Statistical Analysis of 'Tube-Like' Structures on Mars Photographed by Curiosity and Opportunity and Comparisons with Terrestrial Analogues

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Abstract

Statistical comparisons were made between various 'tube-like' structures photographed on Mars by Curiosity and Opportunity rovers in Gale and Endurance craters respectively and the worm 'cases' of terrestrial tube worms.Various statistical analyses, including principal components analysis (PCA) based on various metrics, suggested considerable similarities between the Martian tube-like structures and their terrestrial counterparts. Although, statistical comparisons cannot 'prove' that these tube-like structures on Mars represent tube worms, they provide a more objective basis for morphological comparison, thus supporting the conclusions of Joseph et al. (2021a). Given the significance and implications of such data, further observations are urgently needed to increase sample sizes available for statistical study.

Key Words: Martian tube worms, Worm tubes, Fossil tube worms, Principal components analysis (PCA)

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1. Tubular Structures on Mars

Previous studies suggest that on Mars there were lakes of water in Gale and Endurance craters in the past which could have provided a suitable habitat for eukaryotes (Grotzinger et al. 2014; Hynek et al. 2015). Moreover, there is evidence that in Endurance crater, 'salty-brine' conditions (Squyres et al. 2006) heated by hydrothermal vents may have existed, which could have provided an environment for a variety of organisms such as tube worms (Monastersky 2012). Hence, there is considerable interest in a recent article in the Journal of Astrobiology (Joseph et al. 2021a) which reports the presence of tubular structures on Mars which may represent tube worms or the outer cases of tube worms. The tube worm-like structures in Endurance crater are visually and subjectively similar in morphology to terrestrial tube worm that inhabit hydrothermal vents (Becker 2021; Joseph et al. 2021a; Suamanarathna et al. 2021). This interpretation is supported by the presence of holes in the surface which could be the remnants of collapsed hydrothermal vents, the observation of numerous tubular structures adjacent to or within a few centimetres of these holes, and the observation that the mineralogy of Endurance crater and its outcrops are similar to those of terrestrial hydrothermal vents and chimneys (see Joseph et al. 2021a). Previous studies have also described structures resembling fossil tube worms in Gale crater photographed by the Curiosity rover (DiGregorio 2018; Baucon et al. 2020), features which have been subjected to preliminary statistical analysis (Josephs et al. 2020a). The similarity of the tube-worm like structures in Endurance crater to possible terrestrial analogues is based on subjective observation. This present study includes additional specimens, a re-analysis of Gale crater tubular specimens (Joseph et al. 2020), and a statistical comparative analysis of the new tubular specimens photographed in Endurance crater (Joseph et al. 2021a). These analyses were performed to test the hypothesis that the perceived similarities between the Martian tube-like structures and terrestrial tube worms have a statistically significant objective basis. Statistical approaches to comparing Martian features with putative terrestrial analogues have been published previously (Joseph et al. 2020, 2021b; Armstrong 2021; Rizzo et al. 2021).

2. Methods

Photographs of Tubular Formations: The images analysed in this study are listed in Table 1. In the Gale crater study, three types of feature were compared: (1) eight examples of tube-like structures from Mars which may represent the fossils of worm cases; an example of which is shown in Fig 1, (2) two images of terrestrial trace fossils of tube worms, and (3) an image of a pseudofossil resembling fossil tube worms. In the Endurance crater study, three types of feature were compared: (1) five Martian tube-like structures which are shown in Fig 2, (2) an image of agroup of terrestrial tube worm cases (Fig 3 , and (3) four images of terrestrial fossil tube worm cases (Turonian, Cyprus)

Image analysis: Quantitative analysis was carried out using ‘Image J' software developed by the National Institute of Health (NIH), Bethesda, USA (Syed et al. 2000; Girish & Vijayalakshmi 2004). Each image was opened using the software and magnified to clearly reveal the features of interest. Images were manipulated using brightness, contrast, sharpening, and if necessary edge detection, to optimize the appearance of the features.

