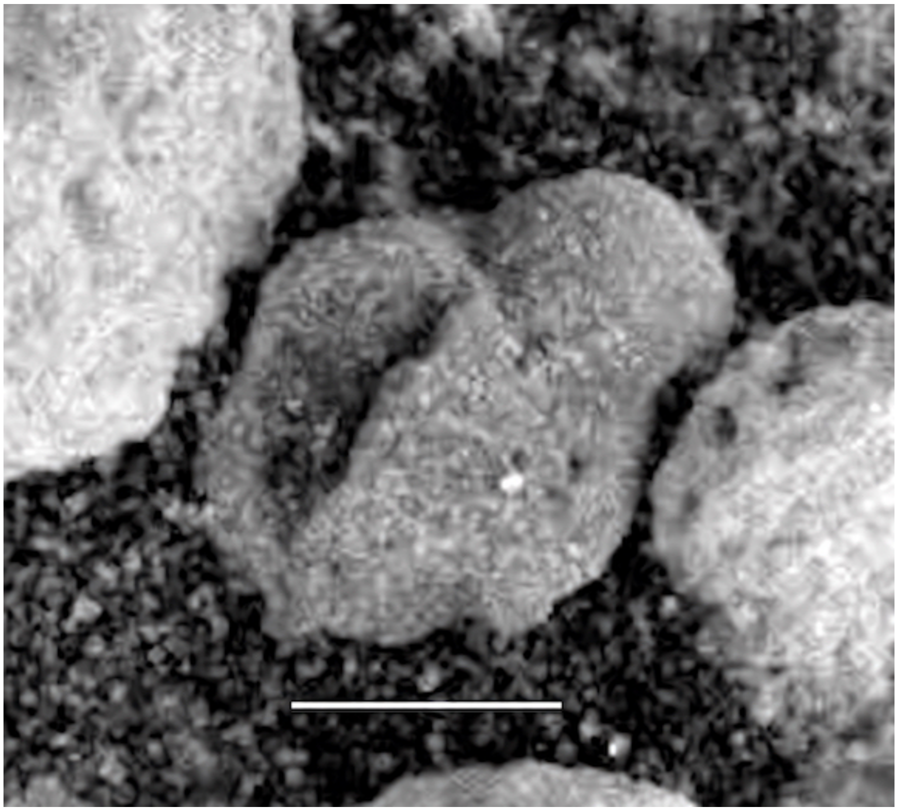


Figure 94: Mars. Endurance Crater. Fibrous open "worm tube" with numerous scoops/leaflets at the entrance of the tube. Possibly this tubes is occupied and a tube worm may be extending to the opening in the tube. Scale bar---2.5 mm. ((1M145405702EFF3500P2957M2M1).

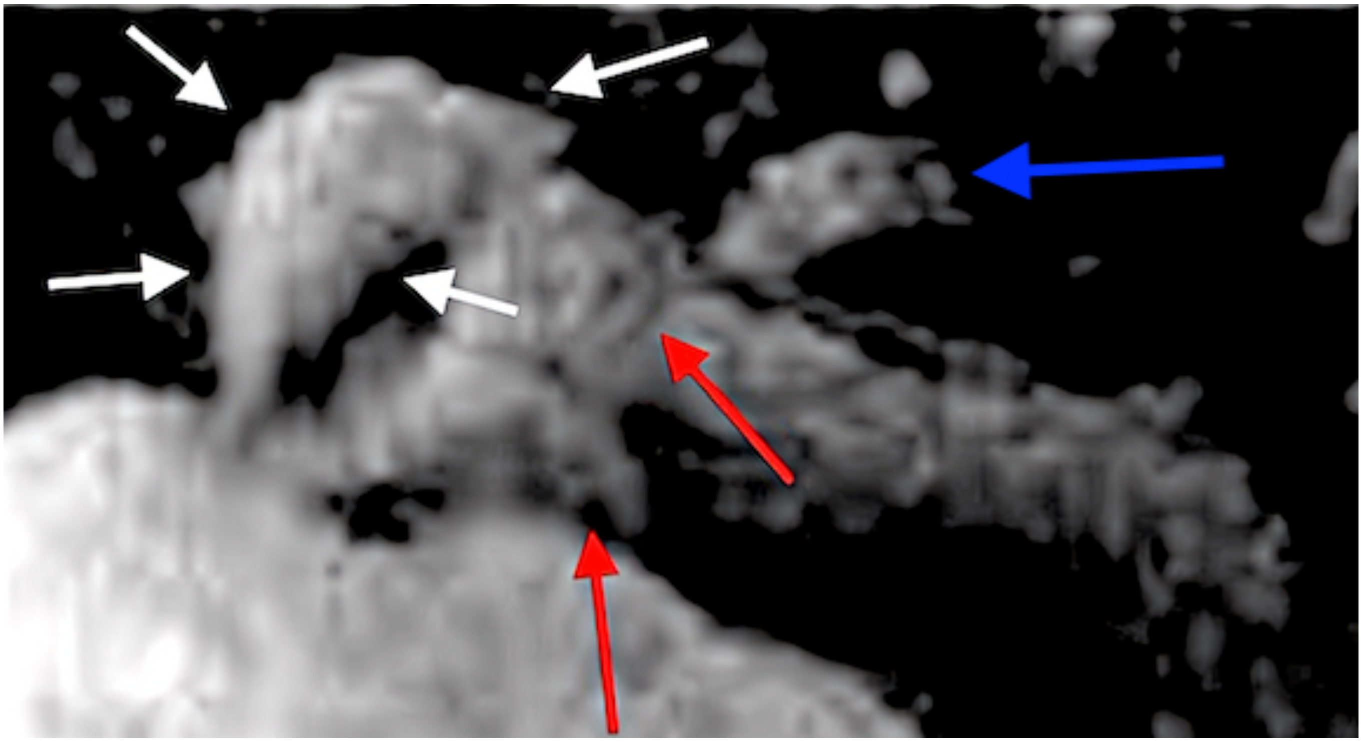


Figure 95: Mars. Endurance Crater. Fibrous open "worm tube" that are possibly occupied by a tube worm, indicated by white arrows pointing to oval structures. Darkening contrast has been applied to the figure. White arrows point to what may be the cap and collar of a tube worm protruding from the tube. Red arrows point to what may be palps (Joseph et al. 2021a).

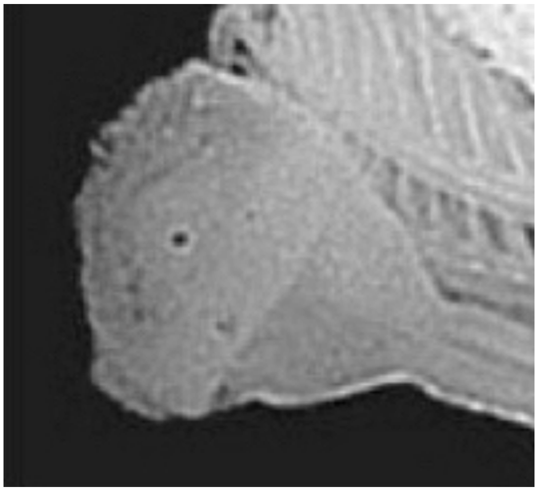


Figure 96: Earth. Eudistylia vancouver photographed in tide pools. Tube worm gill plumes and worm protruding from tube (from https/theoutershores.com/ 2015/02/11/northern-feather-duster-worm).

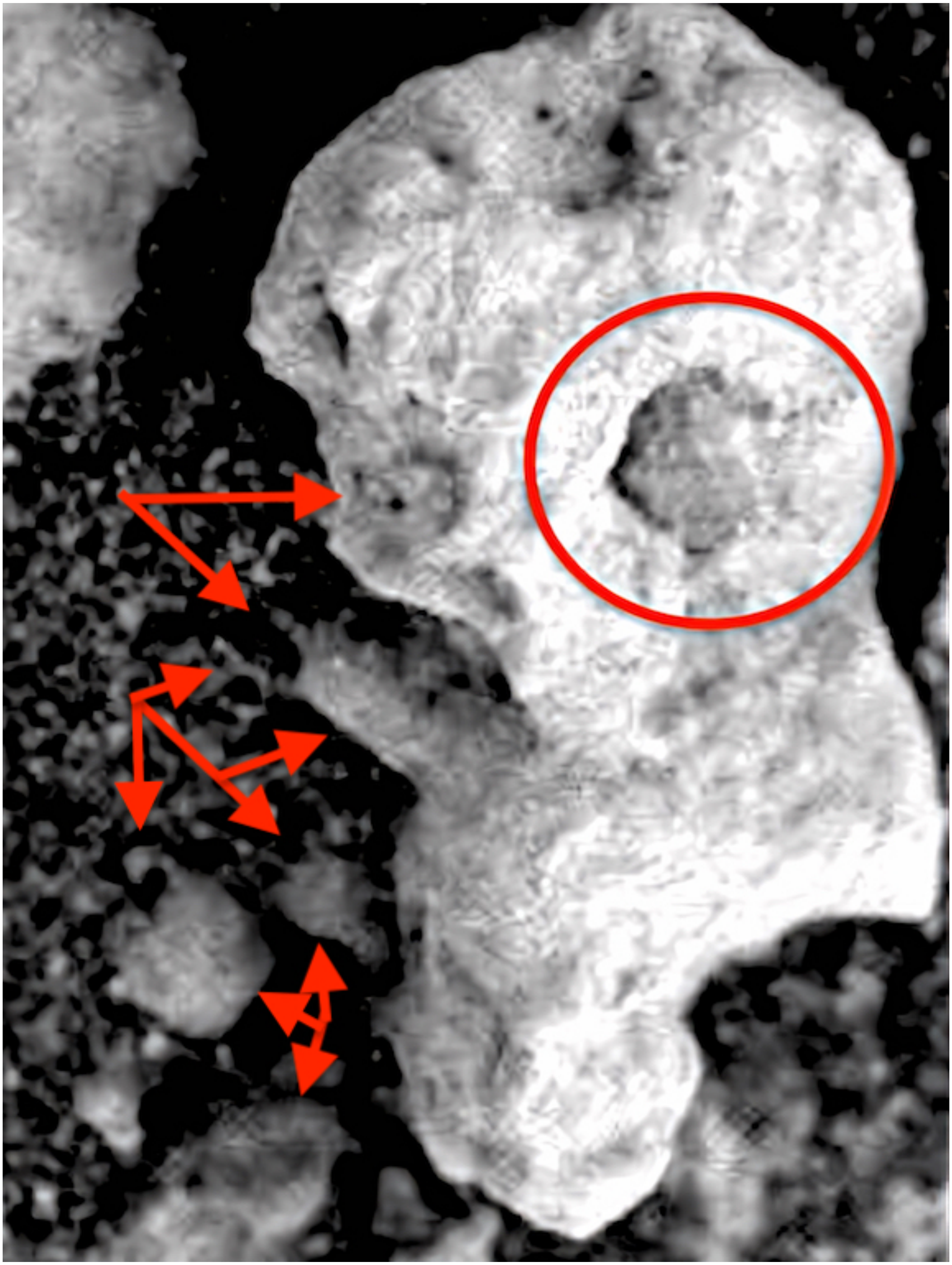


Figure 97: Mars. Tube worms and worm tubes? (M145850485EFF3505P2977M2M1). A detailed morphological analysis of these Endurance Crater "tube like" specimens was performed by Armstrong (2021a) and Suamanarathna et al (2021a).

