Tube Worm-Like Structures, Hematite, and Hydrothermal Vents on Mars: Support for, and Opposition to Joseph et al.

[1,*]Aravinda Ravibhanu Suamanarathna, [2]Majda Aouititen,
[3]Abdelouahed Lagnaoui,

[1,2,3]Department of Research & Innovation - South Asian Astrobiology & Earth Sciences Research Unit of Eco Astronomy Sri Lanka, Colombo, Sri Lanka.

[2]Beijing Forestry University School of Ecology and Nature Conservation, Beijing, China.

[3]Interdisciplinary Research Laboratory in Sciences, Education and Training, Higher School of Education and Training Berrechid (ESEFB), Hassan First University, Route de Casablanca Km 3.5, BP 539, 26100 Berrechid, Grand-Casablanca, Morocco.

Journal of Astrobiology, Vol 10, 38-62, Published 11/18/2021
Editors-in-Chief: K. Wołowski, G. Bianciardi, R. del Gaudio

Abstract

The observation of tubular structures within Endurance Crater, Mars, has been reported by Joseph et al (2021a,b) who hypothesized these may be mineralized and fossilized remnants of tube worms that in the ancient and recent past flourished within lakes of water heated by thermal vents. The discovery of what may be spherical hematite in this same vicinity supports the hydrothermal vent scenario, whereas the claims by Joseph (2021; Joseph et al. 2021c) that these spherules are fungal puffballs does not. This evidence from Endurance Crater and associated mineralogy and chemistry is reviewed. We conclude that the ancient lakes of Endurance Crater may have been heated by thermal vents and inhabited by tubular organisms that became mineralized, as hypothesized by Joseph et al; and that these same hydrothermal vents formed hematite spherules as hypothesized by the rover Opportunity team.

Key Words: Tube Worms, Hydrothermal Vents, Evolution, Life on Mars, Mineralization, Chemistry, Fossils, Gale Crater, Endurance Crater, Burns Formation, Fossils

*Corresponding email: aravinda@ecoastronomy.com

1. Tube Worms and the Evolution of Life on Mars?

A number of investigators have discussed the extreme environments of Mars, the limitations on habitability, and the possibility various organisms could have inhabited the Red Planet in the recent or ancient past (Cockell et al., 2005; Osman et al., 2008; Mahaney & Dohm, 2010; Sanchez et al., 2012; Sumanarathna, 2015, 2018; Selbman et al., 2015; Pacelli et al., 2016; Schuerger et al., 2017). It is believed that lack of liquid water, the extremely cold conditions that prevail in the winter and at night, and the high levels of radiation that bombard the surface would have a profoundly negative impact on the habitability of modern-day Mars (Dartnell, 2010). Joseph and colleagues (2020a,b, 2021c,d; Armstrong

2021a; Latif et al. 2021) however, have presented evidence of formations and structures on Mars they argue resemble living algae, fungi, and lichens that adapted to these harsh conditions and evolved the ability to employ radiation as a nutrient and energy source (Joseph 2021). Joseph and colleagues have hypothesized that the high levels of iron promote the production of melanin that protects organisms from radiation, and that high levels of magnetization within craters located in the equator and southern hemisphere also provides a protective shield thus promoting habitability and accounting for the observation of what may be fungi, lichens, and algae within the Eagle and Gale Craters (Joseph et al. 2020a; 2021b). Endurance Crater is also located in the equatorial region and like Gale Crater long ago hosted lakes that may have been heated by thermal vents that were colonized by tube worms and associated bacteria and marine organisms (Armstrong 2021b; Joseph et al. 2020a, 2021a,b).

What may be fossilized tube worms were first observed by DiGregorio (2018) within the ancient lake beds of Gale Crater. Comparative morphological analysis of these specimens has supported the tube worm hypothesis (Armstrong 2021a; Baucon et al 2020; Joseph et al. 2020b; 2021b). Joseph et al. (2021a,b) also observed numerous tubular specimens adjacent to vents and holes on the surface of Endurance Crater, in the same general vicinity in which spherical formations have also been observed (Christensen et al., 2004; Squyres & Knoll 2005). Although Joseph and colleagues (2020a, 2021c; Joseph 2016, 2021; Armstrong 2021b; Dass 2017) have argued that these spheres are fungal puffballs and have no resemblance to hematite, Christensen et al. (2004), Squyres et al. (2004) and Weitz et al., (2004) argue that the 1mm to 4mm sized spherules, dubbed "blueberries" consist of hematite.

Hematite is an iron-oxide mineral. Because, on Earth, the gray crystalline variety forms mostly in association with hot liquid water this had led the Opportunity team to hypothesize that Eagle and Endurance Craters may have long ago been filled with water heated by hydrothermal vents (Squyres et al, 2004. Squyres & Knoll 2005). The hematite hypothesis, therefore, supports the findings of what may be fossilized tube worms that long ago dwelled in briny lakes of water heated by thermal vents; whereas Joseph (2014, 2016, 2021) and colleagues (Joseph et al. 2021c; Armstrong 2021b; Dass 2017) argument in favor of fungal puffballs does not.

The hydrothermal vent hypothesis is also supported by the mineralogy and high levels of sulfur detected in outcrops of Endurance crater, in the same are where tubular specimens have been observed in close proximity to what may be vents on the surface (Joseph et al. 2020a). For example, based on the analysis via mineralogy at Meridiani Planum from the Mini-TES experiment on the Opportunity Rover high concentration of sulfur in the form of calcium and magnesium sulfates have been detected, as well as arekieserite, sulfate anhydrate, bassanite, hexahydrite, epsomite, and gypsum. Salts, such as halite, bischofite, antarcticite, bloedite, vanthoffite, or gluberite may also be present (Christensen et al., 2004). As pointed out by Joseph et al. (2021) many of these minerals including salts and sulfur are also found in close proximity to hydrothermal vents. The waters in these lakes would also be salty; and salty brines are a favored habit of tube worms.

The abundance of these minerals, including hematite, raises two possibilities as to what may or may not be tube worms. Joseph et al. (2021a) believe these tubes are mineralized fossils. However, it is also possible that what these scientists believed to be fossilized tube worms and crustaceans, may consist entirely of minerals and may be pseudo-fossils. It is true, however, that Joseph et al. (2020, 2021b). Baucon et al. (2020) and Armstrong (2021) have also presented statistical evidence which supports a biological interpretation. If the statistical findings and the observations of what may be fossilized tube worms and crustaceans are accepted as valid, this would indicate that life must have evolved on Mars. That Mars has been inhabited and that life evolved is consistent with petrological data and eco astronomy mechanics (Sumanarathna, 2018) and supported by geochemical analysis of mineralized substrates and findings from Martian meteorite ALH 84001; i.e. that microbial life may have been proliferating on Mars between 3000 Myr to 4200 Myr (McKay et al., 1996, 2009; Thomas-Keprta et al., 2009; Macey et al., 2020). A number of investigators also agree that ancient Mars was habitable and harbored life (Squyres & Knoll, 2006; Ehlmann et al., 2011; Vago et al., 2017) and have hypothesized that prokaryotic and eukaryotic organisms may have become fossilized (Squyres et al., 2004; Grotzinger et al., 2014, 2015). The observation of what may be fossilized algae (Bianciardi et al. 2021; Kaźmierczak 2016, 2020), fossilized microbialites and stromatolites (Bianciardi et al. 2014; Joseph et al. 2020b; Elewa 2021), fossilized tube worms in Gale and Endeavor Crater sediments (Armstrong, 2021a, Baucon et al. 2020; DiGregorio, 2018; Joseph et al., 2020a, 2021ab) and what appear to be an assemblage of metazoan fossils discovered in Gale Crater, support the hypothesis life evolved on Mars.

2. Source Data: Mineralogy and Tubular Specimens

The evidence pro and con in support of the evolutionary hypothesis is presented in a series of Tables and Figures. Petrological data and analysis is also reviewed and found to be supportive of the habitability hypothesis. Mineralogical conditions in Meridiani Planum is also summarized and a hypothetical model of the biomineralization process is examined.

Specifically, Tables 1 and 3, presents a summary of the mineralogy and petrology as based on outcrop spectra and ex-ray diffraction, whereas Table 2 summarizes the chemical composition. The geology and stratigraphy of the Burns formation which extends from Eagle to Endurance to Endeavor Craters is summarized in Table 4 and depicted in Figure 1. The outcrops of the Burns formation has the chemistry and mineralogy consistent with a large body of briny water that was heated by thermal vents. It is within this same vicinity where what may be fungi, lichens, fungal puffballs, spherical hematite, and fossilized tube worms have been observed. The tube worm hypothesis is supported by the assemblage of tubular specimens discovered by Joseph et al., (2021ab), the comparative statistical analysis performed by Armstrong (2021a) and Figure 2 which compares these tubular formations with those observed in Gale Crater (see also Figure 3) and tube worms on Earth (see also Figures 4, 5, 6, 7). Figure 8 depicts spherical formations that have been identified as fungal puffballs vs spherical hematite.

3. Figures, Tables, Analysis

Table 1: Analysis of microscopic images of non-linearized full frame EDR of Sols 177-199-299 and 1905 Mineralogy and Petrology. Numerical deconvolution results for Mini-TES outcrop spectra. The volume abundances listed have been rounded to the nearest 5% from the values from the deconvolution model (Christensen et al., 2004).

Mineral group	Guadalupe	Gills	Last Chance Lower	Last Chance Left	Hippo	Pilbara	Tamanend Park	Chantry Flats	Tres Creek	Rhino Horn	Bunny Slope	Dolphin	Hamersley
Sulfate	25	25	10	15	25	30	35	30	35	30	25	25	15
Hematite	25	25	0	20	35	0	35	30	45	45	10	40	5
Sheet silicate	0	0	0	0	0	0	10	20	0	0	0	5	0
Glass	25	15	15	20	10	20	10	10	5	5	20	15	20
Oxide/hyroxide	0	5	20	20	5	10	0	0	5	5	5	0	0
Feldspar	10	15	25	10	15	20	0	0	0	5	15	0	45
Olivine	10	10	20	10	5	10	10	10	5	10	15	5	0
Pyroxene	5	5	10	5	5	5	0	5	0	5	15	5	15
Total	100	100	100	100	100	95	100	105	95	105	105	95	100

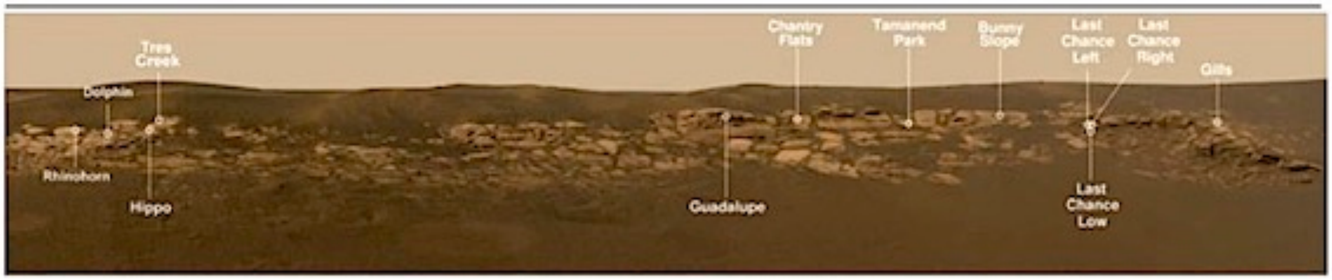


Table 2: Chemical composition and proportion of XRD amorphous component in Rocknest Portage from APXS and CheMin data(Blake et al., 2013).