Data Collection: It is difficult to establish an absolute scale measure for all images to enable accurate comparisons of metrics. As a consequence, all metrics were based either on degree of variation such as the coefficient of variation (CV); a measure of variation independent of the mean, or the ratios of different measurements, e.g., total length to width, which do not depend on establishing an accurate absolute scale. In the Gale crater study, both the Martian and terrestrial specimens consist of filaments each comprising a number of often distinct segments connected together and exhibiting multiple changes in direction (Fig 1). The following data were obtained from each of these ‘filaments’: (1) total number of segments, (2) the number of directional changes along the filament per segment, (3) the length of each segment in arbitrary units, and (4) the width of each segment measured from 3 – 8 randomly located positions along its length, (5) the shortest distance between the two ends of the filament, and (6) the angle between each pair of adjacent segments. In the Endurance crater study, the following data were obtained from each tube case: (1) variation in the width of the case measured from 5 – 13 randomly located positions along its length, (2) the shortest distance between the two visible ends of the case, and (3) the width of the 'opening' at the end of the case.

Table 1. Details of images analyzed. All figure numbers refer to images in Joseph et al. 2020, 2021a.

Study	*Origin*	*Images*
Gale crater	Mars (Curiosity)	Sols 1905, 1923; Josephs et al. 2020, Fig 7
	Terrestrial trace fossils	Josephs et al 2020, Fig 6
	Pseudofossil	Hänzschel 1975, Joseph et al. 2020, Fig 5
Endurance crater	Mars (Opportunity)	Sols 177,199; 299; Joseph et al. 2021a, Figs 2,5,11,15
	Terrestrial tube worm cases	www.sanibelseaschool.org
	Terrestrial fossil worm cases	Georgieva et al. 2019, Joseph et al. 2021a, Fig 21

Data analysis: In the Gale crater study, a number of metrics were calculated from the data to compare the Martian (Fig 2) with the terrestrial specimens (Fig 3) and the pseudofossil: (1) the number of directional changes per segment, (2) degree of variation in segment length along the filament expressed as the CV (CVL), (3) variation in width of the segments along each filament expressed as the CV (CVW), (4) ratio of mean lengths of segments per filament to mean width (L/W), (5) the degree of 'tortuosity' (T) of the filament, i.e. the ratio of the total length of all the segments to the shortest distance between the two ends of the filament, and (6) the degree of 'bending' (B) of the filament per segment, i.e., the total of the angles between adjacent pairs of segments divided by the total number of segments (Hoffman et al. 2008). In the Endurance crater study, the following metrics were calculated: (1) the degree of variation in case width along its length expressed as the CV (CVW), (2) the ratio of the width of the 'opening' to the mean width of the case (Op/W), and (3) the degree of 'tortuosity' (T) of the specimen (Hoffman et al. 2008). In both studies, the metrics were either ratios or sources of variation and hence, not likely to be normally distributed. Consequently, either the non-parametric Mann-Whitney or Kruskal-Wallis test was used to compare among the various groups.

The data were also analysed using principal components analysis (PCA) (Statistical Software, Statsoft Inc., Tulsa, OK, USA) (Armstrong and Hilton 2011, Rizzo et al. 2021). The analyses were carried out using all individual filaments or tubes as variables and the various metrics as defining features. In a PCA scatter plot of the different structures, the distance between them reflects their relative similarity or dissimilarity based on the defining metrics. To correlate the location of a filament or tube on a PC axis with a specific metric, correlations (Pearson's 'r')were calculated between the values of each metric from each variable and the factor loadings of the structure relative to the PC1 and PC2. For example, a high correlation between a specific metric and PC1 would identify that feature as particularly important in determining the separation of filaments or tubes along PC1.