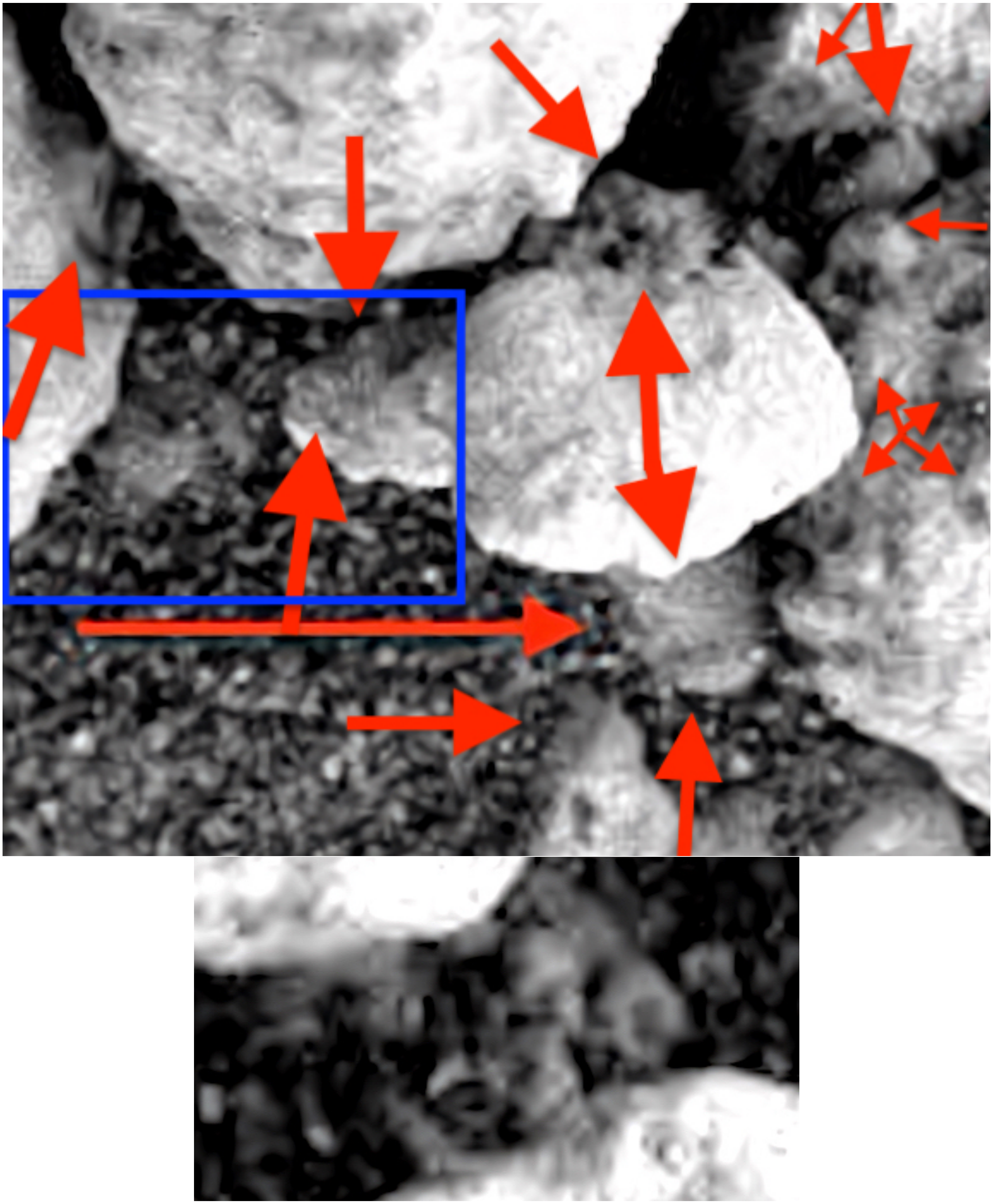
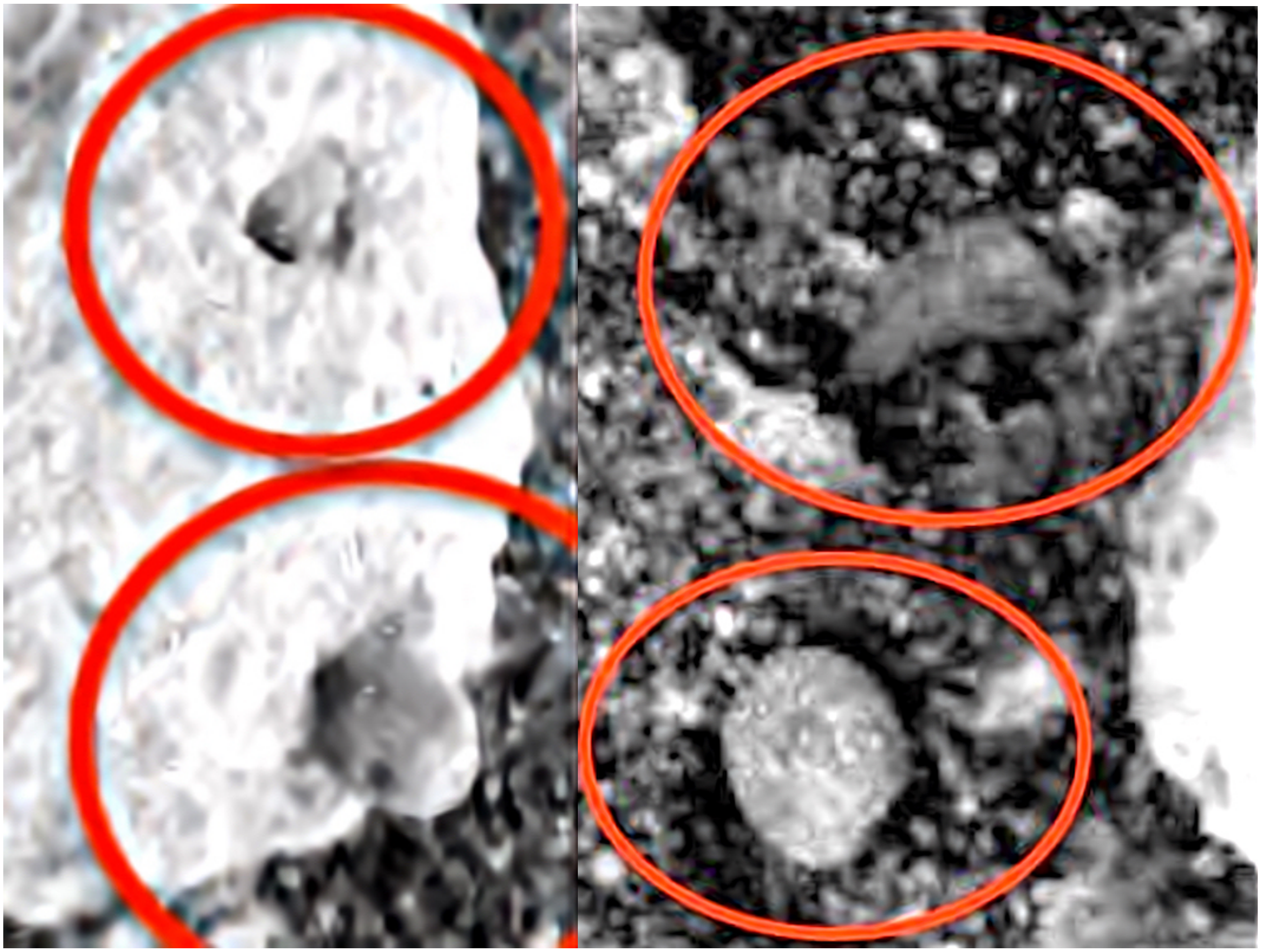
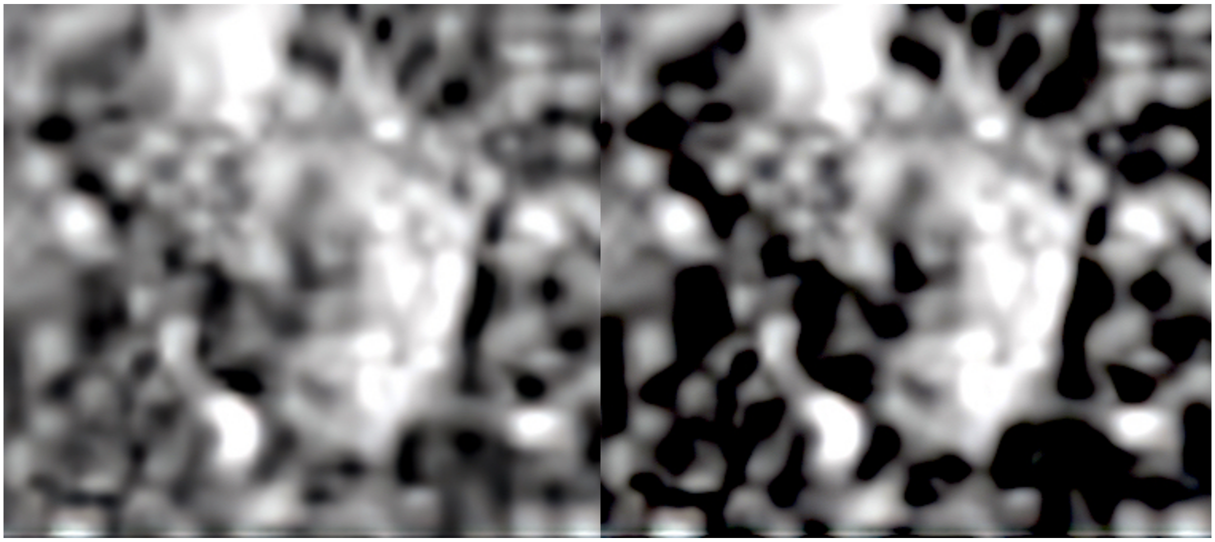