	Rocknest	Gusev	Meridiani
Number	1*	48†	29†
SiO_2 (wt %)	42.88 ± 0.47	46.1 ± 0.9	45.7 ± 1.3
TiO_2	1.19 ± 0.03	0.88 ± 0.19	1.03 ± 0.12
Al_2O_3	9.43 ± 0.14	10.19 ± 0.69	9.25 ± 0.50
Cr_2O_3	0.49 ± 0.02	0.33 ± 0.07	0.41 ± 0.06
Fe_2O_3 + FeO	19.19 ± 0.12	16.3 ± 1.1	18.8 ± 1.2
MnO	0.41 ± 0.01	0.32 ± 0.03	0.37 ± 0.02
MgO	8.69 ± 0.14	8.67 ± 0.60	7.38 ± 0.29
CaO	7.28 ± 0.07	6.30 ± 0.29	6.93 ± 0.32
Na_2O	2.72 ± 0.10	3.01 ± 0.30	2.21 ± 0.18
K_2O	0.49 ± 0.01	0.44 ± 0.07	0.48 ± 0.05
P_2O_5	0.94 ± 0.03	0.91 ± 0.31	0.84 ± 0.06
SO_3	5.45 ± 0.10	5.78 ± 1.25	5.83 ± 1.04
Cl	0.69 ± 0.02	0.70 ± 0.16	0.65 ± 0.09
Br (μg/g)	26 ± 6	53 ± 46	100 ± 111
Ni	446 ± 29	476 ± 142	457 ± 97
Zn	337 ± 17	270 ± 90	309 ± 87
Sum (wt %)	99.85	99.88	99.88
Cl/SO_3	0.13 ± 0.02	0.12 ± 0.02	0.11 ± 0.01

Table 3: Mineralogy of Rocknest soil [CheMin x-ray diffraction (XRD)]and normative mineralogies of basaltic materials from Gusev Crater and of martian meteorites (Blake et al., 2013).

Location	Gale	Gusev			Meteorites			
Sample	Rocknest sand shadow	Adirondack	Backstay	Irvine	Shergotty	NWA 6234	EETA 79001A	QUE 94210
Quartz	*1.4*	0	0	0	0.2	0	0	3
Plagioclase	40.8	39	49	32	23	19	19	32
K-spar	*1.3*	1	6	6	1	0.5	0	0
Low-Ca Pyx	13.9	15	14	21	46	30	47	15
High-Ca Pyx	14.6	15	5	13	25	16	16	38
Olivine	22.4	20	15	16	0	27	13	0
Fe-Cr oxides	*3.2*	6	4	6	3	4	2	0
Ilmenite	*0.9*	1	2	2	2	2	1	4
Apatite	–	1	3	2	2	2	1	6
Anhydrite	*1.5*							
Mg no.	61 ± 3	57	62	55	51	63	63	40
An	57 ± 3	42	29	19	51	50	60	62

Table 4a: Bulk and residual compositions (weight %) for 20 Burn formations RATed targets and residual compositions (Cino et al 2016).

	Millstone_**Drammenfjord**		**DiamondJenness**_Holman3		**Mackenzie**_Campbell2		Inuvik_**Tuktoyaktuk**		**Bylot**_Aktineq3	
	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue
Na_2O	1.58	0.00	1.72	1.08	1.93	0.34	1.79	0.57	1.86	0.56
K_2O	0.59	0.35	0.63	1.39	0.69	1.12	0.67	1.28	0.60	1.19
P_2O_5	1.17	4.06	1.05	3.39	1.15	3.31	1.11	3.47	1.01	3.44
SO_3	21.11	0.00	19.62	0.00	17.01	0.00	18.17	0.00	19.33	0.00
Cl	1.98	0.55	1.37	0.00	1.90	0.00	1.67	0.00	1.69	0.00
SUM	99.88	100.0	99.90	100.0	99.89	100.0	99.86	100.0	99.83	100.0
CIA	33.1	80.6	34.5	68.5	37.2	70.2	34.5	63.2	33.7	68.6
NORM:										
Quartz	-	24.65	3.91	27.46	7.50	34.65	1.74	25.00	-	19.40
Plagioclase	27.84	-	29.40	9.14	31.37	2.88	30.89	11.44	29.58	4.74
Orthoclase	4.55	2.07	4.73	8.21	5.02	6.62	4.96	7.56	4.49	7.03
Corundum	-	21.18	-	18.34	-	19.12	-	17.60	-	19.96
Diopside	10.38	-	10.17	-	6.36	-	10.92	-	11.18	-
Hypersthene	45.36	35.24	41.83	21.66	39.46	21.23	40.66	21.07	36.29	31.79
Olivine	1.15	-	-	-	-	-	-	-	7.80	-
Ilmenite	1.84	4.96	1.90	4.84	2.01	4.71	2.05	5.09	1.84	4.96
Magnetite	4.96	4.12	4.68	2.51	4.63	2.75	5.16	3.22	5.42	3.20
Apatite*	3.52	9.43	3.08	7.83	3.29	7.65	3.22	8.02	2.97	7.95
Chromite	0.40	1.08	0.31	0.81	0.37	0.85	0.41	1.03	0.43	1.15
Plag An-Content	36.3	0.0	36.2	0.0	34.4	0.0	37.3	56.4	31.5	0.0

	Escher_Kirchner		Blackcow_**Wharenhul**		**Yuri_Gagarin**		**IceCream**_OneScoop		**FruitBasket**_LemonRind	
	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue
SiO_2	36.53	42.52	37.54	42.71	32.64	37.09	36.24	43.48	35.10	38.87
TiO_2	0.75	2.76	0.81	2.75	0.68	3.29	0.78	3.01	0.75	2.88
Al_2O_3	6.06	22.28	6.43	21.85	4.90	23.69	5.91	22.81	6.17	23.67
Cr_2O_3	0.18	0.66	0.20	0.68	0.17	0.82	0.21	0.81	0.19	0.73
FeO_T	15.70	14.43	15.08	14.60	15.86	14.57	15.84	13.76	15.99	17.18
MnO	0.24	0.88	0.32	1.09	0.35	1.69	0.31	1.20	0.38	1.46
MgO	8.37	7.54	9.11	10.02	7.33	0.00	7.31	3.16	7.83	6.19
CaO	5.00	0.98	4.10	0.23	5.78	0.21	5.49	2.42	5.20	2.08
Na_2O	1.63	2.43	1.83	1.27	1.35	2.31	1.74	3.26	2.02	1.69
K_2O	0.57	1.81	0.56	1.13	0.51	2.28	0.58	2.07	0.54	1.23
P_2O_5	1.01	3.71	1.08	3.67	1.07	5.17	1.04	4.01	1.05	4.03
SO_3	23.03	0.00	21.33	0.00	28.62	8.88	23.81	0.00	23.12	0.00
Cl	0.78	0.00	1.49	0.00	0.61	0.00	0.64	0.00	1.54	0.00
SUM	99.86	100.0	99.90	100.0	99.88	100.0	99.88	100.0	99.89	100.0
CIA	32.8	74.2	36.7	85.4	26.9	78.1	30.5	65.5	31.6	75.0
NORM:										
Quartz	-	2.46	-	7.96	-	7.47	-	4.52	-	5.18
Plagioclase	27.95	20.48	29.99	10.75	24.28	21.41	28.17	27.50	30.81	14.22
Orthoclase	4.43	10.70	4.25	6.68	4.25	14.77	4.55	12.23	4.25	7.27
Corundum	-	16.29	-	18.49	-	19.06	-	15.17	-	19.50
Diopside	11.62	-	5.95	-	18.62	-	15.23	-	14.10	-
Hypersthene	34.96	35.75	39.82	42.55	25.68	19.42	31.26	23.96	18.22	37.08
Olivine	10.79	-	9.66	-	16.08	-	10.18	-	22.04	-
Ilmenite	1.86	5.22	1.99	5.20	1.82	6.84	1.96	5.70	1.88	5.45
Magnetite	4.97	3.48	4.71	3.52	5.41	3.86	5.06	3.32	5.12	4.15
Apatite*	3.06	8.57	3.24	8.48	3.50	13.11	3.17	9.27	3.22	9.31
Chromite	0.35	0.97	0.38	1.00	0.35	1.33	0.41	1.19	0.37	1.08
Plag An-Content	33.9	0.0	31.8	0.0	32.5	0.0	29.7	0.0	25.3	0.0

Table 4b: Bulk and residual compositions (weight %) for 20 Burn formations RATed targets and residual compositions (Cino et al 2016).

	McKittrick_MiddleRAT		**Guadalupe**_King3		**FlatRock**_Mojo2		**Lionstone**_Numma		**Tennessee**_Vols	
	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue
SiO_2	38.27	45.36	36.24	45.12	36.26	41.81	37.17	43.40	34.98	41.51
TiO_2	0.81	2.76	0.65	2.60	0.74	2.74	0.77	2.74	0.79	3.27
Al_2O_3	6.20	21.13	5.85	23.44	6.18	22.88	6.22	22.11	5.87	24.32
Cr_2O_3	0.19	0.65	0.17	0.68	0.20	0.74	0.18	0.64	0.20	0.83
FeO_T	16.53	13.52	14.78	10.66	15.26	15.53	14.33	12.74	15.71	14.97
MnO	0.30	1.02	0.30	1.20	0.26	0.96	0.29	1.03	0.32	1.33
MgO	8.00	7.34	8.45	5.22	8.38	5.76	8.80	8.69	8.38	4.87
CaO	4.42	0.14	4.91	1.78	5.19	0.29	5.03	0.95	5.03	0.39
Na_2O	1.67	2.96	1.66	3.30	1.64	3.56	1.72	2.45	1.36	2.07
K_2O	0.56	1.74	0.53	2.09	0.59	1.99	0.58	1.67	0.58	2.18
P_2O_5	0.99	3.37	0.97	3.89	1.01	3.74	1.01	3.59	1.03	4.27
SO_3	21.31	0.00	24.91	0.00	23.61	0.00	22.84	0.00	24.94	0.00
Cl	0.60	0.00	0.50	0.00	0.54	0.00	0.91	0.00	0.65	0.00
SUM	99.85	100.0	99.92	100.0	99.86	100.0	99.85	100.0	99.84	100.0
CIA	35.2	75.1	32.4	68.2	32.6	72.8	33.0	74.5	32.8	79.0
NORM:										
Quartz	–	3.24	–	4.45	–	–	–	2.99	–	5.85
Plagioclase	28.01	24.96	28.09	27.84	28.49	30.04	28.93	20.65	26.47	17.43
Orthoclase	4.25	10.28	4.20	12.35	4.61	11.70	4.49	9.87	4.61	12.82
Corundum	–	14.34	–	15.73	–	14.84	–	16.24	–	18.52
Diopside	8.17	–	12.23	–	12.40	–	11.68	–	11.17	–
Hypersthene	46.20	34.23	35.63	25.48	32.08	19.06	35.45	36.53	35.21	29.72
Olivine	3.01	–	10.09	–	12.26	10.34	9.59	–	11.87	–
Ilmenite	1.98	5.22	1.65	4.94	1.84	5.18	1.92	5.18	2.01	6.19
Magnetite	5.10	3.26	4.78	2.57	4.86	3.74	4.54	3.07	5.09	3.61
Apatite*	2.94	7.78	3.01	8.99	3.08	8.64	3.06	8.29	3.20	9.87
Chromite	0.35	0.96	0.34	1.00	0.38	1.09	0.35	0.94	0.40	1.22
Plag An-Content	34.0	0.0	31.8	0.0	34.5	0.0	32.9	0.0	40.1	0.0