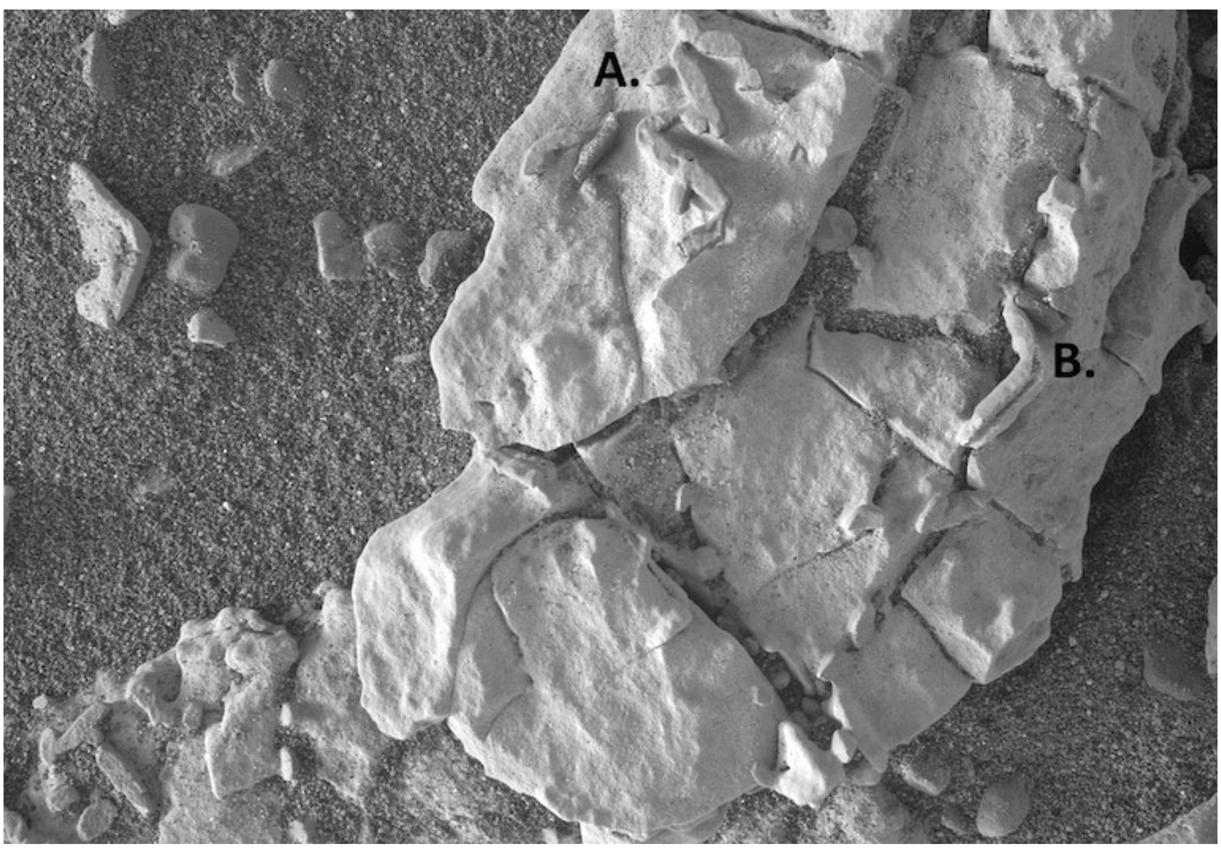

Figure 1. Tubular formations photographed in Gale Crater (Sol 1905).

