Gale Crater

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1. Introduction

This paper will analyse the formation of Gale Crater and the post impact environment. Images from the Mars Reconnaissance Orbiter(MRO) have shown sedimentary deposits covering Gale crater (Schwenzer et al. 2012). This along with physical evidence of fan-like deposits and small channels in the northwestern rim point towards the presence of flowing water which might have led to the formation of a lake (Thomson et al. 2011). This evidence has led to Gale crater being the destination of the Mars Science Laboratory(MSL) Curiosity rover. Curiosity aims to understand the changing climate and the role of water along with the possible habitability of life. Curiosity rover findings of alteration halos in the Murray and Stimpson formation point to hydrothermal activity which has implications for many minerals found in the Gale crater (Yen et al. 2021). Figuring out how these mineral forming processes occurred has implications for understanding the regional environment. Further the paper will focus on the importance of organics found by curiosity in relation to habitability of life. Understanding how the region evolved over time with the changing climate will help in aiding future missions to Mars. This will help us in identifying regions with high probability of finding biosignatures in similar sedimentary deposits where life supporting minerals were present along with liquid water.

2. Crater Formation and Features

Gale crater is a 150 Km wide impact structure, formed during the late Noachian (3.5 to 3.8 billion years ago), at the border of the southern highlands and elysium planitia (4.49°S,137.42°E). There are 4 major geological features that have been identified: the ejecta blanket, a raised rim, a flat floor and the central mound (Schwenzer et al. 2012). It has been calculated that between 3600 to 2100 Km^3 of impact melt was generated out of which 50% remained inside while the rest produced the ejecta blanket (Schwenzer et al. 2012). Carved out by an asteroid or a meteorite, the impact left a central peak in the crater as the surface rebounded. Therefore, the distribution and thickness of the melt was not uniform in the crater moat. The ejecta blanket is believed to have been around 600m in thickness post impact; however, today much of it is only preserved on the southern rim as the northern rim and its adjacent areas have experienced strong erosion (Schwenzer et al. 2012). However, out of these 4 features, the central mound along with the deposits formed on it are of most importance.