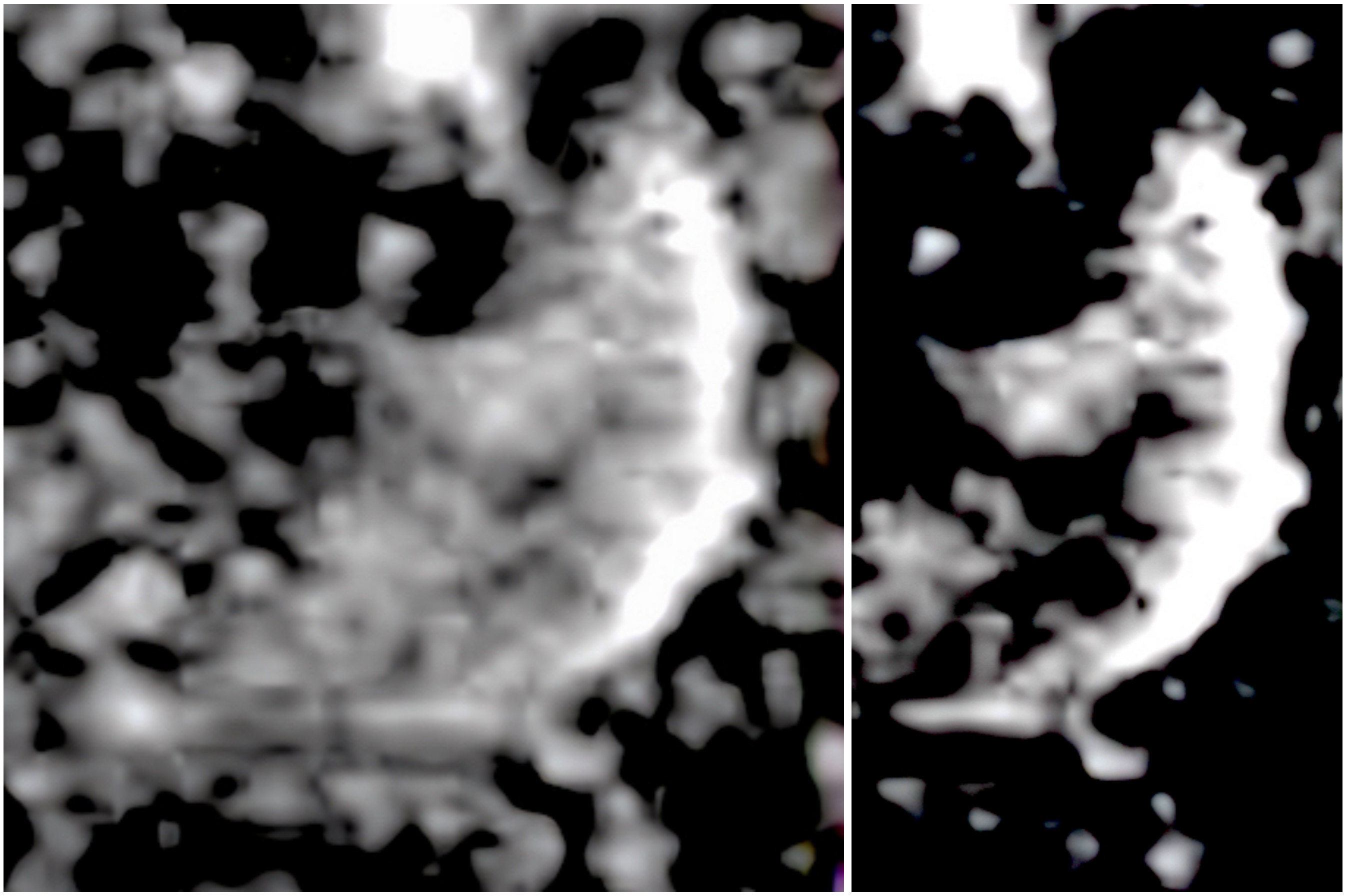
Figure 98: Mars. Tube worms and worm tubes? 1M145851070EFF3505P2977M2M1



Figures 99: Mars. Endurance Crater. Worm tubes some with denticulate collars with ornaments? (Right: 1M145850659EFF3505P2977M2M1. Left 1M145852935EFF3505P2906M2M1).



Figures 100: Mars. Endurance Crater. Worm tubes? Crustacean? 1M145849709EFF3505P2976M2M1



Figures 101: Mars. Endurance Crater. Shrimp-like specimen with eyes? 1M143896318EFF3336P2957M2M1

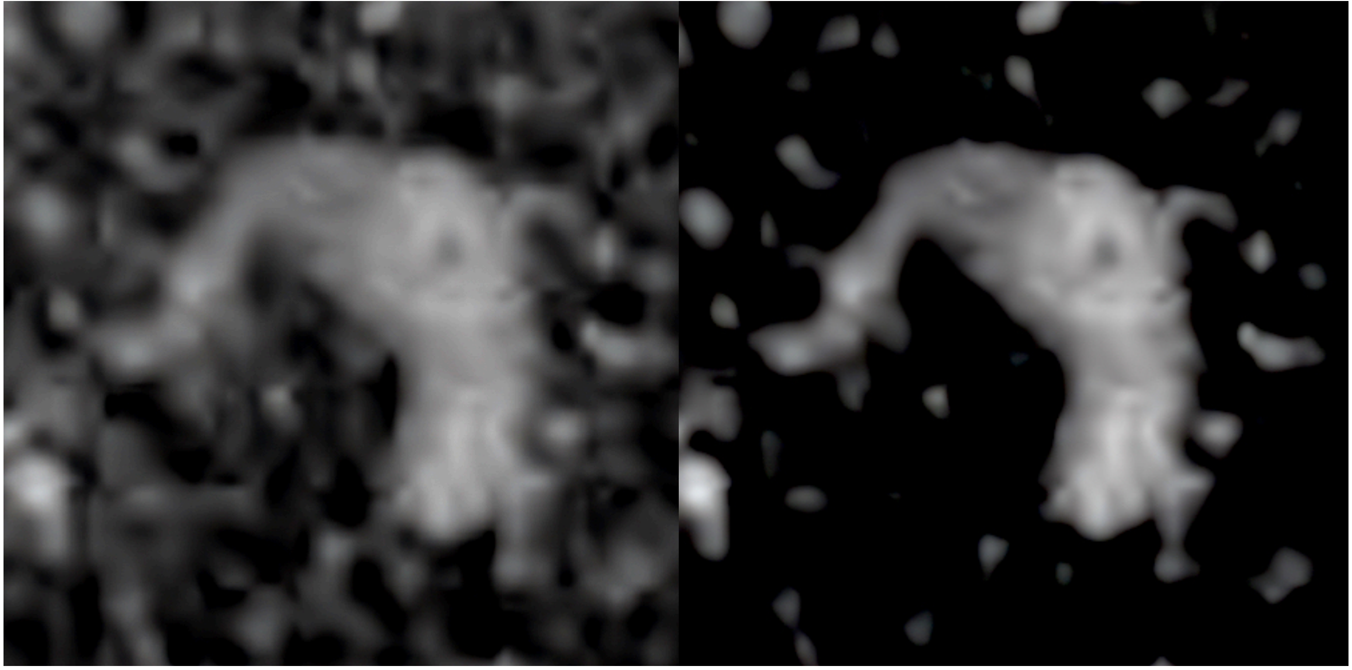
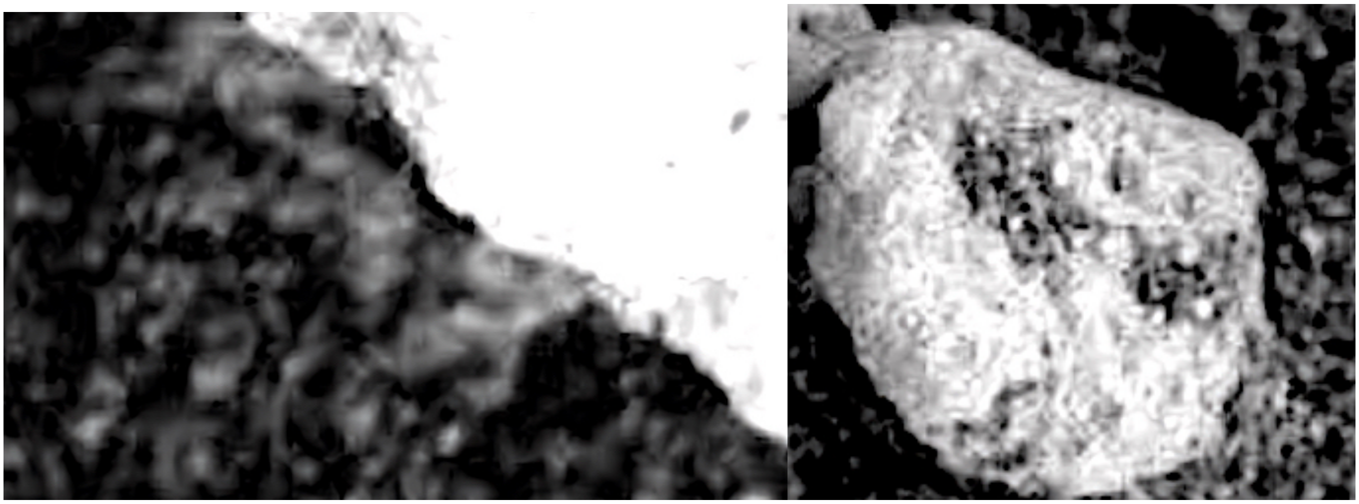


Figure 102: Mars. Endurance Crater. Salamander-like specimen with eyes? 1M145851070EFF3505P2977M2M1



Figures 103: Mars. Endurance Crater. coiled worm like specimens. 1M145853458EFF3505P2957M2M1

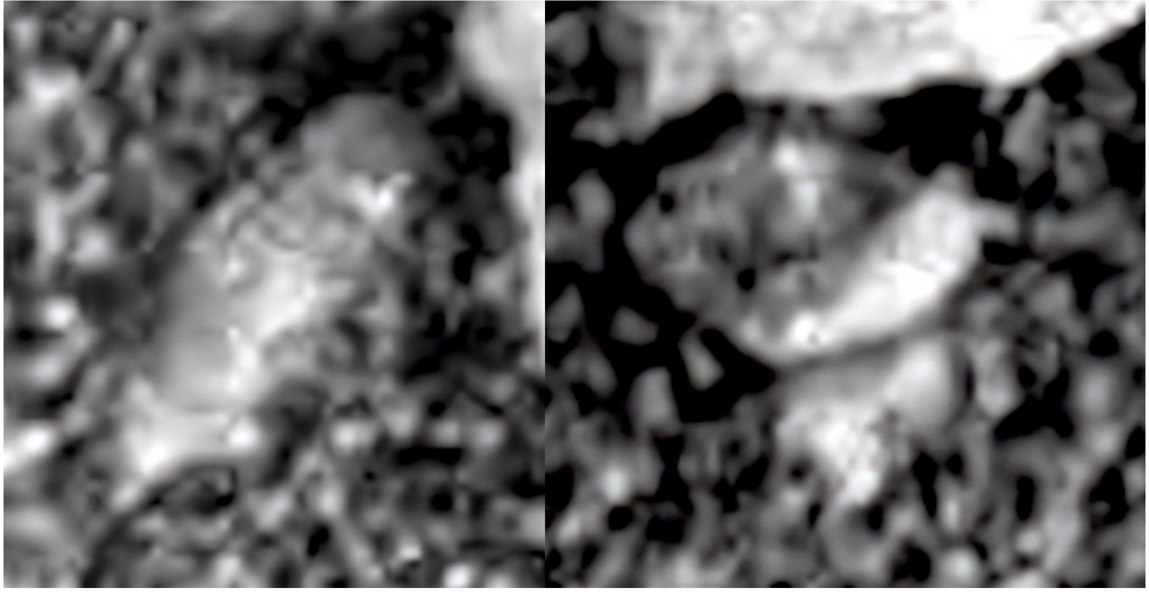


Figure 104: Mars. Endurance Crater. Tube worms protruding from tubes? 1M145851070EFF3505P2977M2M1