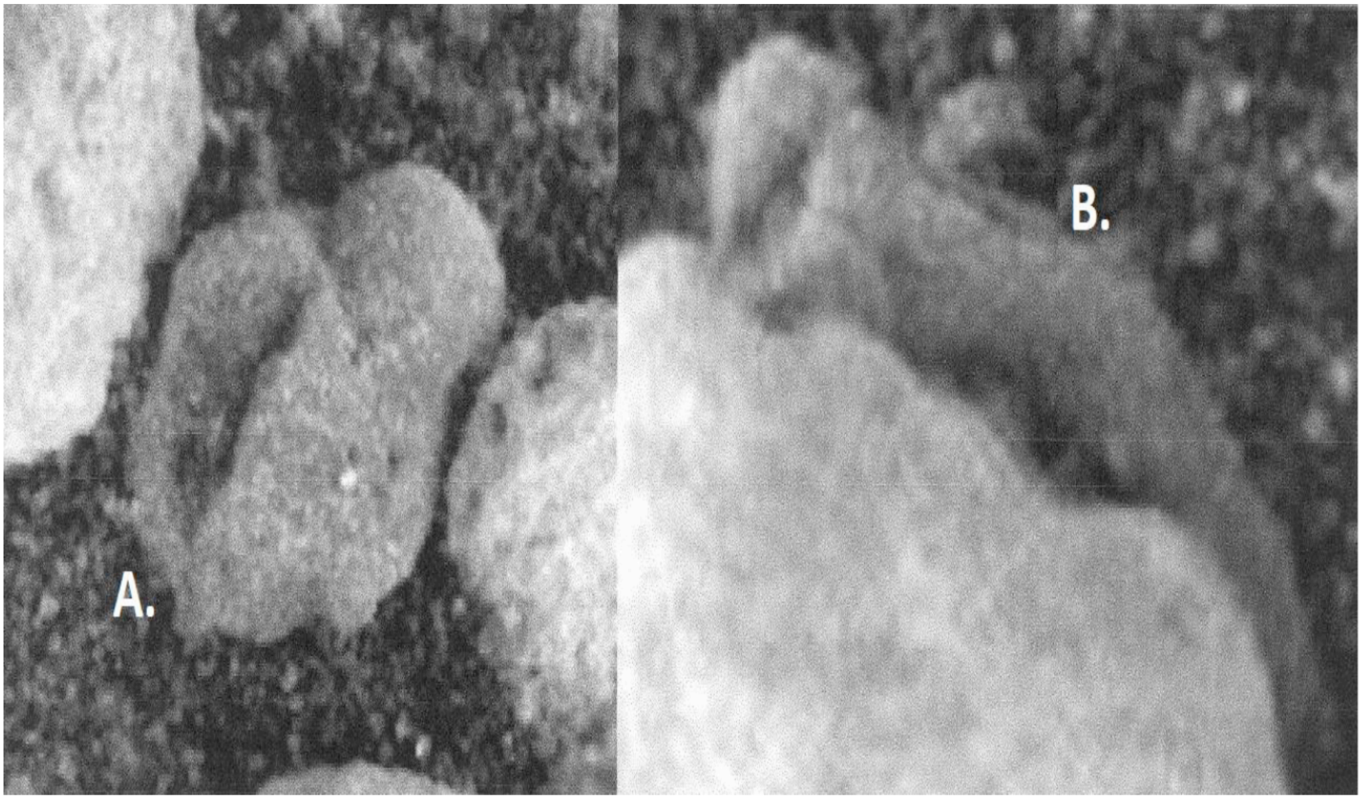

Figure 2. Example of 'tube-like'structures on Mars (A,B) resembling fossil tube worms and worm tubes, photographed in Endurance crater (Opportunity Sols 177,199; Joseph et al. 2021a; NASA/JPL-Caltech.