	Kentucky_CobbleHill		LayerC_**Virginia**		Ontario_**London**		Manitoba_**Grindstone**		Manitoba_**Kettlestone**	
	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue
SiO_2	35.91	41.58	36.94	40.61	36.38	41.56	38.03	44.69	36.23	42.67
TiO_2	0.71	2.70	0.84	2.85	0.74	2.70	0.83	2.84	0.80	3.03
Al_2O_3	5.90	22.42	6.32	21.44	5.99	21.82	6.36	21.76	5.85	22.18
Cr_2O_3	0.18	0.68	0.21	0.71	0.20	0.73	0.19	0.65	0.20	0.76
FeO_T	14.73	15.11	15.55	14.50	14.53	15.09	14.82	14.20	15.20	16.42
MnO	0.33	1.25	0.39	1.32	0.31	1.13	0.33	1.13	0.33	1.25
MgO	9.20	7.09	9.00	9.19	9.14	7.98	8.38	8.28	8.63	8.49
CaO	4.72	0.52	4.43	0.41	4.85	0.32	4.64	0.60	4.85	0.23
Na_2O	1.54	2.72	1.83	3.47	1.64	2.84	1.70	0.96	1.45	0.00
K_2O	0.57	1.93	0.60	1.87	0.57	1.79	0.58	1.23	0.55	0.52
P_2O_5	1.05	3.99	1.07	3.63	1.11	4.04	1.07	3.66	1.03	3.90
SO_3	24.38	0.00	22.09	0.00	23.71	0.00	21.50	0.00	23.03	0.00
Cl	0.65	0.00	0.60	0.00	0.72	0.00	1.45	0.00	1.75	0.54
SUM	99.88	100.0	99.87	100.0	99.87	100.0	99.89	100.0	99.88	100.0
CIA	33.5	74.9	35.0	71.7	33.1	75.2	34.9	84.5	33.1	95.7
NORM:										
Quartz	–	–	–	–	–	–	–	14.22	–	18.96
Plagioclase	27.35	22.93	29.37	29.28	27.99	23.95	29.01	8.12	26.65	–
Orthoclase	4.49	11.41	4.55	11.05	4.43	10.58	4.43	7.27	4.31	3.07
Corundum	–	15.82	–	13.67	–	15.19	–	18.80	–	21.68
Diopside	9.94	–	8.23	–	10.35	–	8.55	–	10.37	–
Hypersthene	35.77	33.51	33.35	8.78	35.23	30.30	44.41	37.60	40.69	41.29
Olivine	12.33	2.09	13.99	23.28	11.71	5.90	3.33	–	7.53	–
Ilmenite	1.80	5.11	2.05	5.39	1.86	5.11	2.05	5.37	2.01	5.77
Magnetite	4.74	3.64	4.86	3.49	4.64	3.64	4.64	3.42	4.87	3.97
Apatite*	3.24	9.22	3.20	8.39	3.41	9.34	3.22	8.46	3.17	9.06
Chromite	0.35	1.00	0.40	1.05	0.38	1.00	0.37	0.96	0.40	1.12
Plag An-Content	35.2	0.0	30.7	0.0	33.1	0.0	34.5	0.0	37.6	0.0

	Millstone_**Drammenfjord**		**DiamondJenness**_Holman3		**Mackenzie**_Campbell2		Inuvik_**Tuktoyaktuk**		**Bylot**_Aktineq3	
	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue	Bulk	Residue
SiO_2	37.63	43.91	40.58	50.39	42.97	51.81	39.85	46.50	37.87	44.00
TiO_2	0.75	2.60	0.79	2.55	0.86	2.48	0.86	2.69	0.77	2.62
Al_2O_3	6.20	21.50	6.71	21.66	7.27	20.93	7.17	22.40	6.52	22.21
Cr_2O_3	0.21	0.73	0.17	0.55	0.20	0.58	0.22	0.69	0.23	0.78
FeO_T	15.82	17.01	15.35	10.40	15.56	11.42	17.07	13.34	17.75	13.30
MnO	0.31	1.08	0.33	1.07	0.32	0.92	0.36	1.12	0.37	1.26
MgO	7.41	5.57	6.47	3.86	5.43	3.18	5.45	2.04	6.81	6.25
CaO	5.11	2.64	5.09	3.67	4.60	3.91	5.48	5.90	5.01	4.37

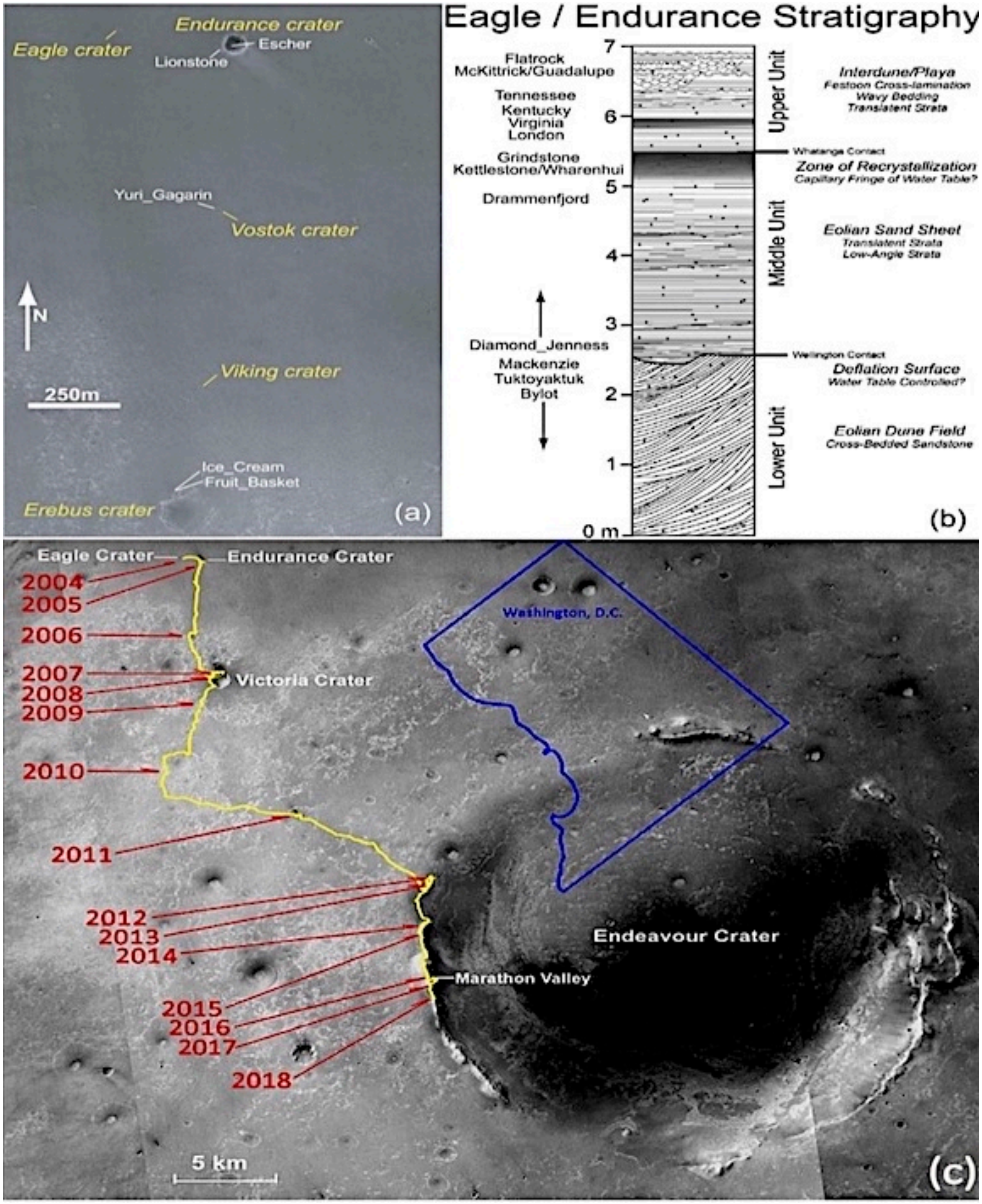


Figure 1: Sample locations (a & c) and the stratigraphy (b) of the Burns formation in the vicinity of Eagle crater and Endurance crater, Meridiani Planum, Mars (adapted from Grotzinger et al., 2005). Base map taken from MRO HiRISE image PSP_005423_1780_RED. The location of Eagle crater, the landing site (c), is 1.9462 °S and 354.4734 °E relative to the International Astronomical Union 20 0 0 body-centered coordinate frame (Squyres et al., 2006; Cino et al.,2016). Joseph and colleagues (2021a,b) identified tubular formations within Endurance Crater. Squyres et al., (2004) hypothesized that this area once hosted a large briny body of water, and was habitable in the ancient past.