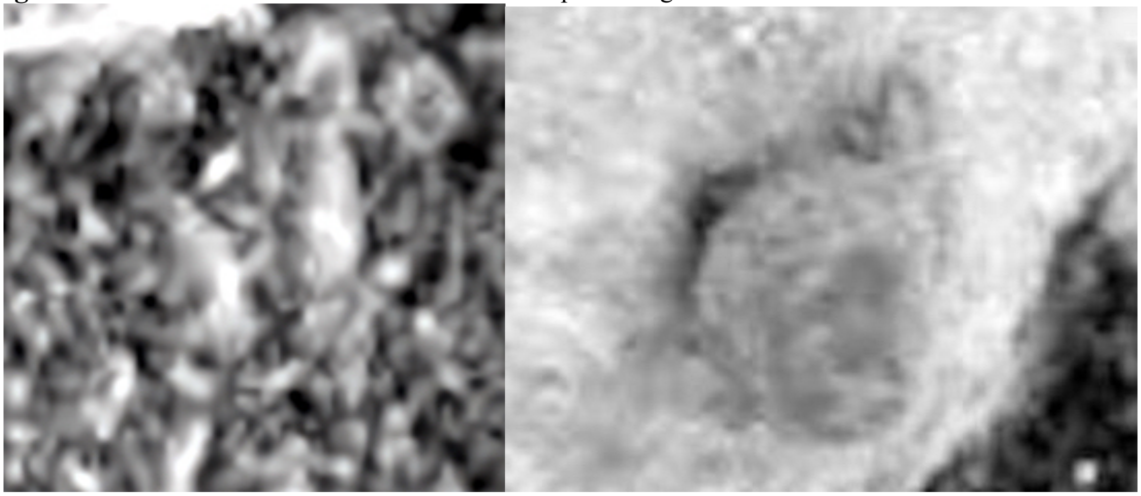


Figure 105: Mars. Endurance Crater. Tube worms? (From Joseph et al. 2021a). 1M143896318EFF3336P2957M2M1 /

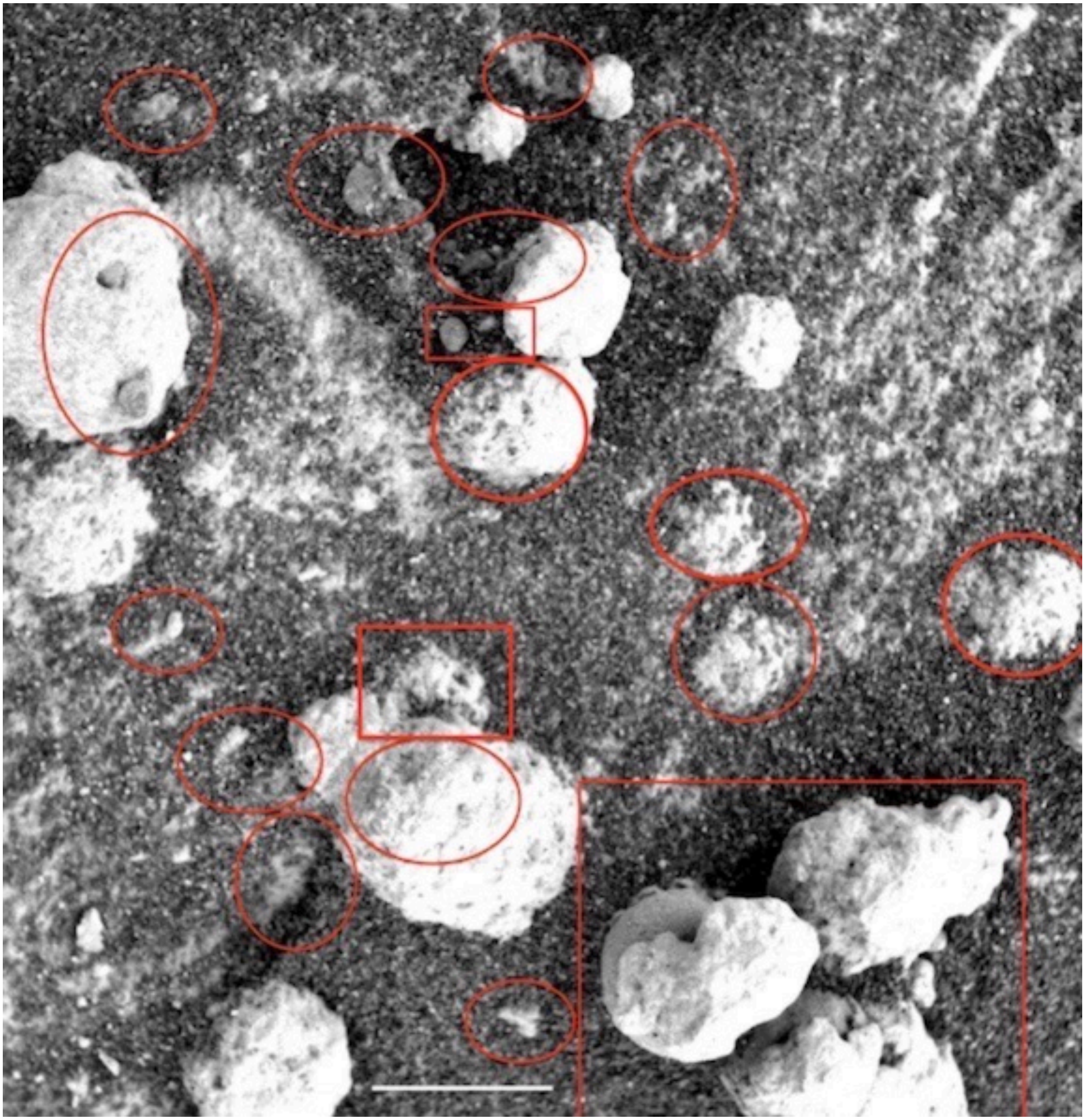


Figure 106: Endurance Crater. 1M145852876EFF3505P2957M2M1. Specimens resembling tube worms and worm tubes upon the surface, and "worms" protruding from small holes in the white matrix which may consist of anhydrite which in turn is associated with the chimneys of active and collapsed hydrothermal vents and their surroundings. Note oval specimens in the lower right with what appear to be pleopods. Scale bar = 5 mm (from Joseph et al. 2021a). A detailed morphological analysis of these Endurance Crater "tube like" specimens was performed by Armstrong (2021a) and Suamanarathna et al (2021a).

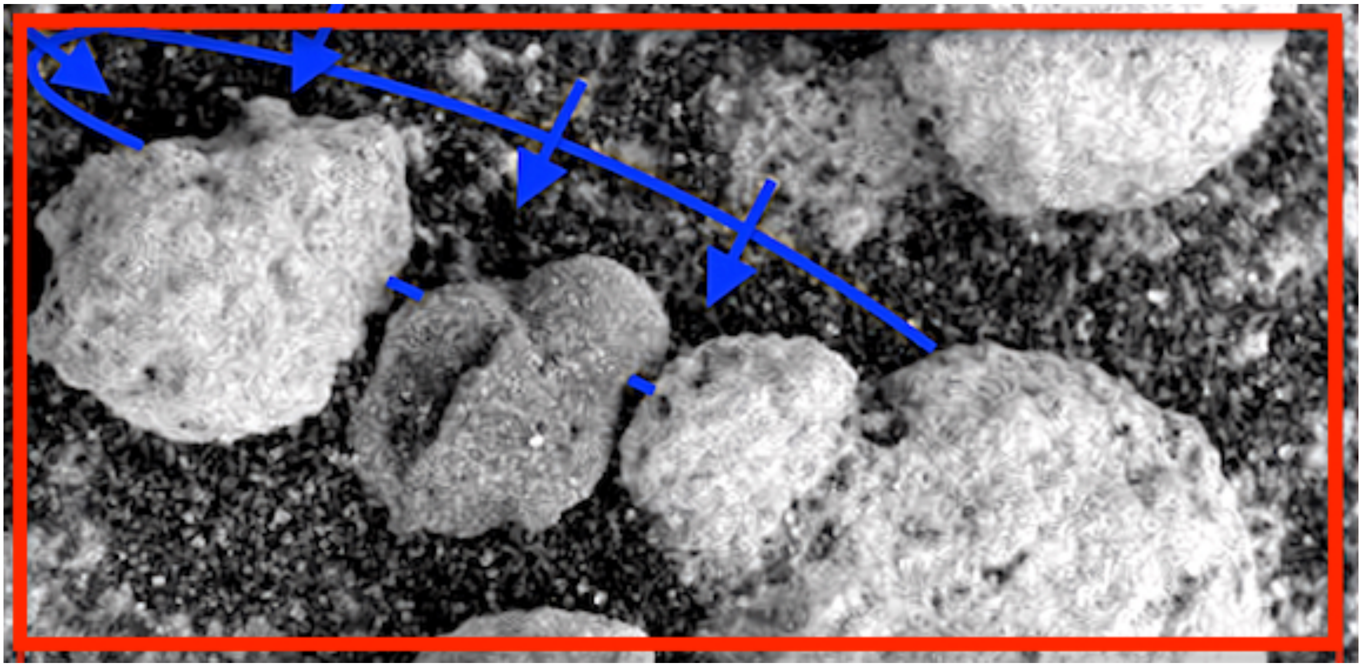


Figure 107: Mars. Tube worm within a worm tube with posterior section extending downward into a vent in the surface? 1M145405531EFF3500P2957M2M1

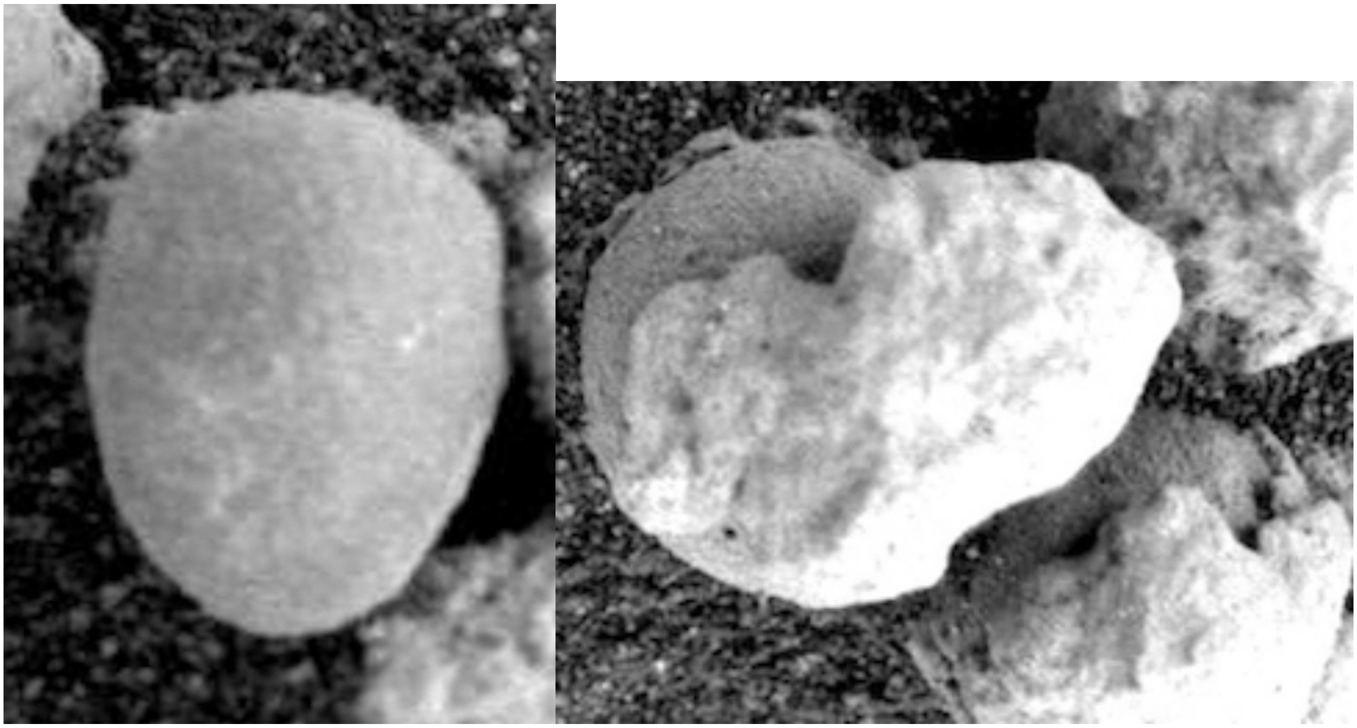


Figure 108: Mars. Note "pleopods" that resemble those of crustaceans. 1M145849709EFF3505P2976M2M1. / 1M145852935EFF3505P2906M2M1 (from Joseph et al. 2021a).