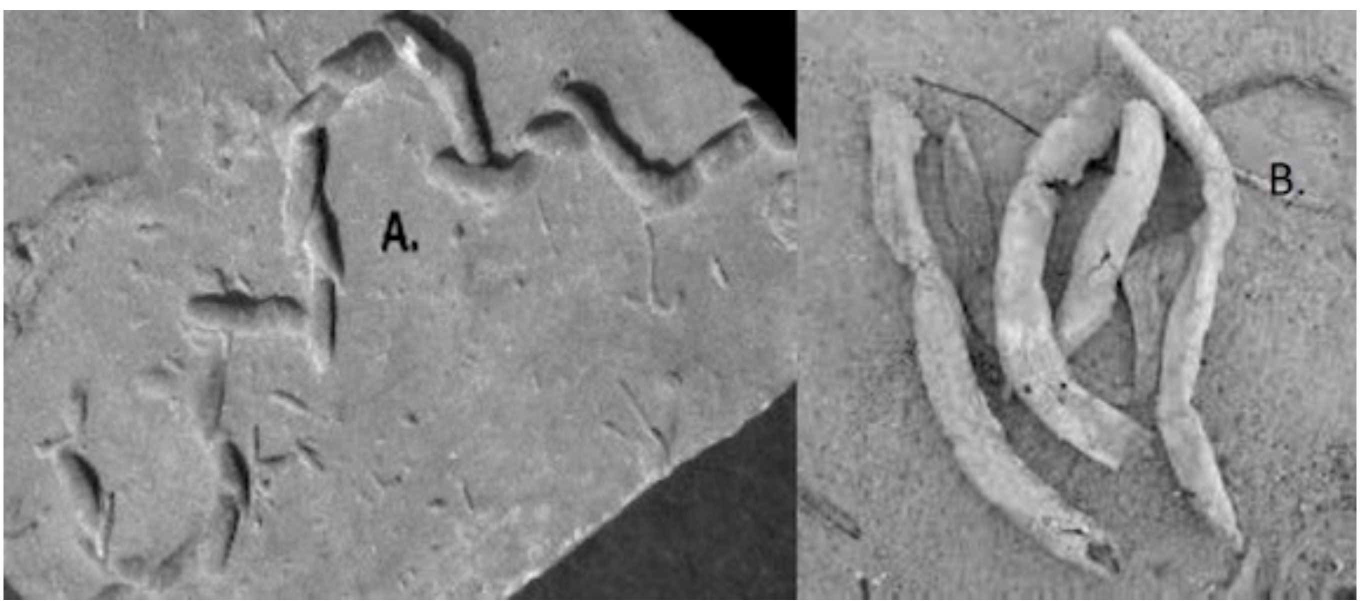

Figure 3. Examples of terrestrial tube worm trace fossils (A) (Joseph et al 2020, Fig 6) and tube worm cases (B) (Stainken 2020) for comparison with the tube-like structures on Mars.

3. Results

As summarized in Table 2, in the Gale crater study, there were no statistical differences between Martian 'tube-like' structures and terrestrial trace fossils in number of directional changes along the filament per segment (P = 0.89), variation in segment length (P = 0.19), variation in segment width (P = 0.51), tortuosity (P = 0.60), and degree of bending (P = 0.19). The exception is the L/W ratio of the segments which is significantly different (P = 0.04), the terrestrial specimens having a higher ratio than the Martian segments. The Martian specimens also had less variation in segment width and a smaller L/W ratio compared with the pseudofossil.

Table 2. Quantitative analysis of various metrics (D/S = Number of directional changes per segment, CV_L = Coefficient of variation of segment lengths, CV_W = Coefficient of variation of width, L/W = Length/width ratio, T = Tortuosity, B = Bending) of 'tube-like' structures (M1-M8) in Gale crater and comparison with terrestrial trace fossils (T1-T2) of tube worms/priapulids and a pseudofossil (PS).

			Metric			
Specimen	*D/S*	*CV_L*	*CV_W*	*L/W*	*T*	*B*
M1	0.75	51	23	3.4	2.28	101.9
M2	0.67	12	14	4	1.14	80
M3	0.6	45	22	3	1.88	102.3
M4	0.75	22	44	2.79	2.5	60.7
M5	0.6	27.8	17	2.41	1.22	50
M6	0.4	52	15	2.54	1.44	32.5
M7	0.89	19	12	3.4	1.48	52.8
M8	0.88	13	31	2.85	1.88	63.7
T1	0.88	34	22	4.8	1.8	75.6
T2	0.43	8	24	4.1	2.06	123.2
PS	0.57	44	39	1.99	1.5	51.4

Mann-Whitney non-parametric U-test to compare between Martian and terrestrial specimens: D/S U = 7.50, P = 0.89; CV_L U = 3.0, P = 0.19; CV_W U = 5.5 P = 0.51; L/W U = 2.08, P = 0.04; Tortuosity U = 6.0, P = 0.60, Bending H =3.0, P = 0.19