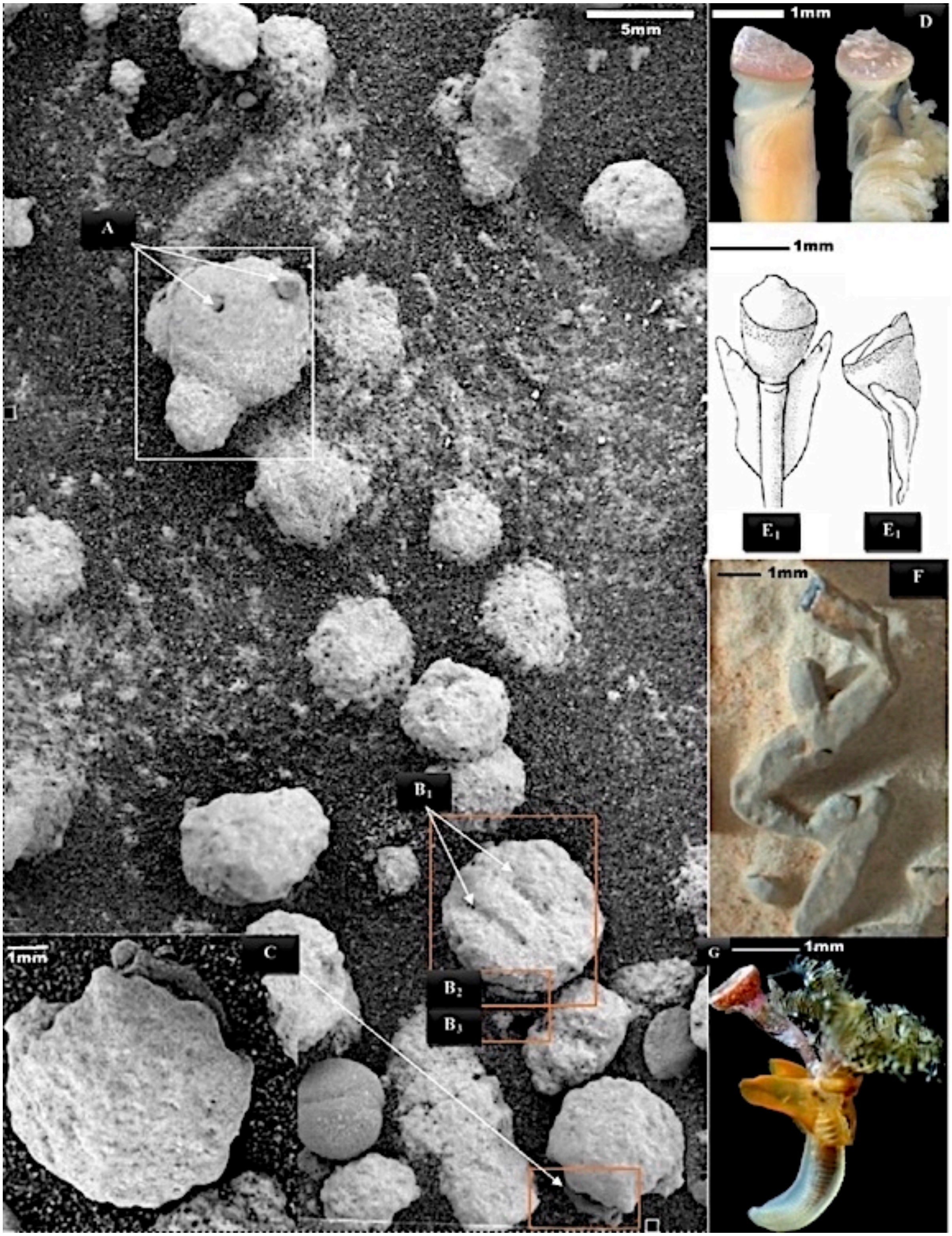
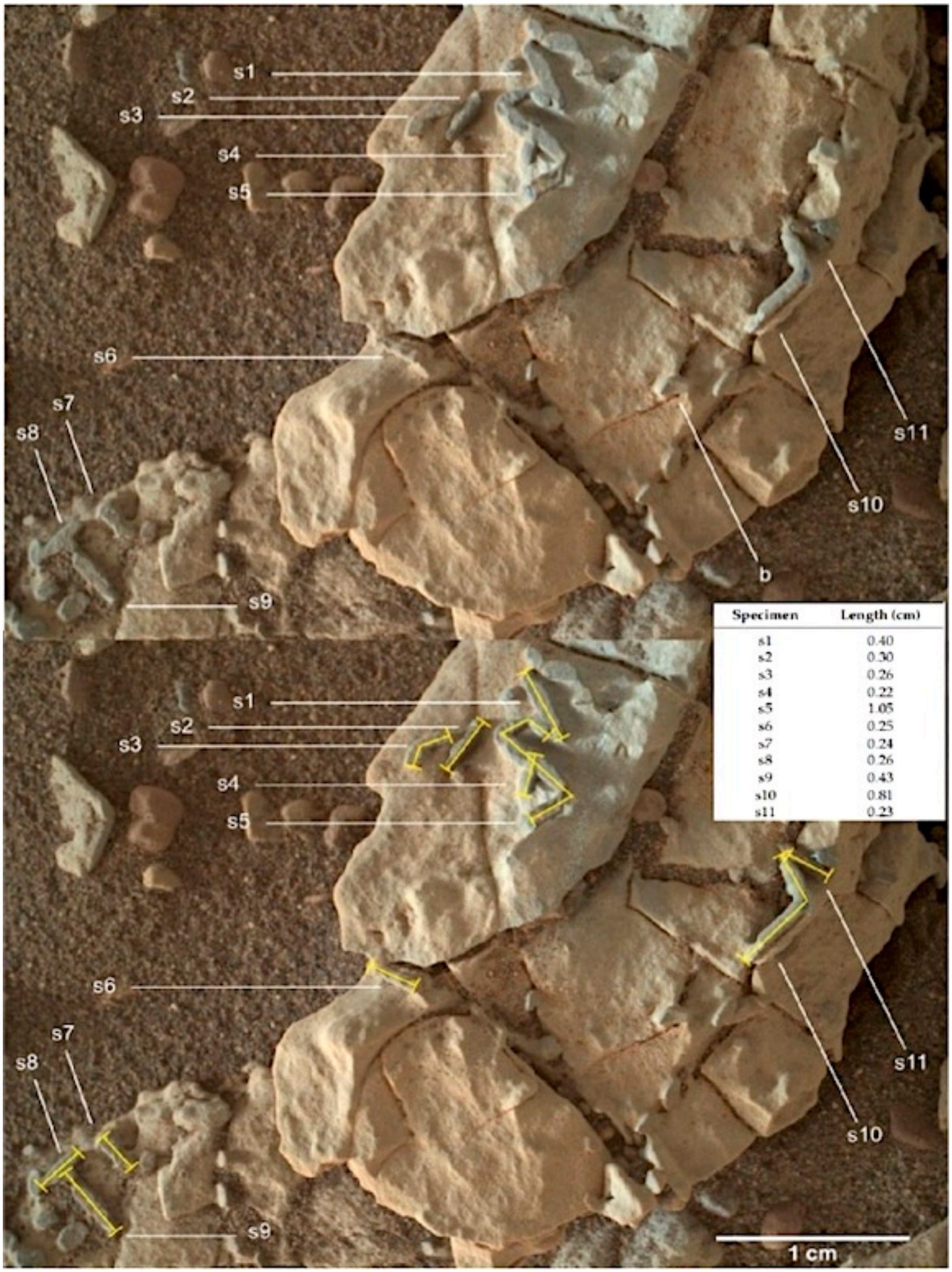


Figure 2: (Left). Joseph et al. (2021a,b) discovered these tubular specimens within Endurance Crater, that resemble (Right) terrestrial tube worms (D,E,G) and tubular fossils observed in Gale Crater (F).

Figure 2 Analysis: Joseph et al. (2021a,b) discovered these tubular specimens within Endurance Crater and hypothesized these are tube worms that had been dwelling within hydrothermal vents when the cater was filled with water. Microscopic images of Non-linearized Full frame EDR ©NASA | Stitcher and assembling ©Eco Astronomy Inc. (Right) | Julie, 1985; Sun j et al., 2012; Kupriyanova et al., 2015; Baucon et al., 2020). **A.** Most probably borehole and type of tube worm opercula at Endurance Crater. Comparing sizing via pictorial matrix and extrema conditions, it can be like *Spirobranchus* and *Coprinisphaera* combination of process of borrowing. *Coprinisphaera* is one of the most common trace fossils in the Tertiary palaeosols of South America, and it was appropriately one of the first recorded insect trace fossils and considered as nests of dung-beetles or scarabs (Frenguelli 1938; Roselli 1939). *Coprinisphaera* are mostly related to the presence and position of a small chamber (interpreted as the original egg chamber) with respect to a large chamber (provision chamber) and emergence hole. We note that the occurrence of at least 2 circular to subcircular holes, or paraboloid external pits in the walls of chamber-like could be compared with the ichnogenus *Tombownichnus* (Mikulas and Genise 2003). The structure described herein consists of isolated, pear-shaped structure. it is composed of two clustered subspherical chamber-like; large main chamber-like and a secondary small one (about 1/3 of the main chamber-like) located in the upper protuberance of the structure. Chamber-like structure is surrounded by a discrete constructed wall, with at least two holes; one in the centre and second one in the margin. The filling of both spheres could not be examined, but it looks a passively filled chamber. This pear-shaped structure presents the diagnosis external morphological features of the ichnogenus *Coprinisphaera* (Sauer 1955. Thus, four ichnospecies of *Coprinisphaera* show the pear-shaped morphology, which are: *Coprinisphaera akatanka* (Cantil et al., 2013), *Coprinisphaera cotiae* (Sánchez and Genise 2015), *Coprinisphaera lazai* (Sánchez et al., 2013), *Coprinisphaera tonnii* (Laza 2006). C. akatanka, and C. tonnii are internally composed of a main spherical chamber separated from a secondary, smaller one. However, in C. akatanka, both spherical chambers are clearly distinguishable by an external deep neck, whereas in C. tonnii, this constriction is absent showing a pear-shaped external aspect. In addition, C. akatanka has a thin wall in contrast to the thicker one of C. tonnii. *C. cotiae* differs from the other ichnospecies by the elongated protuberance that is internally crossed by a conduit that ends in a very tiny pore (Laza 2006; Cantil et al. 2013; Sánchez et al. 2013). The internal features could be examined; therefore, we can tentatively compare these structures with the ichnogenus *Coprinisphaera* (Sauer 1955).

B1 - Most probably survival or feeding trace effected by micro boring or borrows. Sometimes possible to occur via living mood habitat of tubular specimen and not compulsory to fossilized stage as a stabilize formation. **B2** – A tubular structure presented is approximately similar sizing to trace. **B3 -** Rich sulfates micro chimney mound as a part of hydrothermal vent (Colín-García M, 2016). **C.** Most probably like unaltered tubular structured of worm which can be primitively adopt via extreme of paleo hydrothermal vent at Endurance Crater, Mars (H Julie et al., 1985; Kuhn et al., 2003; Christensen et al., 2004; M Thomas et al., 2005; Sun j et al., 2012; Blake et al., 2013; Kupriyanova et al., 2015; Magdalena et al., 2019). **D.** Opercula of fixed specimens, AM W.21678 (Kupriyanova et al., 2015). **E1, E2.** Opercula of *Spirobranchus dennisdevaneyi* (H Julie et al., 1985). **F.** This is Sol 1905, Outcrop imaged by rover Curiosity using MAHLI at Vera Rubin Ridge, Mars presented mold likes Ichno fossils. (Baucon et al., 2020; Joseph et al., 2020a, 2021a,b). The structure reported here is simple flattened, branched, oblong, to sub rectangular in cross section. This structure consists of a Hypichnial semi-relief zigzag meanders, associated with short horizontal branched twig-like segments. Joined points of segments start from the middle part of the tube not from the V-point of the zigzag. With of the tube-structure is not the same along the specimen. This whole zigzag morphology shows similarities with the ichnospecies *Belorhaphe zickzack* (Heer, 1877), but the subhorizontal, zigzag, subcylindrical trail froked at each angle are typical features of the ichnogenus *Treptichnus* (Miller, 1889). The zigzag morphology in ichnology indicates a deposit-feeding or a farming and trapping life strategy (Rindsberg and Kopaska-Merkel, 2005). The deposit-feeding strategy consists of the shifting from from one segment to the next as it feeds on the sediment, maintaining probably the last segment as a bioirrigated open hole, while in the trapping strategy, the open segments play the role of a trap to catch meiofauna, or playing the role a farm for microbes that are periodically scraped from the walls (Rindsberg and Kopaska-Merkel, 2005). The structure reported herein could be a piece of evidence of the potential presence of organism able to migrate laterally and perhaps vertically to reach food resources. **G.** Sp. *corrugatus,* live animals removed from their tubes, stn. G246 SAM and AM W.43887 respectively (Kupriyanova et al., 2015).



Specimen	Length (cm)
s1	0.40
s2	0.30
s3	0.26
s4	0.22
s5	1.05
s6	0.25
s7	0.24
s8	0.26
s9	0.43
s10	0.81
s11	0.23

Figure 3: Tubular like structures at Vera Rubin Ridge, and pictorial data points employed by Baucon et al., (2020).

Figure 3 Analysis: Tubular like structures at Vera Rubin Ridge, Mars and processing to Length analysis map. (Baucon et al., 2020). Sol 1905, Outcrop imaged by rover Curiosity using MAHLI at Vera Rubin Ridge, Mars presented Labels indicate individual specimens of stick-like structures (Baucon et al., 2020). Anyhow, further analysis regards same specimen interpreted as mold likes Ichno fossils (Sun et al., 2012; Magdalena et al., 2019; Joseph et al., 2020a, 2021). Image credit: NASA/JPL-Caltech/MSSS.

The odd tubular structures that Curiosity has been investigating lately were probably formed by crystal growth that can be suspected. Considering the mineralogical context (*Table 2,3,4)***;** it is likely minerals contributed to the extreme fossilized process (Christensen et al., 2004; Blake et al., 2013; Baucon et al., 2020). Therefore, mineralization may have led to the compartmental crystal formation in the body of the tube worms on Mars (Joseph et al. 2021a,b) as well as Earth (Chan, 2015).