Martian Permafrost, Aquifers, Geysers, Mud Volcanoes and Surface-Subsurface Life

Rivers, lakes and aquifers below the surface of Earth are populated by vast microbial communities including anaerobic methanotrophic archaea, sulfate reducing bacteria, algae and cyanobacteria as well as tube worms and crustaceans (reviewed in Joseph et al 2021b). As noted there are numerous subsurface locations on Mars that host vast quantities of ice, water-ice, water as well as aquifers that are heated by unknown thermal anomalies (Arnold et al. 2019; Sori et al. 2019). Endurance Crater may host or may have hosted an aquifer that is thermally heated as based on mineralogy of what appear to be collapsed chimneys and fossilized fauna that typically colonize hydrothermal vents (Joseph et al. 2021a; Suamanarathna et al. 2021a). Similar fauna, as well as algae, methanogens, and sulfur-reducers may dwell in the waters below the surface.

If Martian subsurface liquid lakes, rivers, and aquifers are thermally heated, it can be predicted that these pressurized bodies of water would eventually and periodically percolate or erupt upon the surface as commonly occurs on Earth; the most dramatic examples of which are geysers and mud volcanoes. For example, Ruff et al (2011; Ruff & Farmer 2016) propose that a thermally heated geyser may have propelled water and living organisms onto the surface of Gusev Crater whereas Joseph et al. (2020h), based on an examination of orbital photos, have proposed that geysers and mud volcanoes eject living organisms, along with organic muck, during the onset of Spring and in response to warming temperatures.

Nearly 20,000 circular cratered mounds believed to be similar to the "mud volcanoes" of Earth have been observed on Mars (Kumar et al. 2019; Pondrelli et al. 2011; Skinner & Adriano 2009). These Martian "mud volcanoes" (MVs) commonly take the form of domes, cones, pits, and elliptical and circular mounds and may be found in clusters, linear chains, or radial-spider-like sequences that radiate outward from a central hub. Possibly, those close together are interconnected and fed by underground rivers, lakes, and reservoirs of water that are heated by anomalous sources. Once heated and pressurized these boiling muddy waters will rush upward and puncture and pour forth upon the surface (Figure 114). Like the mud volcanoes of Earth, it is not likely that Martian MVs erupt hot lava, but watery-mud, methane, CO_2, nitrogen, sulfur, and other gases and debris; a mix that could provide nourishment for innumerable organisms (Joseph et al. 2020h). On Earth, MV are inhabited by anaerobic methanotrophic archaea, sulfate reducing bacteria, algae and cyanobacteria (Ali et al. 2007; Wrede et al. 2012; Niemann et al. 2006; Remizovschi et al. 2018) all of which, along with an organic muck, erupt upon the surface.

It is possible that Martian geysers are fed by subsurface reservoirs of trapped CO_2, geophysically obtained from rock, or produced via organic decay and by aerobic organisms that release CO_2 as a waste product. As CO_2 accumulates, pressures increase, and these Martian geysers erupt water, organic material, and, presumably, a variety of organisms onto the surface (Figure 114) including cyanobacteria, micro-algae and diatoms (Ruff & Farmer 2016).

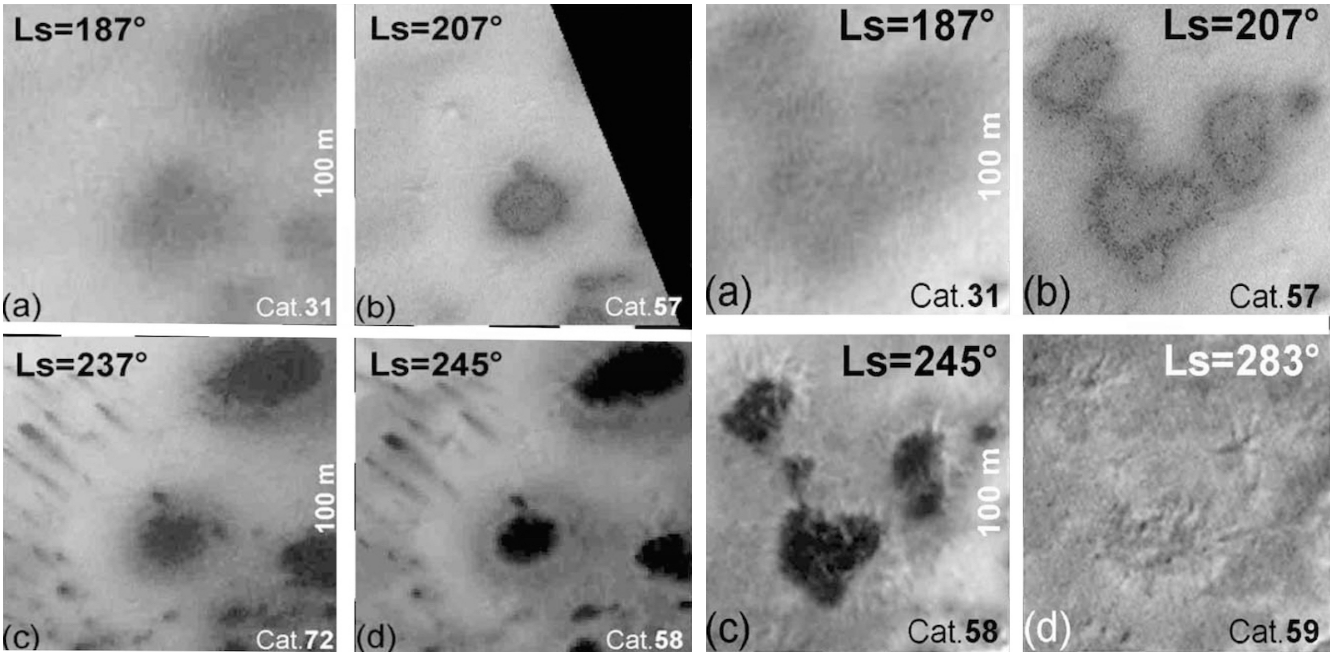
Top soils within Valles Marineris and in the polar and near polar latitudes are often described as permafrost. Much of Earth's permafrost is host to a diverse and biologically active microbial communities including methanogenic bacteria that engaged in methanogensis even at temperatures of −16.5 °C (Rivkina et al. 2004). Radiolabeled and stable isotope probing confirm that active respiration, DNA replication, growth and reproduction occurs in permafrost soils even as subzero temperatures; made possible via a multitude of molecular and evolutionary adaptations, such as increased expression of cold shock and metabolite transport proteins (Altshuler et al. 2017). It has also been determined that arctic "microorganisms... carry out redox reactions after thousands to millions years of existence in permafrost" and upon thawing have been involved in "the production and consumption of greenhouse gases over a large portion of the Earth's surface (Rivkina et al. 2004).

Black pigmented fungi, algae, and lichens, as well as moss, campion plants, nematodes, and bdelloid rotifers (tardigrades) --a radiation resistant eukaryote-- flourish within Earth's permafrost (Roads et al. 2014; Yeshina et al. 2012; Shain et al. 2016; Newsham et al. 2006; Shmakova et al. (2021; Shatilovich et al. 2018). And, nematoids (worms), and bdelloid rotifers have a nervous system, reproductive organs and the capability of remaining dormant and coming back to life even after 24,000 years of being frozen 10 feet (over 3 meters) beneath the surface (Shmakova et al. 2021; Shatilovich et al. 2018). Dormant microbes can reawaken even after 250 million years (Vreeland et al. 2000). It has also been reported that dormant "living bacteria" isolated from salt deposits over 600 million years in age were brought back to life in a laboratory, experimental setting (Dombrowski 1963).

Martian permafrost may host vast colonies of black-pigmented algae, fungi, and lichens, as well as methanogens and sulfur-reducing bacteria that remain dormant during the Autumn and Winter, and become biologically active during Spring and Summer in response to warming temperatures and melt water (Ganti et al. 2003; Ness, 2001; Joseph et al. 2020h; Kereszturi et al. 2012). Orbital studies document the growth of what resembles colonies of dark pigmented organisms that appear in the Spring and grow up to hundreds of meters in size, then wane in the Fall and disappear by Winter (Figure 109, 113). The same patterns occur each Spring in response to melting glaciers and the eruption of mud volcanoes and geysers that may be spewing living organisms onto the surface (Ganti et al. 2003; Ness, 2001; Joseph et al. 2020h; Kereszturi et al. 2012). After increasing in length, width, and diameter, and ranging in size from a few to several hundred meters, most completely disappear by late Summer and Winter, and are indications of the growth of vast colonies of black pigmented organisms (Figures 109, 113).

Many of these immense blackening surface features also occur in association with erupting "mud volcanoes" and "geysers" whereas yet others appear as expanding blotches and linear "grass-blade/tree-like" streaks atop and in the shelter of arctic dunes and other locales (Figures 109-113). That these waxing dark surface features coincide with the onset of Spring and the melting water-ice and CO_2 as it's transformed from solid to gas raise several distinct possibilities: **(1)** subsurface black organic muck and brines along with immense colonies of subsurface organisms including methanogens and sulfur-reducing colonies are propelled to the surface by geysers and mud volcanoes and then grow in size in response to the continued melt-off and/or **(2)** ice-bound dormant surface-dwelling Martian organisms become metabolically active when exposed to this melt-water and subsurface organic muck thereby forming huge colonies that turn black as a function of pigmentation and then **(3)** these organisms die as warm temperatures turn cold and after prolonged exposure to UV rays bombarding the surface and/or (**4**) when melt-waters begin to freeze, surface/subsurface organisms migrate beneath the surface and/or form spores, become dormant and lose their black pigmentation, or die.