A PCA of the various specimens from the Gale crater study plotted in relation to PC1 and PC2 is shown in Fig 4. Most of the variation (90% of total variance) was associated with PC1 and only 6% of the total variance was associated with PC2. Four of the Mars filaments and the terrestrial fossils exhibit a close similarity and form a cluster to the left of the plot. The remaining Mars filaments either form a cluster nearby or at a considerable distance to the right. The latter filament has relatively few segments compared to the others and therefore, less statistical variation among widths and segment lengths and fewer directional changes. All Martian and terrestrial fossil filaments were not similar to the pseudofossil which is located towards the upper centre of the plot. Degree of 'bending' and L/W ratio were the metrics most closely related to variation along PC1.

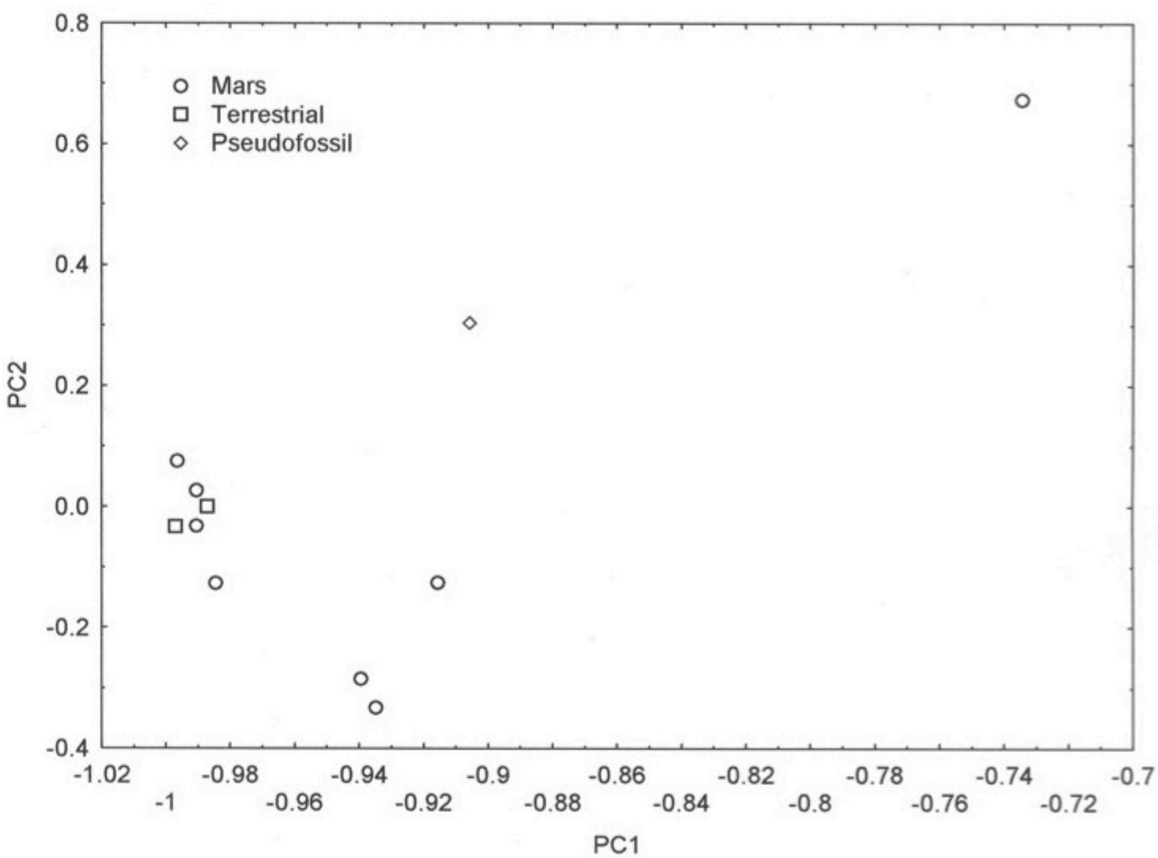

Figure 4. Gale crater study: PCA of Martian tube-like structures, terrestrial tube worm fossils, and a terrestrial pseudo-fossil resembling tube worms: A plot of PC1 against PC2. PC1 accounts for most of the variation in the data (90%).