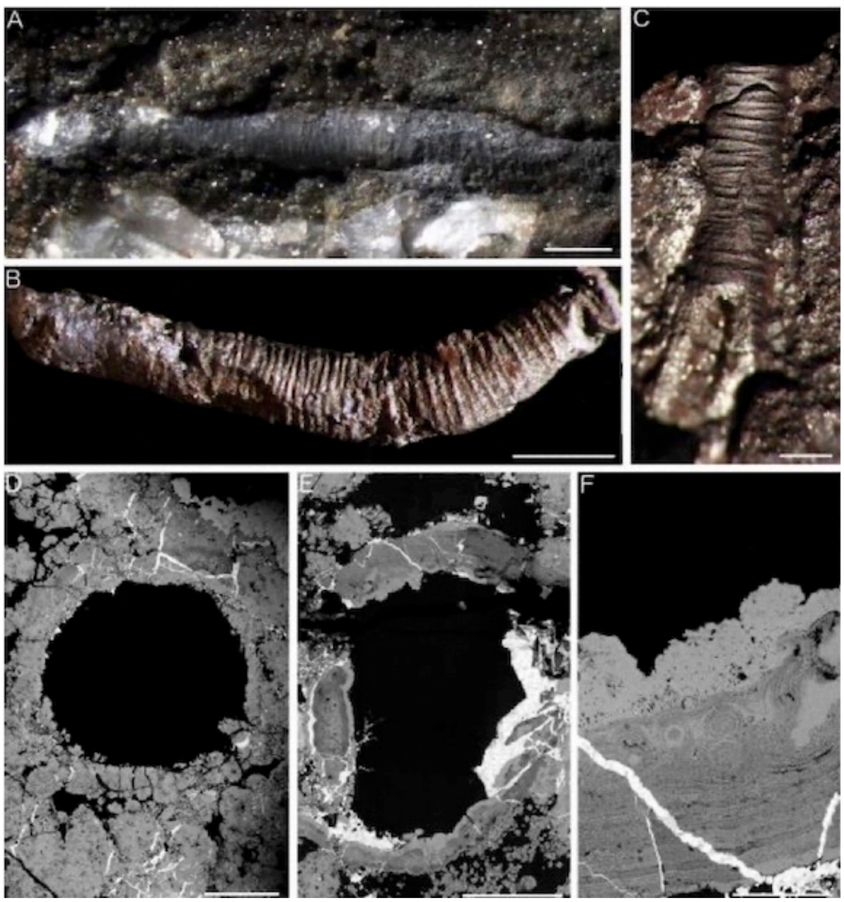


Figure 4: Tube worms from Earth**:** *Eoalvinellodes annulatus*, Silurian, Yaman Kasy, Russia. **A–C**, NHMUK OR1388a, NHMUK VF52 and NHMUK VF53, respectively, hand specimens of gently curving tubes with folded fabric-like tube wall texture. **D, E**, UL YKB1, transverse sections of tubes showing thick walls with thick, possibly multi-layered walls. **F**, UL YKB1, detail of tube wall in transverse section showing preservation by colloform pyrite many layers thick. **Scale bars**: A, B =2mm | C =1mm D & E= 500 μm ; F= 100 μm. (Sun j et al., 2012; Magdalena et al., 2019).

Figure 5: Tube worms and worm tubes from Earth**:** Morphology of tubes made by annelid lineages occurring at modern hydrothermal vents and cold seeps. **A**, disorganized tubes of *Alvinella* spp. (Alvinellidae). **B**, agglutinated tube of *Mesochaetopterus taylori* (Chaetopteridae). **C**, agglutinated Sabellidae tube. **D**, branched tube of *Phyllochaetopterus claparedii* (Chaetopteridae). **E**, segmented tubes of *Spiochaetopterus costarum* (Chaetopteridae). **F**, *Phyllochaetopterus polus* (Chaetopteridae) tubes bearing short collars and wrinkled-fabric ornamentation. **G**, collared Serpulidae tubes (likely *Serpula narconensis*). **H**, collared tubes of *Serpula vermicularis* (Serpulidae). **I**, large tube of the vestimentiferan *Riftia pachyptila* (Siboglinidae). **Scale bars**: A, B =2mm | C =1mm D & E= 500 μm ; F= 100 μm. (Sun j.et al., presented mold likes Ichno fossils. (Baucon et al., 2020; Joseph et al., 2020a, 2021a).

Figure 6: Tube worms and worm tubes from Earth: Tubes from the Turonian of Cyprus. **A–C**, 'Troodos collared tubes'; **A, B**, Kambia 4061 and Memi 212b2, respectively, sinuous worm tubes with collars; **C**, Kambia 401b, worm tube with collar attached at an oblique angle. **D, E**, 'Troodos wrinkled tubes', Kapedhes 2101 and 204b, respectively, worm tubes bearing longitudinal and transverse wrinkles. **F, G,** 'Troodos attached tubes', Memi 2021 and Kinousa 2023, respectively, sinuous tubes that appear attached to a surface, tubes in **F** bearing fine parallel transverse wrinkles. **Scale bars**: A–D, F,G = 1 mm; E = 0. 5 mm. (Sun J et al., 2012; Magdalena et al., 2019).

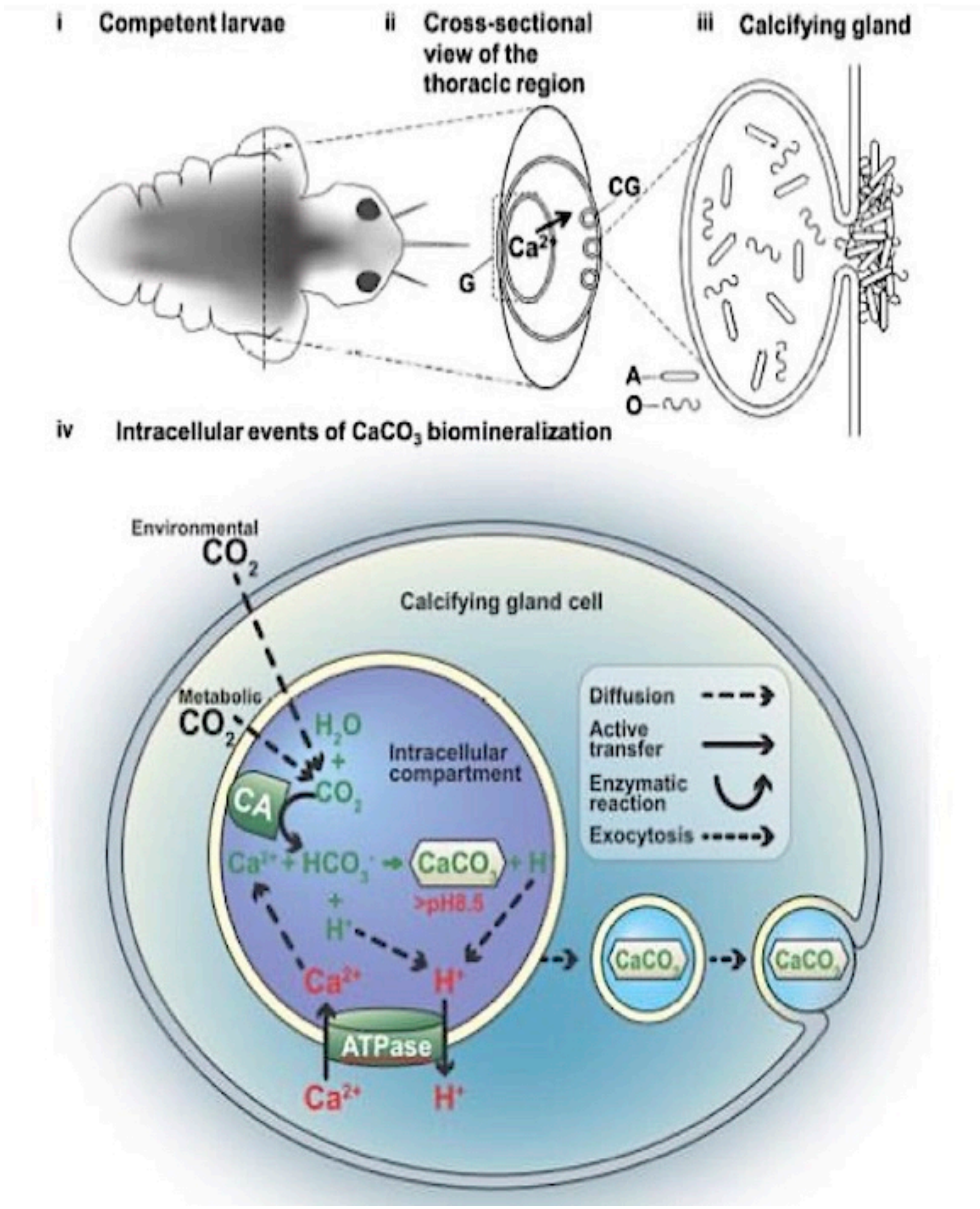


Figure 7: Tube worm in Earth as an analog**:** A hypothetical model of the compartmental crystal formation in the body of the tube worm (Chan, 2015).

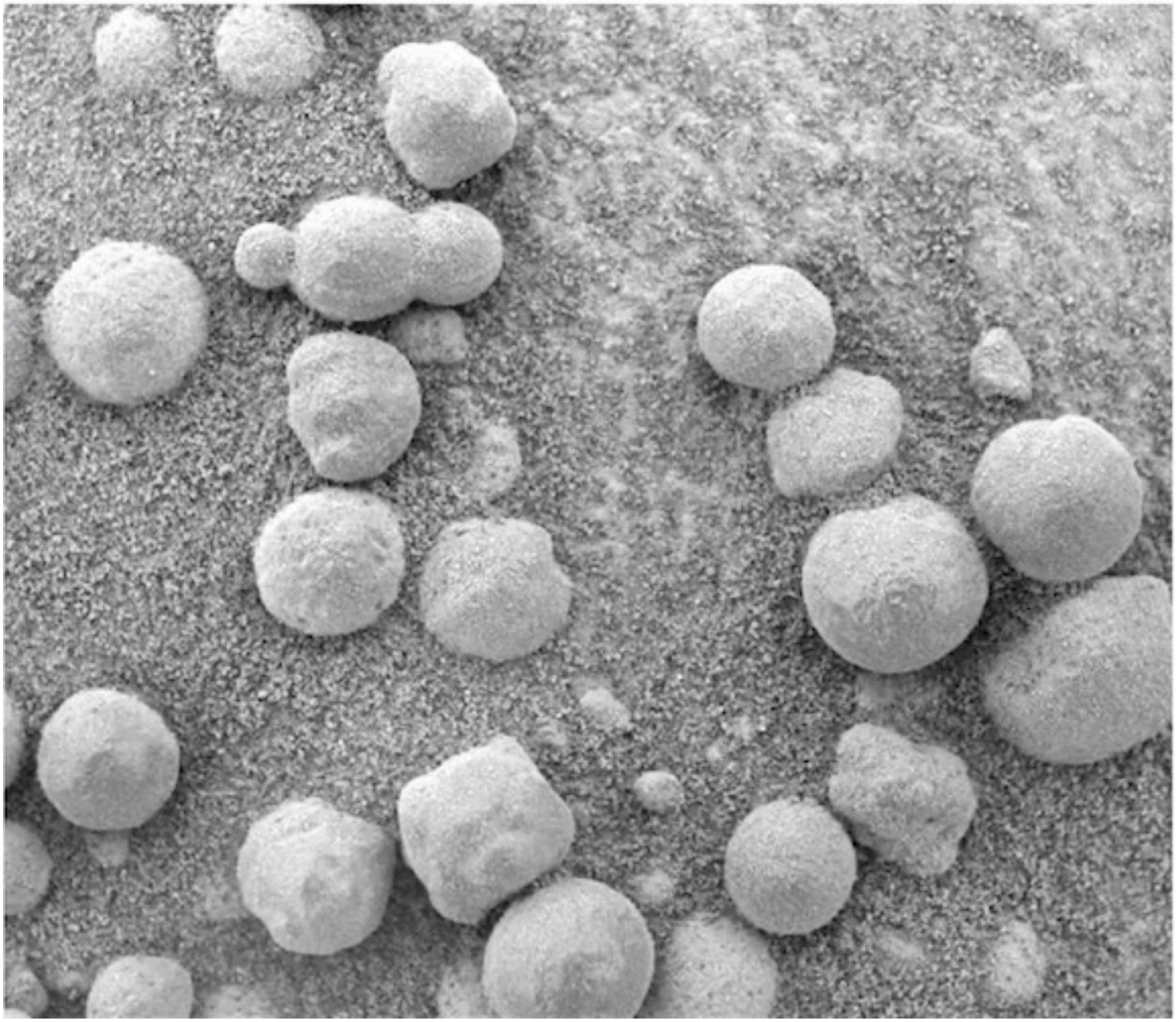


Figure 8: Spherical formations that have been identified as hematite spheres, tektites, lapilli, and fungal puffballs. Photographed on a rocky outcrop at Eagle Crater (NASA/JPL/Cornell/USGS 2008).