The implications are that a variety of organisms dwell in the Martian permafrost and within subsurface aquifers and lakes of water, including anaerobic methanotrophic archaea, sulfate reducing bacteria, alga/ cyanobacteria, fungi, and metazoan invertebrates such as nematodes, tube worms, and crustaceans and organisms similar to rotifers. If these are in fact living organisms, it can be predicted that during periods of high obliquity and global warming, that Martian organisms dwelling in melting permafrost or in waters below the surface, would flourish throughout the year, turning the surface of Mars black and green with life.



Figures 109: Mars. Waxing from gray in the to black during the Summer and then to gray in the Autumn / Winter. Photographed, via satellite, from orbit. From Ganti, et al. 2003.

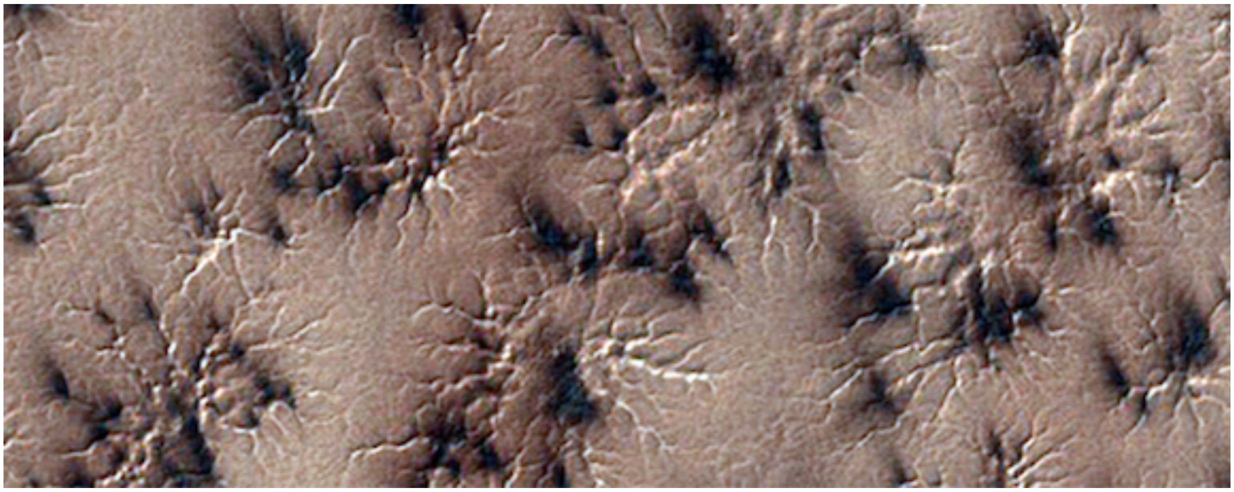
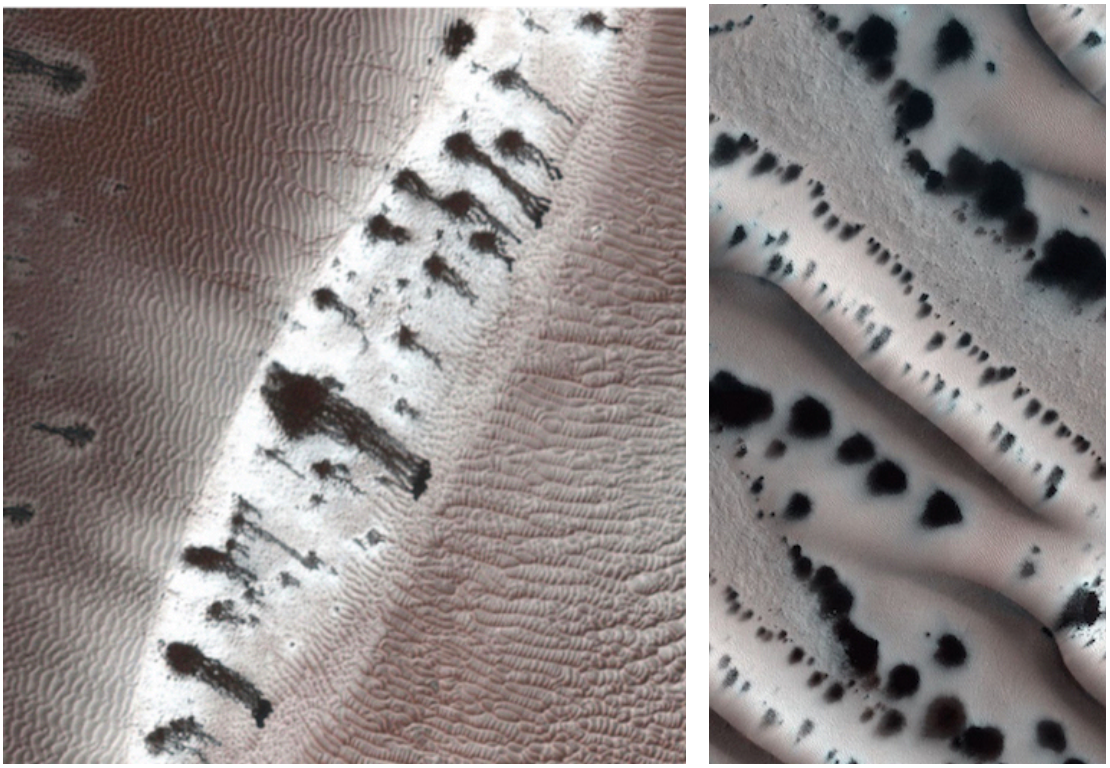


Figure 110: Mars. Massive black spiral growths along spider-like tributaries. HiRise photograph, via satellite, Mars Global Surveyor, from orbit.



Figures 111: Mars. Massive black growths, dozen of meters in length, upon the polar dunes during Spring and Summer. HiRise photograph, via satellite, Mars Global Surveyor, from orbit.

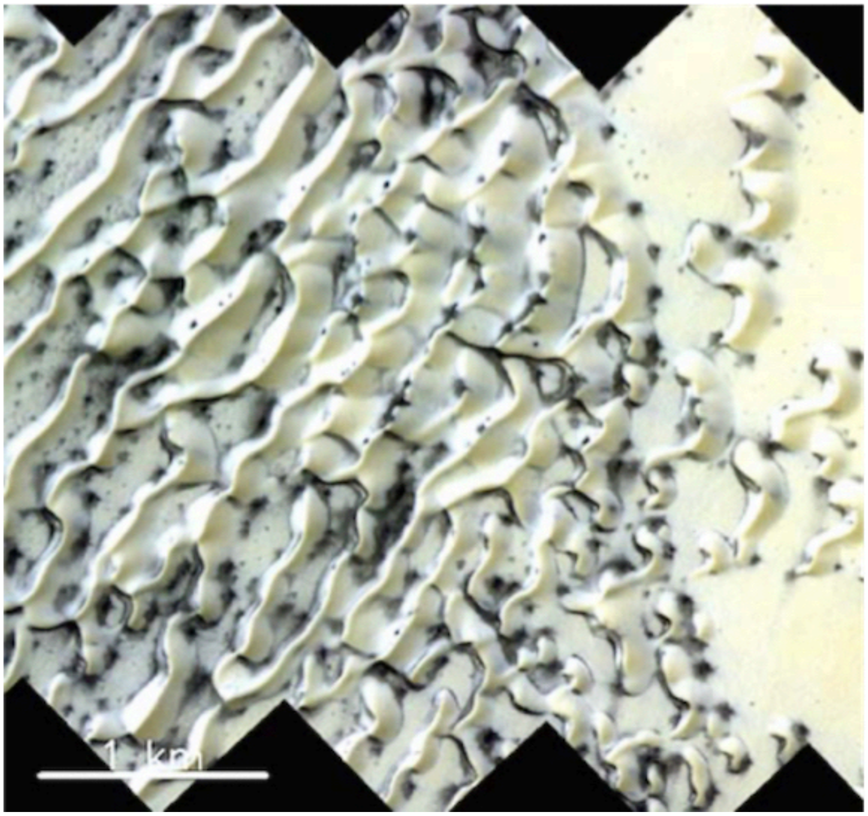


Figure 112: Mars. Massive black growths, dozen to hundreds of meters in length or diameter, upon the polar dunes during Spring and Summer. HiRise photographs, via satellite, Mars Global Surveyor, from orbit.

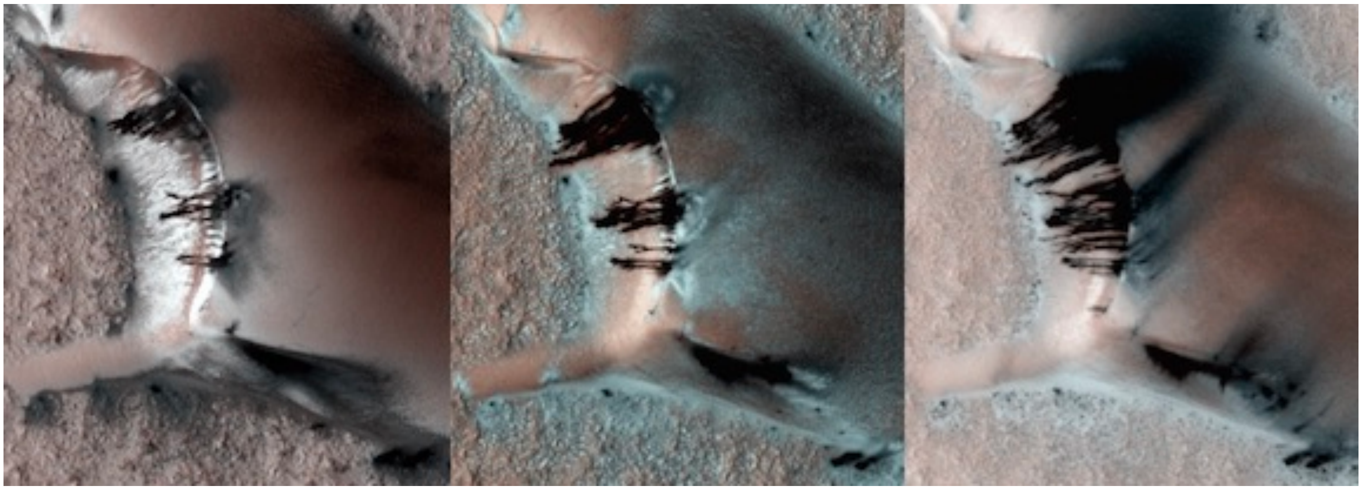


Figure 113: Mars. Sequence of photos: Left: Day 1. Central Day 22. Right Day 34. Final length is estimated at 60 meters, with an estimated growth rate of 5 meters per day. HiRise photographs, via satellite, Mars Global Surveyor, from orbit.