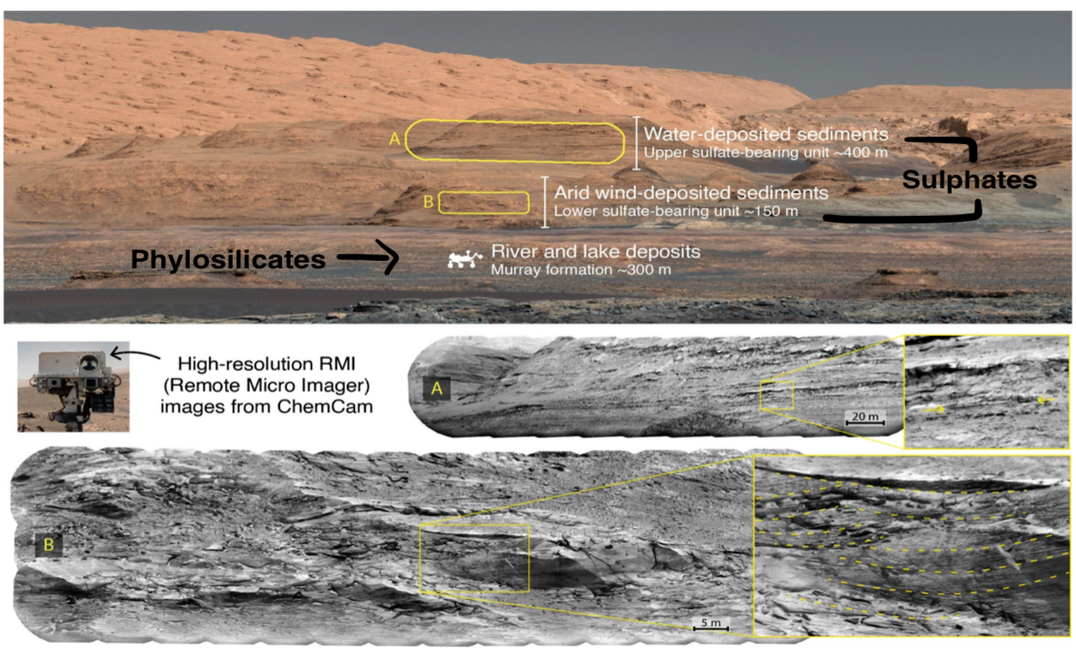
3. Layered Deposits

3.1. Implication and Importance

It is believed that dust, volcanic ash, fine-grained impact products, and possibly snow deposited by settling from the atmosphere, as well as wind-blown sands cemented in the crater centre, creating the Aeolian Mons deposits (Deit et al. 2013). On top of these, there are layered deposits which are sedimentary in nature and hold importance as they help in differentiating planets which had/have an active hydrosphere or atmosphere from those which don't (Thomson et al. 2011). These sedimentary deposits also point to the fact that liquid water was present some time after the crater formation, this will be discussed further in the paper. If deposition and layering took place over long periods of time then these deposits must have captured the cyclic change in the martian environment. For the above mentioned reasons, the layered deposits are important research subjects giving us insight into how the region and climate evolved/changed. Fluvial fan-like deposits carved into the crater walls and lower mounds were also observed by orbital imaging and for all these reasons Gale crater was chosen as the landing site for the MSL Curiosity rover (Wray, 2013). Curiosity rover landed on 5th August, 2012 in the crater's northwestern flank and will carry out research on the evolution of the environment and the possible habitability of life in the past.

3.2. Evidence for water

These layered deposits themselves act as the biggest physical evidence for the presence of water in the late Naochian along with the presence of fluvial fan-like deposits which are carved into the crater walls and lower mounds in the northern rim as observed by orbital imaging . Sedimentary in nature - clay, silt and other particulate matter is believed to have precipitated or settled on the bottom of a lake, which over time underwent compaction and lithification. Data from Compact Reconnaissance Imaging Spectrometer for Mars (CRISM) on the MRO helped identify 2 different depositional groups based on the different IR reflectance spectra along with the presence of an angular unconformity (Thomson et al. 2011). The upper group is dominated by sulphur signatures whereas the lower group has many depositional layers rich in hydrous phyllosilicates, indicating a rich hydrological past in the crater (figure 1) (Thomson et al. 2011). The presence of these minerals provides chemical evidence of water and points to the fact that Gale crater underwent a lucustrine phase. How did this water originate in the gale crater! Did subaqueous activity or overland flow lead to the formation of a lake? The answer to this question will be discussed in section 4.



(Figure 1: https://www.eurekalert.org/news-releases/511608)

3.3 Fluxes in regional environmental conditions

3.3.1 Alkalinization and acidification of hydrothermal fluid

Change in mineral types from phyllosilicates(clay-Si_2O_5) to sulphate bearing minerals indicates a shift in global environmental conditions. How? Phyllosilicate formation takes place due to chemical weathering in neutral/alkaline conditions. Curiosity rover drill cores from the Bradburry group found deposits which were formed in fluvial and lacustrine environments: mudstone, sandstone and conglomerate (Tu et al. 2021). Data from Curiosity further pointed out the phyllosilicate diversity especially in terms of smectite. Smectite has a general formula of $(Ca,Na,H)(Al,Mg,Fe,Zn)_2(Si,Al)_4O_{10}(OH)_2$-$xH_2O$ where x indicates variable amount of water. Smectite is a group of phyllosilicates that is greatly affected by changes in temperature and pressure. Therefore, changes in structure and composition of smectite within the group points to changes in the environment (Tu et al. 2021). Such diversity therefore points to the fact that a variety of aqueous environments were present in Gale crater (Tu et al. 2021). Sulphate mineral formation on the other hand requires a substantial amount of water. Sulphate precipitation requires evaporation of water and certain sulphate minerals require acidic conditions (Bibring et al. 2006). Hence, a shift took place from neutral/alkaline conditions to acidic conditions. Acidic conditions would have been present in large areas of Mars since sulphate deposits are found in abundance from the late Naochian to the Hesperian age (Bibring et al. 2006).