Figure 8 Analysis: Spherical specimens upon the surface were photographed by the rover Opportunity which Squyres et al., (2004) and Christianson (2004) identified as spherical hematite. Other investigators have disputed this interpretation and suggested these spheres may include tektites, lapili, soil concretions (Robbins, 2021) and spherical puffballs (Armstrong, 2021a; Dass, 2017; Joseph et al. 2020a,b,, 2021c; Joseph 2014, 2016, 2021). It is well stablished that terrestrial tektites, lapilli, soil concretions and hematite are infiltrated with bacteria and fungi (Joseph et al. 2019; Robbins, 2021).

The shape of spherules is presented in Figure 8, can also be result of weathering erosion and deposition. There is also evidence of a *Spirobranchus* sp and *Coprinisphaera* sp. process of borrowing of structural formation like a "berries" as a part of habitat? The same may be true of some of the tubular specimens identified by Joseph et al. (2021). The spheres and the tubular structures may be contaminated or consist of anhydrite, kieserite, hexahydrite, bischofite, vanthoffite like minerals as a primary formation and includes CaO, MgO (Tables 2 & 4). However, the tubular formations are completely different from what may be hematite spherules. Moreover, whereas many of these minerals are associated with the biological activity of tube worms that have colonized hydrothermal vents, hematite is a major iron-bearing element, which, however, are also formed in heated pools of water (Misra et al., 2018). If the spheres are hematite, they support the hypothesis that Eagle and Endeavor Crater hosted lakes of water that were heated by hydrothermal vents that may have been colonized by tube worms.

4. Discussion: Mineralogy, Chemistry, Hydrothermal Vents, Tube Worm Fossils on Mars

Baucon et al., (2017) have critically reviewed the concepts of ichnological fossils and the tools necessary for the search for extra-terrestrial life, highlighting a new direction of astrobiological research. They argued that these and other biogenic-like structures may serve as biosignatures for past and present extra-terrestrials life. Subsequently, following the observation of what may be tubular fossils in Gale Crater by DiGregorio (2018), Baucon et al., (2020), Joseph et al. (2020a, 2021b) and Armstrong (2021a) performed complex comparative analysis of these specimens and those of Earth and concluded they were similar to terrestrial fossils. Moreover, Joseph et al. (2021a) summarized and documented that the mineralogy and chemistry of Endurance Crater and its outcrops, is similar and in many respects identical to that of terrestrial hydrothermal vents that have been colonized by tube worms and their symbiotes. Therefore, these are likely tube worms that have been mineralized and fossilized.

CheMin data (Tables 2-4) at Meridiani Planum, shows concentration mean value abundancy of associate sulfur and hematite is approximately 49.2% from 13 numbered samples (Christensen et al., 2004). Therefore, the conditions in Meridiani Planum are ideal for the preservation of micro fossils via association of sulfurization and ionization and synchronizing with SiO_2(45.7) CaO (6.93), MgO (7.38) (Tables 1-4). Joseph et al (2021) argues that this mineralogy is also typical of hydrothermal vents that have been colonized by tube worms. Christensen et al., (2004) and Squyers et al. (2004) also believe this area once hosted lakes and hydrothermal vents that were inhabited. Joseph et al. (2021) has suggested that the tubular formations are in fact tube worms and worm tubes, and that the former may be "dormant" "mineralized" or "pickled" by their salty briny watery environment. Based on the petrological analysis and summation of minerals reported here, we concur that Endurance crater was habitable and inhabited by tubular organisms that became mineralized and fossilized. Further, as based on Table1, 2 & 4

(Ulyanova et al., 2015), the high concentration of sulfur in the form of calcium and magnesium sulfates and given the history of Endeavor crater, we hypothesize that tube worms flourished and became fossilized in the ancient past; and we note the resemblance to fossil worm tubes of Cretaceous age preserved in the Bayda massive sulfide deposit of the Samail ophiolite, Oman (Haymon, 1984; McNamara ME, 2016). The substates and crustose-like rocks in this area are also similar to those of Earth and typical of tube-worm fossilized strata. (Wilson & Jones, 1983).

If there is and/or was life on Mars, there should be substantial evidence of organics. Unfortunately, destruction or transformation of organic compounds may occur in the near-surface environment of Mars either by oxidants present in the regolith that can permeate the subsurface (Biemann et al., 1977; Kounaves et al., 2014) or by ultraviolet and ionizing radiation (Oro & Holzer, 1979; Pavlov et al., 2012).

Based on numerous reports of the sedimentary structures, and what may be organic compounds in ancient sedimentary rocks on Mars that may include polycyclic aromatic hydrocarbons, it is not unreasonable to assume that this refractory organic material, either formed on Mars from igneous, hydrothermal, atmospheric, or biological processes (Shock, 1990; Steele et al., 2012; Sumanarathna, 2019, 2020a,b). Or alternatively, delivered directly to Mars via meteorites, comets, or interplanetary dust particles (Gibson, 1992; Sephton, 2012; Sumanarathna, 2020c).

The ability to detect organic compounds in Martian sedimentary rocks with SAM is a function of their initial abundance and entrainment as the rock formed, the extent of subsequent degradation during diagenesis, exhumation, and exposure to the surface and near-surface, and the volatility/polarity and minimal combustion of products released during pyrolysis (Anderson et al., 2015; Freissinet et al., 2015).

It has been postulated that organic compounds in near-surface rocks may undergo successive oxidation reactions that eventually form metastable benzene carboxylates, including phthalic and mellitic acids (Benner et al., 2000). Energetic cosmic rays can further degrade organics in the top 2 m of the surface (Pavlov et al., 2012). SAM measurements of the abundance of noble gas isotopes in the CB sample (Organic molecules in the Sheepbed Mudstone, Gale Crater, Mars), produced by spallation and neutron capture, established that the mudstone analyzed was exposed to cosmic radiation for ~78 Ma (Farley et al., 2014; Freissinet et al., 2015), which could have reduced the abundance of organic matter originally present in sample of CB(Oro & Holzer, 1979; Freissinet et al., 2015).

The widespread presence of chlorine on Mars (Keller et al., 2006) and the detection of perchlorate and/or oxychlorine compounds at two very different locations (Hecht et al., 2009; Glavin et al., 2013) and findings from EETA79001 meteorite (Kounaves et al., 2014) support the hypothesis that oxychlorine compounds may be widely distributed in the regolith of Mars (Christensen et al., 2004; Blake et al., 2013; Sumanarathna, 2020). How much of this material is due to biological process or purely geological activity, is unknown.

5. Conclusions

A number of investigators have provided evidence of what they interpret to be the fossilized remains of tube worms and other metazoans (Armstrong, 2021a; DiGregorio, 2018; Baucon et al., 2020; Elewa, 2021; Joseph et al. 2020a,b, 2021a,b). Many of the compounds ubiquitous on the Martian surface could have played a critical role in the organic preservation state, especially in Meridiani Planum and Gale Crater; the same areas in which these “fossilized” impressions have been discovered. Although these fossilized structures resemble those from Earth, and have been found to be statistically similar, morphologically, if these are in fact fossilized organisms is unknown. What is required is extraction and direct biochemical analysis to confirm the existence of tubular specimen at Meridiani Planum.

There is great debate as to the exact identify of the spherical structures photographed in Meridiani Planum. If they are hematite, this supports the hypothesis that Eagle and Endeavor Crater were inhabited thermally heated lakes. Likewise, the discovery of what be tube worm fossils also support the hydrothermal vent hypothesis (Joseph et al. 2021a,b) whereas the fungal puffball hypothesis (Joseph 2016, 2021a; Dass, 2017; Armstrong 2021b) does not. It is true that Joseph (2021) has shown that the spherules of Mars do not resemble the hematite spherules of Earth. However, this does not rule out or negate the substantial evidence of hematite in the surface. It is also true that some of the important observations of Martian spherules cannot be explained by a concretion model and they have no resemblance to terrestrial hematite. Here, these observations include the following: (1) spherules are size limited, (2) they are located only on the top soil (Figure 8), (3) they show no internal structure, and (4) they lack grains of the host matrix. However, white color eroded-spherules formation that around the area of tubular structure is not similar to hematite spherules due to trace fragments of Figure 2 (Figure 2 interpretation based on data of figure 4,5,6,7 and table 1,2,3,4). It is possible that the spherules include hematite, tektites and lapilli and soil concretions (Robbins, 2021). Moreover, if Joseph et al (2021a,b) is correct in their identification of what may be tube worms, then it is logical to assume that hematite spherules were also fashioned in these hydrothermal vents, and were formed via the accretion and rotation of solid particles with the liquid water (Hypothesis of “Weli-Thalapa” formation on Mars).

We conclude that the evidence supports the hypothesis that hematite spherules were fashioned within thermally heated bodies of water which were inhabited by tube worms.

REFERENCES

Anderson, M. S., Andringa, J. M., Carlson, R. W., Conrad, P., Hartford, W., Shafer, M., ... & Hand, K. (2005). Fourier transform infrared spectroscopy for Mars science. *Review of Scientific Instruments*, *76*(3), 034101.

Armstrong, R. (2021a). Statistical Analysis Of 'Tube-Like' Structures On Mars Photographed By Curiosity And Opportunity And Comparison With Putative Terrestrial Analogues, Journal of Astrobiology, Vol 10, 11-26.

Armstrong, R. (2021b). Martian Spheroids: Statistical Comparisons with Terrestrial Hematite ('Moqui Balls') and Podetia of the Lichen Dibaeis Baeomyces, Journal of Astrobiology, Vol 7, 15-23.

Baucon, A., de Carvalho, C.N., Barbieri, R., Bernardini, F., Cavalazzi, B., Celani, A., Felletti, F., Ferretti, A., Schönlaub, H.P., Todaro, A., & Tuniz, C. (2017). Organism-substrate interactions and astrobiology: Potential, models and methods. Earth-Science Reviews, 171, 141-180. https://doi.org/10.1016/j.earscirev.2017.05.009

Baucon, A., Neto De Carvalho, C., Felletti, F., & Cabella, R. (2020). Ichnofossils, cracks or crystals? A test for biogenicity of stick-like structures from Vera Rubin Ridge, Mars. *Geosciences*, *10*(2), 39.

Benner, S. A., Devine, K. G., Matveeva, L. N., & Powell, D. H. (2000). The missing organic molecules on Mars. *Proceedings of the National Academy of Sciences*, *97*(6), 2425-2430.

Bianciardi, G., Rizzo, V., Cantasano, N. (2014). Opportunity Rover's image analysis: Microbialites on Mars? International Journal of Aeronautical and Space Sciences, 15 (4) 419-433.

Bianciardi, G., Nicolò, T., Bianciardi, L. (2021). Evidence of Martian Microalgae at the Pahrump Hills Field Site. A Morphometric Analysis. Journal of Astrobiology, Vol 7, 70-79.

Biemann, K., Oro, J. I. I. I. P. T., Toulmin III, P., Orgel, L. E., Nier, A. O., Anderson, D. M., ... & Lafleur, A. L. (1977). The search for organic substances and inorganic volatile compounds in the surface of Mars. *Journal of Geophysical Research*, *82*(28), 4641-4658.

Blake, D. F., Morris, R. V., Kocurek, G., Morrison, S. M., Downs, R. T., Bish, D., ... & Sarrazin, P. (2013). Curiosity at Gale crater, Mars: Characterization and analysis of the Rocknest sand shadow. *Science*, *341*(6153).