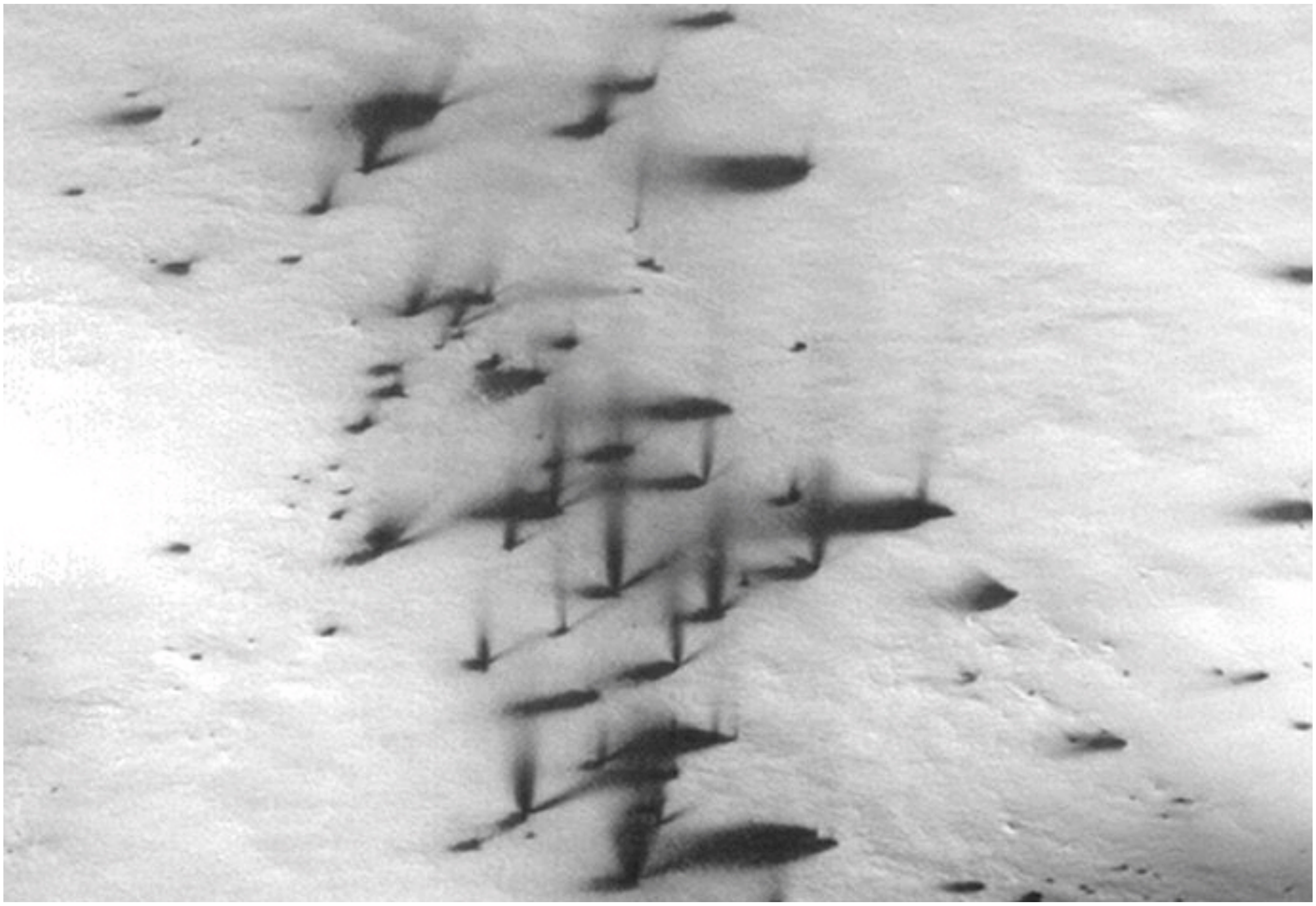


Figure 114: Mars. Satellite photo, geysers of Mars?

DISCUSSION AND CONCLUSIONS:
OCEANS, LAKES, AND THE EVOLUTION OF LIFE ON MARS?

Obliquity, Oceans, Extinctions and Evolution. The Martian atmosphere and climate are dramatically affected by chaotic increases and decreases in obliquity. Low obliquity of less than 30 degrees can trigger the collapse of the Martian atmosphere and cause a dramatic decline in atmospheric pressure, regolith thermal conductivity and subsurface heat transport. At high obliquity exceeding 40 degrees and beyond, temperatures, humidity, sedimentary thermal conductivity and atmospheric pressures significantly increase, and powerful winds blow grit upon snow-packs and permafrost reducing albedo and increasing heat absorption. In consequence, glaciers melt, and rivers, lakes and oceans of water flood then stabilize upon the surface. As axial tilt decreases, surface waters recede, evaporate, seep beneath the surface and form vast aquifers and glacial deposits of water-ice, as well as freeze at the poles and atop dusty layers of icy-sediment; the remnants of previous obliquity-driven freeze-thaw cycles that have caused oceans to repeatedly form, stabilize, endure, and then recede and freeze again.

Due to extreme chaotic obliquity, Mars has been subject to numerous episodes of global warming. Oceans, lakes and rivers have repeatedly flooded across the surface and endured for hundreds of thousands and perhaps even millions of years. Within these seas there is evidence that life evolved including stromatolite constructing cyanobacteria, green algae, acritarchs, seaweeds, and marine metazoan invertebrates such as sponges, tube worms, crustaceans, reef-building corals, bivalves, *Kimberella*, *Namacalathus* and *Lophophorates*. Thus we have evidence of an evolutionary progression, paralleling evolution on Earth, beginning with unicellular organisms and leading to multi-cellular metazoans similar to those of the Ediacaran and Cambrian era. The pictorial evidence presented in this report also indicates that these putative organisms were left upon the surface when waters suddenly receded. If these were in fact living organisms, most may have now become extinct, dormant, or they adapted and evolved.

On Earth, each major mass extinction event has led to evolutionary innovation and increased cellular complexity in response to the changing environment. During the Cambrian Explosion, every phyla in existence today had evolved in the oceans of Earth, including phyla that was extremely bizarre in appearance and soon became extinct. Because of the chaotic changes in the Martian biosphere, it is also likely that metazoans and other organisms quite unlike those of Earth may have evolved; some of which may have also become extinct whereas other may continue to flourish in subsurface aquifers and tunnels and caves, and for which there is evidence.

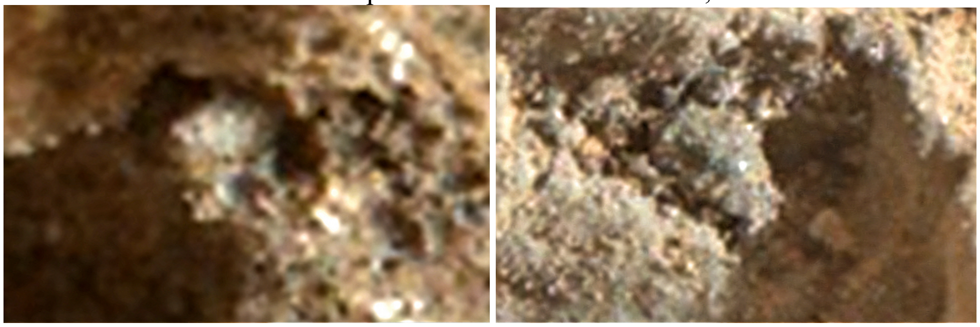


Figure 115: Mars. Gale Crater (Sol 889): Two spheroidal specimens in rock crevices with what could be pleopod and pareiopod appendages and two forward facing orifices that could be interpreted as "eyes." If these are living organisms or anomalous life-like mineral-soil concretions is unknown (0889MH0002270000302739R00_DXXX).

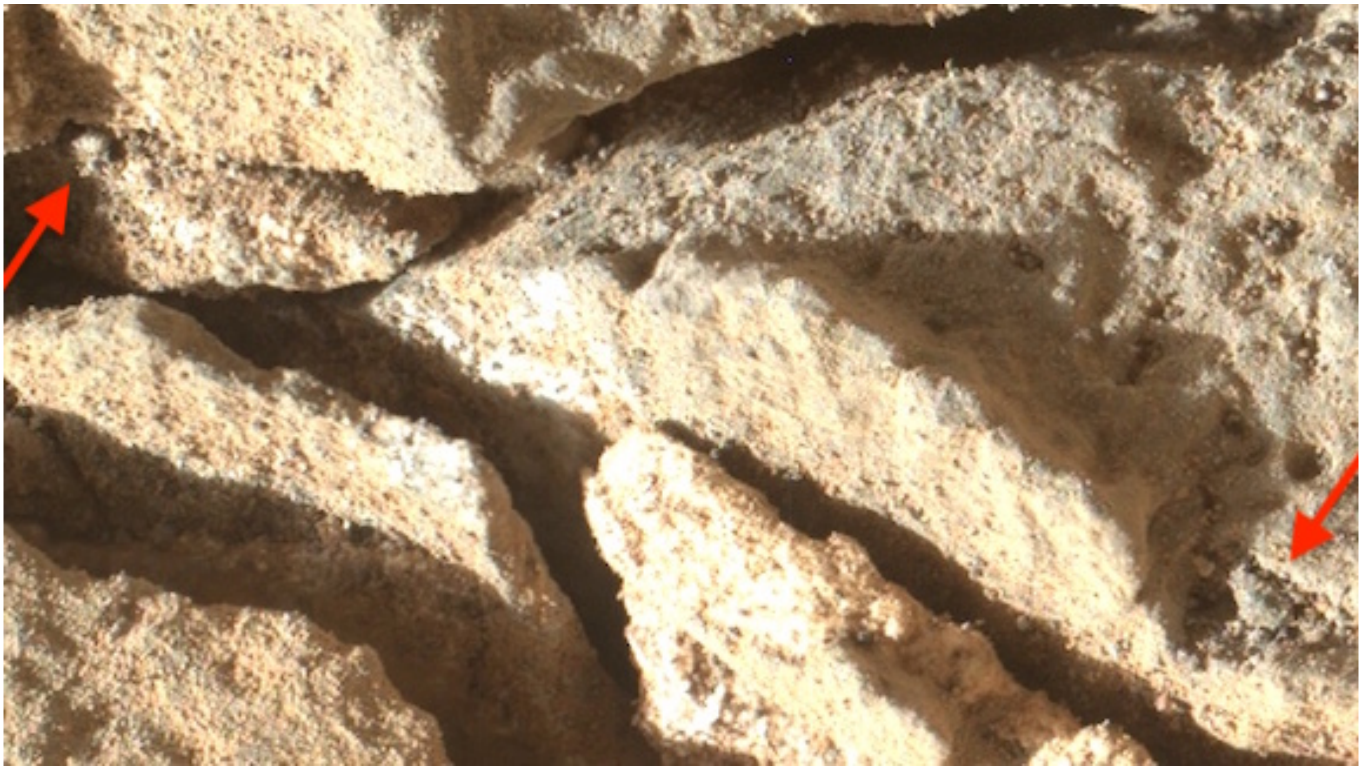


Figure 116: Mars. Gale Crater (Sol 889): Two spheroidal specimens in rock crevices with appendages resembling pleopods and pareiopods. Among terrestrial species, pleopods and pareiopods enable movement and serve as walking legs and arms for gathering food. Note specimen to upper left has two forward facing orifices that could be interpreted as "eyes" (0889MH0002270000302739R00_DXXX). If these are living organisms or "weird" life-like mineral-soil concretions is unknown.