Table 3. Quantitative analysis using various metrics (CV_W = Coefficient of variation of segment widths, Op/W = ratio of 'opening' to width, T = Tortuosity, of putative Martian 'tube-like' structures (M1 –M5), terrestrial worm tubes (T1-T3, and fossil worm tube cases (F1-F4) in Endurance crater.

		Metrics	
Specimen	CV_W	*OP/W*	*T*
M1	11	1.19	1.06
M2	12.5	1.6	1.41
M3	32	1.3	1.0
M4	11	0.69	1.0
M5	16	0.71	1.0
T1	9	1.25	1.01
T2	8	0.91	1.1
T3	13	0.65	1.05
F1	7.4	0.96	1.05
F2	16	1.14	1.03
F3	4	0.67	1.06
F4	8	1.09	1.01

Kuskal-Wallis non-parametric test to compare among multiple groups: CV_W H = 3.56 P = 0.17; Op/W H = 1.14, P = 0.57; Tortuosity H = 0.76, P = 0.68

4. Discussion

The major limitation of this type of statistical study is inevitably the small sample sizes. Considerable time, effort, and observational skills are necessary to detect and interpret these rare Martian structures (Josephs et al. 2021a). In addition, tube-like structures on Mars do not show the entire length of the specimen, are orientated differently to the camera, and exhibit few characters on which to base metrics making it difficult to quantify and compare with terrestrial specimens. Of the two most 'complete' Endurance crater specimens examined in detail, in specimen A (Fig 2 left), only the upper contorted portion of the 'tube' is apparent with an anterior depression which could constitute an anterior ‘opening’. More of specimen B is present (Fig 2 right) with a more convincing ‘opening’ but not all the specimen is visible and is obscured by an adjacent partially eroded ‘spheroid’. The remaining specimens analysed (Joseph et al. 2021a, Fig 11,15) also suffer from these limitations to varying extents. However, this article includes all specimens known to date from which suitable metrics can be extracted.

Small sample sizes result in low statistical ‘power’ such that small but ‘real’ differences between Martian and terrestrial specimens may not be detected; a statistical Type 2 error. The results of a PCA in particular are strongly affected by the specific images selected for analysis and the metrics used to define them (Costello and Osborne 2005). In mitigation, however, both the Gale and Endurance crater data sets have a ‘simple structure’ in which the variables show strong loadings onto a single component (PC1), which makes smaller samples more valid. Nevertheless, he results should be regarded as a preliminary analysis of these features until further more complete specimens and additional metrics can be added to the data set. Despite these caveats, the data suggest there are considerable similarities in the quantitative metrics between the Martian tube-like structures in Gale and Endurance craters and various terrestrial specimens. These include similarities in width variation (CV) along the specimens (both studies), which is relatively small, the ratio of the number of directional changes along the filament (Gale crater only), and the degree of tortuosity (both studies). All of these variables are more characteristic of biotic than abiotic structures (Schopt et al. 2007, Williams et al. 2015). If confirmed by more extensive analyses, these data in combination with the evidence of ‘salty-brine’ like habitats have considerable implications for the presence of ancient life on Mars and its subsequent evolution, issues extensively discussed in Josephs et al. (2021a)

5. Conclusion

Statistical analysis of data based on images reported in Joseph et al. (2020a)suggest considerable morphological similarities between Martian ‘tube-like’ structures and various terrestrial analogues such as tube worm cases and fossils. Although, such statistical comparisons can never ‘prove’ that these ‘tube-like’ structures on Mars represent tube-worms, they do provide a more objective basis for morphological comparison and within their limitations, are consistent with the conclusions of Josephs et al. 2021a.

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