Chan, V., Toyofuku, T., Wetzel, G., Saraf, L., Thiyagarajan, V., & Mount, A. S. (2015). Direct deposition of crystalline aragonite in the controlled biomineralization of the calcareous tubeworm. *Frontiers in Marine Science*, *2*, 97.

Cantil, L. F., Sánchez, M. V., Bellosi, E. S., González, M. G., Sarzetti, L. C., & Genise, J. F. (2013). Coprinisphaera akatanka isp. nov.: the first fossil brood ball attributable to necrophagous dung beetles associated with an Early Pleistocene environmental stress in the Pampean region (Argentina). Palaeogeography, Palaeoclimatology, Palaeoecology, 386, 541–554.

Christensen, P. R., Wyatt, M. B., Glotch, T. D., Rogers, A. D., Anwar, S., Arvidson, R. E., ... & Wolff, M. J. (2004). Mineralogy at Meridiani Planum from the Mini-TES experiment on the Opportunity Rover. *Science*, *306*(5702), 1733-1739. Christensen, P. R., Jakosky, B. M., Kieffer, H. H., Malin, M. C., McSween, H. Y., Nealson, K., ... & Ravine, M. (2004). The thermal emission imaging system (THEMIS) for the Mars 2001 Odyssey Mission. *Space Science Reviews*, *110*(1), 85-130.

Christensen, P.R., N.S. Gorelick, G.L. Mehall, and K.C. Murray, THEMIS Public Data Releases, Planetary Data System node, Arizona State University, <http://themis-data.asu.edu>.

Cino, C., Dehouck, E., & McLennan, S. (2017). Geochemical constraints on the presence clay minerals in the Burns formation, Meridiani Planum, Mars. *Icarus*, *281*, 137–150. https://doi.org/10.1016/j.icarus.2016.08.029

Cockell, C. S., Schuerger, A. C., Billi, D., Friedmann, E. I., & Panitz, C. (2005). Effects of a simulated martian UV flux on the cyanobacterium, Chroococcidiopsis sp. 029. *Astrobiology*, *5*(2), 127-140.

Colín-García, M., Heredia, A., Cordero, G., Camprubí, A., Negrón-Mendoza, A., Ortega-Gutiérrez, F., ... & Ramos-Bernal, S. (2016). Hydrothermal vents and prebiotic chemistry: a review. *Boletín de la Sociedad Geológica Mexicana*, *68*(3), 599-620.

Dass, R.S. (2017). The high probability of life on Mars: A brief review of the evidence. Cosmology 27.

DiGregorio, B. (2018, October). Ichnological evidence for bioturbation in an ancient lake at Vera Rubin Ridge, Gale Crater, Mars. In *Proceedings of the 3rd International Convention on Geosciences and Remote Sensing* (Vol. 19, p. 20).

Ehlmann, B. L., Mustard, J. F., Murchie, S. L., Bibring, J. P., Meunier, A., Fraeman, A. A., & Langevin, Y. (2011).
Subsurface water and clay mineral formation during the early history of Mars. Nature, 479(7371), 53-60.

Elewa, A.M.T, (2021) Fossils on Mars. Journal of Astrobiology, Vol 7.

Farley, K. A., Malespin, C., Mahaffy, P., Grotzinger, J. P., Vasconcelos, P. M., Milliken, R. E. et al. (2014). In situ radiometric and exposure age dating of the Martian surface, Science, 343.

Fergason, R. L., Christensen, P. R., & Kieffer, H. H. (2006). High-resolution thermal inertia derived from the Thermal Emission Imaging System (THEMIS): Thermal model and applications. Journal of Geophysical Research: Planets, 111(E12).

Frenguelli, J., (1938). Nidi fossili di Scarabeidi e Vespidi. Bolletino della Società Geologica Italiana 57, 77–96.

Freissinet, C., Glavin, D. P., Mahaffy, P. R., Miller, K. E., Eigenbrode, J. L., Summons, R. E., ... & MSL Science Team. (2015). Organic molecules in the sheepbed mudstone, gale crater, mars. Journal of Geophysical Research: Planets, 120(3), 495-514.

Georgieva, M. N., Little, C. T., Watson, J. S., Sephton, M. A., Ball, A. D., & Glover, A. G. (2019). Identification of fossil worm tubes from Phanerozoic hydrothermal vents and cold seeps. *Journal of Systematic Palaeontology*, *17*(4), 287-329.

Gibson Jr, E. K. (1992). Volatiles in interplanetary dust particles: A review. *Journal of Geophysical Research: Planets*, *97*(E3), 3865-3875.

Glavin, D. P., Cleaves, H. J., Schubert, M., Aubrey, A., & Bada, J. L. (2004). New method for estimating bacterial cell abundances in natural samples by use of sublimation. *Applied and Environmental Microbiology*, *70*(10), 5923-5928.

Grotzinger, J. P., Gupta, S., Malin, M. C., Rubin, D. M., Schieber, J., Siebach, K., ... & Wilson, S. A. (2015). Deposition, exhumation, and paleoclimate of an ancient lake deposit, Gale crater, Mars. *Science*, *350*(6257).

Grotzinger, J. P., Sumner, D. Y., Kah, L. C., Stack, K., Gupta, S., Edgar, L., ... & Yingst, A. (2014). A habitable fluvio-lacustrine environment at Yellowknife Bay, Gale Crater, Mars. *Science*, *343*(6169).

Heer, O. von (1877). Flora fossilis Helvetiae. Die vorweltliche Flora der Schweiz. p. 182.

Julie, H. & Brock, B., (1985). Polychaetes from Fijian Coral Reefs. Pacific Science | The University of Hawaii Press, 39(02), 195–220.

Haymon, R. M., Koski, R. A., & Sinclair, C. (1984). Fossils of hydrothermal vent worms from Cretaceous sulfide ores of the Samail Ophiolite, Oman. *Science*, *223*(4643), 1407-1409.

Hecht, M. H., Kounaves, S. P., Quinn, R. C., West, S. J., Young, S. M. M., Ming, D. W., ... & Smith, P. H. (2009). Detection of perchlorate and the soluble chemistry of martian soil at the Phoenix lander site. *Science*, *325*(5936), 64-67.

Joseph, R. (2014). Life on Mars: Lichens, Fungi, Algae, Cosmology, 22, 40-62.

Joseph, R., 2016). A high probability of life on Mars, the consensus of 70 experts. Cosmology, 25, pp.1-25.

Joseph, R. (2021). Lichens on Mars vs the Hematite Hoax. Why Life Flourishes on the Radiation- Iron-Rich Red Planet, The Journal of Cosmology, 30, 2021, 1-102

Joseph, R.G., Duxbury, N.S. Kidron, G.J. Gibson, C.H., Schild, R. (2020b) Mars: Life, Subglacial Oceans, Abiogenic Photosynthesis, Seasonal Increases and Replenishment of Atmospheric Oxygen, Open Astronomy, 2020, 29, 1, 189-209.

Joseph, R. Graham, L., Budel, B., Jung, P., Kidron, G. J., Latif, K., Armstrong, R. A., Mansour, H. A., Ray, J. G., Ramos, G.J.P., Consorti, L., Rizzo, V., Gibson, C.H., Schild, R. (2020c). Mars: Algae, Lichens, Fossils, Minerals, Microbial Mats and Stromatolites, in Gale Crater. Journal of Astrobiology and Space Science Reviews, 3 (1); 40-111, ISSN 2642-228X, DOI: 10.37720/jassr.03082020.

Joseph, R.G., Armstrong RA, Latif K, Elewa, A.M.T., Gibson CH, Schild R (2020a). Metazoans on Mars? Statistical quantitative morphological analysis of fossil-like features in Gale crater. J Cosmology, 29: 440-475.

Joseph, R. J., Graham, L., Büdel, B., Jung, P., Kidron, G. J., Latif, K., ... & Schild, R. (2020b). Mars: Algae, Lichens, Fossils, Minerals, Microbial Mats, and Stromatolites in Gale Crater. *Journal of Astrobiology and Space Science Reviews*, *3*(1), 40-111.

Joseph, R., Planchon, O., Duxbury, N.S., Latif, K., Kidron, G.J., Consorti, L., Armstrong, R. A., Gibson, C. H., Schild, R., (2020d). Oceans, Lakes and Stromatolites on Mars, Advances in Astronomy, 2020, doi.org/10.1155/2020/6959532

Joseph, R., Armstrong R.A., Wei, X., Gibson, C., Planchon, O., Duvall, D., Elewa, A.M.T., Duxbury, N., Rabb, H., Latif, K., Schild, R. (2021a). Fungi on Mars? Evidence of Growth and Behavior From Sequential Images.

Astrobiology Research Report, 5/1/2021, ResearchGate.net https://www.researchgate.net/publication/351252619. Journal of Cosmology, 30: 440-475.

Joseph, R., et al. (2021b) Tube Worms, Hydrothermal Vents, Life On Mars? A Comparative Morphological Analysis Journal of Astrobiology, 8.

Joseph, R. et al. (2021c). Life in the Extreme Environments of Mars: Tube Worms, Subsurface Aquifers, Hydrothermal Vents, Endurance Crater , Journal of Cosmology, 31, 157-200.

Joseph, R. G., Armstrong, R., Kidron, G. J., Latif, K., Planchon, O., Duvall, D., ... & Schild, R. (2021d). Proof of Life on Mars in 200 Pictures: Algae, Microbial Mats, Stromatolites, Lichens, Fungus, Fossils, Growth, Movement, Spores and Reproductive Behavior. *Journal of Cosmology*, *30*(4), 1-154.

Kaźmierczak, J., (2016). Ancient Martian biomorphs from the rim of Endeavour Crater: similarities with fossil terrestrial microalgae. In book: Paleontology, Stratigraphy, Astrobiology, in commemoration of 80th anniversary of A. Yu. Rozanov, Publisher: Borissiak Paleontological Institute RAS, Moscow, Editor: S.V. Rozhnov, pp. 229-242.

Kazmierczak, J. (2020). Conceivable Microalgae-like Ancient Martian Fossils and Terran Ana- logues:MER Opportunity Heritage. Astrobiol Outreach 8: 167. DOI: 10.4172/2332-2519.1000167.

Keller, J. M., Boynton, W. V., Karunatillake, S., Baker, V. R., Dohm, J. M., Evans, L. G., ... & Williams, R. M. S. (2006). Equatorial and midlatitude distribution of chlorine measured by Mars Odyssey GRS. *Journal of Geophysical Research: Planets*, *111*(E3).

Kounaves, S. P., Carrier, B. L., O'Neil, G. D., Stroble, S. T., & Claire, M. W. (2014). Evidence of martian perchlorate, chlorate, and nitrate in Mars meteorite EETA79001: Implications for oxidants and organics. *Icarus*, *229*, 206-213.

Kuhn, T., Herzig, P. M., Hannington, M. D., Garbe-Schönberg, D., & Stoffers, P. (2003). Origin of fluids and anhydrite precipitation in the sediment-hosted Grimsey hydrothermal field north of Iceland. *Chemical Geology*, *202*(1-2), 5-21.

Kupriyanova, E. K., Sun, Y., Ten Hove, H. A., Wong, E., & Rouse, G. W. (2015). Serpulidae (Annelida) of Lizard Island, Great Barrier Reef, Australia. *Zootaxa*, 4019(1), pp. 275-353: 329-331.

Latif, K., Ray, J.G., Planchon, O. (2021). Algae on Mars: A Summary of the Evidence. Journal of Astrobiology, 7, 22-28.

Laza, J. H. (2006). Dung-beetle fossil brood balls: the Ichnogenera *Coprinisphaera* Sauer and *Quirogaichnus* (Coprinisphaeridae). Ichnos 13, 217–235.

Macey, M. C., Fox-Powell, M., Ramkissoon, N. K., Stephens, B. P., Barton, T., Schwenzer, S. P., ... & Olsson-Francis, K. (2020). The identification of sulfide oxidation as a potential metabolism driving primary production on late Noachian Mars. *Scientific reports*, *10*(1), 1-13.