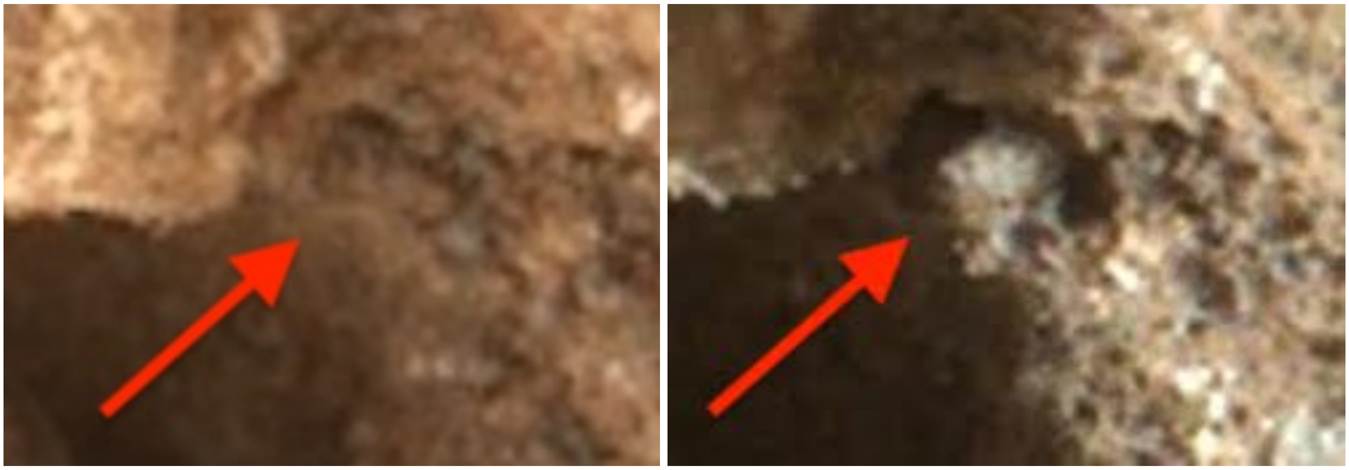


Figure 117: Mars. Gale Crater **Left/Sol 888:** There is no specimen in the crevice. The hole appears to be occluded by something within the hole. **Right/Sol 889:** The following day (one day later) a life-like specimen appears on the ledge in front of the hole that is no longer occluded. It is evident that the entrance to the hole appears to be empty and shadows from the specimen are to its right and not behind it. To speculate: the specimen is live and had been occluding the entrance to the hole and then emerged, via what could be interpreted as pleopods and pareiopods, and leaving an empty hole behind it.

Figure 118: Mars. Gale Crater (Sol 744): Multi-tentacled specimens ranging from 2mm to 3mm in size and diameter and attached to honeycomb sediment with numerous filaments. Algae fruiting bodies with radiating hyphae / mycelium enmeshed within some unknown substrate? (0744MR0031900180403311E01_DXXX).

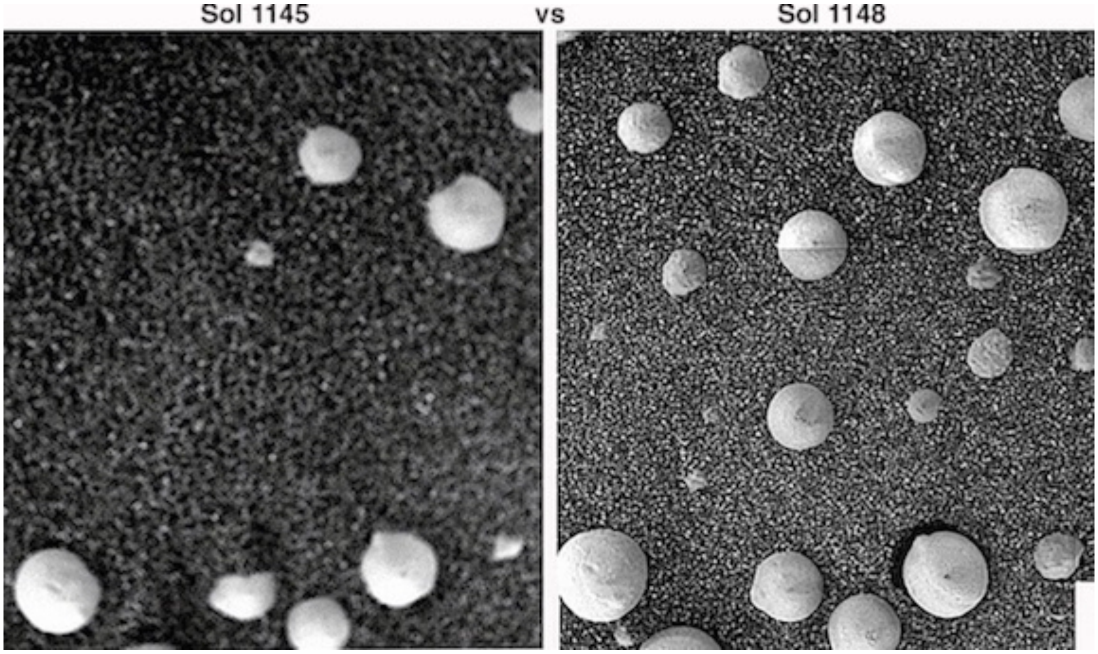


Figure 119: Mars. Gale Crater Sol 1145 vs Sol 1148. Nine spherical specimens lay upon the coarse grain sand of Meridiani Planum. Three days later, 12 additional spheres and semi-spheres appear and the original 9 have increases in size and diameter. Specimens are approximately 3-8 mm in size. Photographed by rover Opportunity (Joseph et al. 2021c)

Figure 120: Mars. Gale Crater Sols 528, 529, 530. (Gale Crater) White amorphous mass alters shape, location, and almost completely disappears from inside the crevice of a rock shelter over a three day (sol) period. Central mass is approximately 6 mm in diameter on Sol 528 and a thin tendril of white appears extends downward and another upward along the lip of the crevice. On 529 the lower tendril has disappeared and there are two tendrils snaking upward. On 530 the white mass and tendrils have nearly disappeared (Joseph et al. 2021c).

Parallels and Origins of Life: Meteors, Nucleotides, Hydrothermal Vents. That there may be life on Mars is supported by observations of specimens that resemble terrestrial cyanobacteria, green algae, lichens, and fungi emerging from the soil and increasing in size. The seasonal fluctuations in Martian atmospheric methane and oxygen that parallel seasonal-biological fluctuation on Earth are also indicative of life.

That these putative living and fossilized Martian organisms so closely resemble their counterparts on Earth, serves not only as evidence of life, but pertains to questions about the origins of life. It could be hypothesized that the presumed similarities are a consequence of the comet-asteroid bombardment stage of planetary development over 3.7 billion years ago; thus similar species evolved because the ancestors of these organisms were delivered throughout this solar system embedded in this cosmic debris (del Gaudio 2014; Joseph et al 2020a). This supports the "genetic seeds of life" hypothesis, that the genomes of viruses and prokaryotes contain the DNA and genetic instructions for the evolution of all life (Joseph 2000, 2021). This scenario does not rule out the likelihood that life was repeatedly transferred to and fro between Earth and Mars via powerful solar winds and impact generated bolides containing organisms that survived the interplanetary journey (Beach 2018; del Gaudio 2014; Joseph et al. 2019; 2020a).

Organized elements that resemble microfossils of cyanobacteria and fungi (Claus & Nagy, 1961; Nagy et al. 1962, 1963; Rozanov & Hoover 2003; Pflug 1978) and the nucleobases (the structural components of nucleic acids) present in DNA and RNA have been identified in carbonaceous chondrites (Martins 2018; Oba et al. 2022). Many in the scientific community believe all the nucleotides necessary for life were delivered by comets and asteroids, and these fragments of DNA were fortuitously mixed together within an undersea thermal vent and the chemicals and minerals produced therein, and life was eventually created (Hartmann & Naukum 2001; Irwin et al., 2013).

Hot springs and subsurface lakes and aquifers heated by volcanic and hydrothermal vents have been tentatively identified in Gusev and Endurance and McLoughlin Craters, and Eridiana basin (Ehlman et al., 2011; Ruff et al. 2011; Ruff & Farmer, 2016; Michalski et al., 2017; Joseph et al. 2021a,b; Suamanarathna et al. 2021a).

As on Earth, beginning over 3.7 billion years ago, at the same time evidence of life appeared on both planets, these hydrothermal vents presumably expelled a variety of chemicals that could sustain and nourish life. Hypothetically, it is possible the shallower Martian oceans and lakes may have been more suitable for the emergence of life, via a combination of radiation, sunlight, hydrothermal chemicals, and nucleotides delivered from space while at the same time providing protection against the extreme and harsh surface conditions as suggested by Hartmann, Naukum (2001) and Irwin et al., (2013). Hence, after a minimal life sustaining gene set and life were fashioned in a Martian hydrothermal vent via nucleotides delivered during the cosmic bombardment from 4.6 to 3.7 bya, life forms with identical genomes were repeatedly transferred from Mars to Earth via bolides and solar winds and similar species evolved leading eventually to metazoan invertebrates on both worlds; and possibly, even the Cambrian Explosion of Life on Earth (Joseph 2000, Joseph & Duvall, 2021). If that incredible scenario were true, all of life on Earth would be descended from Martians. One problem with the “life originated on Mars” theory is that studies examining genetic complexity and the origins of the genome (Sharov 2006, 2010) --beginning with a single complete functional gene-- have determined it would require 10 billion years of gene and whole genome duplicative events to fashion a minimal genome capable of sustaining life (Joseph & Wickramasinghe 2011).

Chaotic Obliquity, Oceans, and the Future of Life. Current axial tilt is 25.19° but has exceeded 80° in the past. These waxing and waning patterns have likely been ongoing for at least 4 billion years. However, because of its chaotic nature, axial tilt may suddenly increase or reverse direction making it currently impossible to make accurate predictions about the timing of past and future obliquity driven climatic events. And with each catastrophic flood, not just rocks and boulders, but surface soils were washed away and likely exposed underlying bedrock, which makes accurate dating of the landscape, based on geological features alone, impossible.

There is substantial evidence that bacteria, algae, lichens, and fungi have colonized the equatorial regions of Mars, and within Meridiani Planum and Gale Crater in particular. During the Spring and Summer, in the far north and southern longitudes, and in response to polar melt water and the eruption of geysers and mud volcanoes, there is evidence that vast colonies of darkly pigmented organisms become biologically active, form vast colonies that grow up to hundreds of meters, and then become dormant or migrate beneath the surface when temperatures decline in Autumn and Winter. Thus, we hypothesize that as obliquity approaches and exceeds 60 degrees and global and winter temperatures dramatically rise, glaciers will melt and flood water will form stable oceans and lakes and rivers that will endure, and Red Planet Mars will become the Blue Green Planet flourishing with life.

Based on the data reviewed in this report, we believe the last episode of extreme obliquity may have begun over a million years in the past and endured until around 110,000 years ago and maybe until more recently given evidence of surface mud and moisture and salty brines and vast deposits of water-ice just below the surface. As axial tilting and temperatures and atmospheric pressures declined, oceans, lakes and rivers of water seeped back below ground and reformed surface-subsurface glaciers and the polar ice caps that are now evident. If obliquity will continue to decline is unknown. However, it can also be predicted that extreme chaotic axial tilting will recur at some unknown date in the future, and oceans of water will again flow across the surface of Mars.

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