Mahaney, W. C., & Dohm, J. (2010). Life on Mars? Microbes in Mars-like antarctic environments. *Journal of Cosmology*, *5*, 951-958.

McKay, D. S., Gibson, E. K., Thomas-Keprta, K. L., Vali, H., Romanek, C. S., Clemett, S. J., ... & Zare, R. N. (1996). Search for past life on Mars: Possible relic biogenic activity in Martian meteorite ALH84001. *Science*, *273*(5277), 924-930.

McKay, D. S., Thomas-Keprta, K. L., Clemett, S. J., Gibson Jr, E. K., Spencer, L., & Wentworth, S. J. (2009). Life on Mars: new evidence from martian meteorites. In *Instruments and Methods for Astrobiology and Planetary Missions XII* (Vol. 7441, p. 744102). International Society for Optics and Photonics.

McNamara, M. E., Van Dongen, B. E., Lockyer, N. P., Bull, I. D., & Orr, P. J. (2016). Fossilization of melanosomes via sulfurization. *Palaeontology*, *59*(3), 337-350.

Mikulas, R., & Genise, J. F. (2003). Traces within traces: holes, pits and galleries in walls and fillings of insect trace fossils in paleosols. Geologica Acta, 1, 4, 339-348.

Miller, S. A., (1889). North American geology and palaeontology for the use of amateurs, students and scientists: Cincinnati, Ohio, Western Methodist Book Concern, 664 pp.

Misra, A. K., & Acosta-Maeda, T. E. (2018). Hematite Spherules on Mars. In *Mineralogy-Significance and Applications* (p. 1). IntechOpen.

Missions, 7441, 744102. N.A.S.A.J.P.L.-C.A.S.U. (2012b, April 1). Meridiani Planum. NASA's Mars Exploration Program. https://mars.nasa.gov/resources/5260/meridiani-planum

N.A.S.A.J.P.L.C.U.S.G.S. (2008, April 8). Mars Exploration Rover | Blueberries" (Hematite Spheres). The National Aeronautics and Space Administration https://mars.nasa.gov/mer/gallery/all/1/m/046/1M132266947EFF05AMP2987M2M1.HTML

Oro, J., & Holzer, G. (1979). The photolytic degradation and oxidation of organic compounds under simulated martian conditions. *Journal of Molecular Evolution*, *14*(1), 153-160.

Osman, S., Peeters, Z., La Duc, M. T., Mancinelli, R., Ehrenfreund, P., & Venkateswaran, K. (2008). Effect of shadowing on survival of bacteria under conditions simulating the Martian atmosphere and UV radiation. *Applied and Environmental Microbiology*, *74*(4), 959-970.

Pacelli, C., Selbmann, L., Zucconi, L., De Vera, J. P., Rabbow, E., Horneck, G., ... & Onofri, S. (2017). BIOMEX experiment: ultrastructural alterations, molecular damage and survival of the fungus Cryomyces antarcticus after the experiment verification tests. *Origins of Life and Evolution of Biospheres*, *47*(2), 187-202.

Pavlov, A. A., Vasilyev, G., Ostryakov, V. M., Pavlov, A. K., & Mahaffy, P. (2012). Degradation of the organic molecules in the shallow subsurface of Mars due to irradiation by cosmic rays. *Geophysical research letters*, *39*(13).

Rindsberg, A. K., & Kopaska-Merkel, D. C., (2005). *Treptichnus* and *Arenicolites* from the Steven C. Minkin Paleozoic Footprint Site (Langsettian, Alabama, USA). In: Buta, R. J., Rindsberg, A. K., and Kopaska-Merkel, D. C., (eds.), Pennsylvanian Footprints in the Black Warrior Basin of Alabama. Alabama Paleontological Society Monograph no. 1, 121-141.

Robbins, E.I. (2021). Martian Spheres Resemble Biological/Terrestrial Soil Concretions. Journal of Astrobiology, Vol 7, 11-14.

Roselli, F. L. (1939). Apuntes de geología y paleontología uruguaya. Sobre insectos del Cretácico del Uruguay o descubrimiento de admirables instintos constructivos de esa época. Boletín de la Sociedad Amigos de las Ciencias Naturales "Kraglievich- Fontana" 1, 72–102.

Sánchez, M. V., Genise, J. F., Bellosi, E. S., Román-Carrión, J. L., & Cantil, L. F., (2013). Dung beetle brood balls from Pleistocene highland palaeosols of Andean Ecuador: A reassessment of Sauer's *Coprinisphaera* and their palaeoenvironments. Palaeogeography, Palaeoclimatology, Palaeoecology 386, 257–274.

Sánchez, M. V. & Genise, J. F. (2015). The Brood Ball of *Canthon (Canthon) Lituratus* Germar (Coleoptera: Scarabaeidae: Scarabaeinae) and Its Fossil Counterpart *Coprinisphaera cotiae* Sánchez and Genise New Ichnospecies, with a Brief Review of South American Fossil Brood Balls. The Coleopterists Bulletin, 69(1), 73–82. http://dx.doi.org/10.1649/0010-065X-69.1.73.

Sauer, W., (1955). Coprinisphaera ecuadoriensis, un fósil singular del Pleistoceno. Boletín del Instituto de Ciencias Naturales del Ecuador 1, 123–132.

Sánchez, F. J., Mateo-Martí, E., Raggio, J., Meeßen, J., Martínez-Frías, J., Sancho, L. G., ... & De la Torre, R. (2012). The resistance of the lichen Circinaria gyrosa (nom. provis.) towards simulated Mars conditions—a model test for the survival capacity of an eukaryotic extremophile. *Planetary and Space Science*, *72*(1), 102-110.

Schuerger, A. C., Ming, D. W., & Golden, D. C. (2017). Biotoxicity of Mars soils: 2. Survival of Bacillus subtilis and Enterococcus faecalis in aqueous extracts derived from six Mars analog soils. *Icarus*, *290*, 215-223.

Selbmann, L., Zucconi, L., Isola, D., & Onofri, S. (2015). Rock black fungi: excellence in the extremes, from the Antarctic to space. *Current Genetics*, *61*(3), 335-345.

Sephton, M. A. (2012). Pyrolysis and mass spectrometry studies of meteoritic organic matter. *Mass spectrometry reviews*, *31*(5), 560-569.

Shock, E. L. (1990). Geochemical constraints on the origin of organic compounds in hydrothermal systems. *Origins of Life and Evolution of the Biosphere*, *20*(3), 331-367.

Steele, A., McCubbin, F. M., Fries, M., Kater, L., Boctor, N. Z., Fogel, M. L., ... & Jull, A. J. T. (2012). A reduced organic carbon component in martian basalts. *Science*, *337*(6091), 212-215.

Sumanarathna, A. R. (2015). Paleontological Evidences of Pleistocene, Interpret The Coming of Intelligence & Harbor Life of Planet Earth. https://www.Researchgate.Net/Publication/305766047_Paleontological_Evidences_of_Pleistocene_Interpret_The_Coming_of_Intelligence_Harbor_Life_of_Planet_Earth

Sumanarathna, A. R., Katupotha, J., Abeywardhana, K., & Madurapperuma, B. (2017). Extinction of Quaternary

Mammalian Habitats of Megafauna in Sabaragamuwa Basin, Sri Lanka. *Journal of Eco Astronomy*, Vol 01, Issue 01, PP 16- 31.

Sumanarathna, A.R. (2018). Union of General Theory - Eco Astronomy Mechanics & Concepts. *Journal of Astronomy*. https://www.researchgate.net/publication/324168160_Union_of_General_Theory_-_Eco_Astronomy_Mechanics_Concepts

Sumanarathna, A. R. (2019). Introduction to Eco Astronomy [Slides]. Grand Day of Eco Astronomy| The Royal Society | *Research Gate*.
https://www.researchgate.net/publication/334289343_Introduction_to_Eco_Astronomy

Sumanarathna, A. R. (2020). An Introduction to Geology of Mars [Slides]. *Research Gate*. https://www.researchgate.net/publication/341201935_An_Introduction_to_Geology_Of_Mars

Sumanarathna, A. R. (2020a). Theories on the Origin of Life & Panspermia: Astrobiology [Slides]. AbSciCon 2015: Online: Nasa Astrobiology Institute | DOI: 10.13140/RG.2.2.30214.52801 | *ResearchGate*. https://www.researchgate.net/publication/340827247_Theories_on_the_Origin_of_Life_Panspermia_Astrobiology

Sumanarathna, A. R. (2020b). Planetary Habitability: Earth Like Planet to Universe [Slides]. *Grand Day of Eco Astronomy: American Journal Experts* | DOI: 10.13140/RG.2.2.32516.48007 |*Research Gate*. https://www.researchgate.net/publication/340768680_Planetary_Habitability_Earth_Like_Planet_to_Universe/citations

Sumanarathna, A. R. (2020c). Meteorites: An introduction to Astrobiology & Concepts 02 [Slides]. *Grand Day of Eco Astronomy* | DOI: 10.13140/RG.2.2.17482.52160 | *Research Gate*. https://www.researchgate.net/publication/340730565_Meteorites_An_introduction_to_Astrobiology_Concepts_02

Squyres, S. W., & Knoll, A. H. (2005). Sedimentary rocks at Meridiani Planum: Origin, diagenesis, and implications for life on Mars. *Earth and Planetary Science Letters*, *240*(1), 1-10.

Squyres, S. W., Grotzinger, J. P., Arvidson, R. E., Bell, J. F., Calvin, W., Christensen, P. R., ... & Soderblom, L. A. (2004). In situ evidence for an ancient aqueous environment at Meridiani Planum, Mars. *science*, *306*(5702), 1709-1714.

Sun, Y., Ten Hove, H. A., & Qiu, J. W. (2012). Serpulidae (Annelida: Polychaeta) from Hong Kong. *Zootaxa*, *3424*(1), 1-42.

Thomas, M., Clarke, J. D. A., & Pain, C. F. (2005). Weathering, erosion and landscape processes on Mars identified from recent rover imagery, and possible Earth analogues. *Australian Journal of Earth Sciences*, *52*(3), 365-378.

Thomas-Keprta, K. L., Clemett, S. J., Mckay, D. S., Gibson, E. K., & Wentworth, S. J. (2009). Origins of magnetite nanocrystals in Martian meteorite ALH84001. *Geochimica et Cosmochimica Acta*, *73*(21), 6631-6677.

Ulyanova, T. M., Krutko, N. P., Vitiaz, P. A., Ovseenko, L. V., & Titova, L. V. (2015). Heat-Resistant SiO 2–Al 2 O 3–TiO 2 Ceramics with Nanostructured Alumina Filler and Their Properties. In *Nanocomposites, Nanophotonics, Nanobiotechnology, and Applications* (pp. 119-128). Springer, Cham.

Vago, J. L., Westall, F., Coates, A. J., Jaumann, R., Korablev, O., Ciarletti, V., ... & Carreau, C. (2017). Habitability on early Mars and the search for biosignatures with the ExoMars Rover. *Astrobiology*, *17*(6-7), 471-510.

Vago, J.L., Westall, F., Pasteur Instrument Teams, Landing Site Selection Working Group, et al.(2017). Habitability on Early Mars and the Search for Biosignatures with the ExoMars Rover. Astrobiology, 17 (6-7), DOI: 10.1089/ast.2016.1533

Weitz, C. M., Lane, M. D., Staid, M., & Dobrea, E. N. (2008). Gray hematite distribution and formation in Ophir and Candor chasmata. *Journal of Geophysical Research: Planets*, *113*(E2).

Wilson, M. J., & Jones, D. (1983). Lichen weathering of minerals: implications for pedogenesis. *Geological Society, London, Special Publications*, *11*(1), 5-12.