3.3.2 Fluxes as seen in the stratigraphy of the Murray Formation

Murray formation is a unit of mudstone exposed on the northern slope of Aeolis Mons. Major concretion assemblages are observed throughout the Murray formation, reflecting different aqueous environments as sediment properties changed after deposition (Sun et al. 2019). The Murray formation (>300m thick) is presently divided into five members representing three major facies in ascending order (C. M. et al. 2018) (Stratigraphy shown in figure 2 on page 14):

1. Pahrump Hills (25 m)
2. Hartmann's Valley (25 m)
3. Karasburg (37 m)
4. Sutton Island (98 m)
5. Vera Rubin Ridge (> 100 m)

From the basal section of the Pahrump hills to the uppermost formation, Petrove Point and Jura - different deposits are found from dendrites and spherules to flat, smooth and irregular concentrations (Sun et al. 2019). The 3 distinct facies represent different chemical enrichments :

1. Mg-S-Ni-Cl enriched dendrites in Pahrump hills
2. Mn, P, and variable Fe, Mg, and Zn in Sutton Island
3. Ca and S enrichments in Blunt's point and additional enrichments in K and Fe occur in more isolated intervals.

These point to the fact that multiple fluid episodes took place in the gale crater with different composition. (Sun et al. 2019) describe at least six, aqueous episodes recorded in the diagenetic features observed in the Murray and Stimson formations:

1. Syn-depositional or early diagenetic crystal laths and sulphate vein formation in Pahrump hills
2. Murray concretion formation that began or extended into late diagenetic stages after sediment compaction and lithification
3. Vein formation that crosscuts pre-existing concretions and veins
4. Concretion and vein formation in the Stimson formation
5. Alteration halo formation
6. Formation of 2 Ga diagenetic jarosite in the mudstone

The figure below expresses the relative time that took place for deposition and diagenesis in the Murray Formation

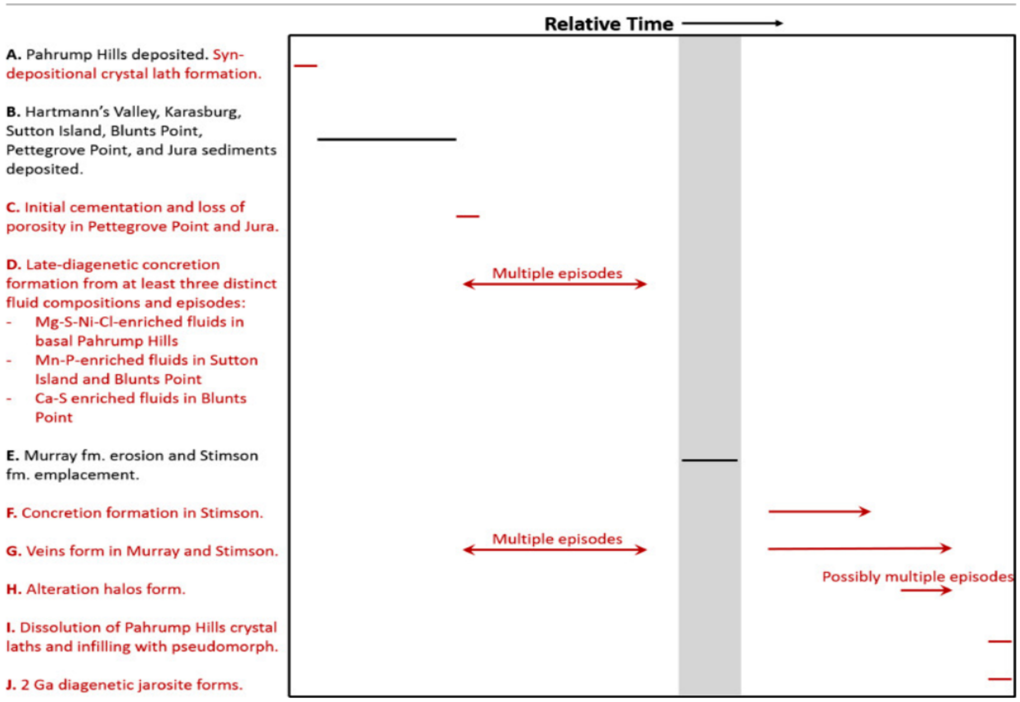


Fig. 22. Relative timeline depicting when depositional and diagenetic features may have formed in the Murray formation. Letters are used to mark events discussed in Section 8 and question marks indicate uncertainties of when events start or end. The grey region corresponds to the emplacement of the Stimson formation. The length of lines is not to scale. Black corresponds to primary depositional events, while red corresponds to syn-depositional or diagenetic formation of features. Please see Section 8 for references to the literature. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

(Figure 3. Sun et al. 2019)

These 6 different depositional events show how multiple fluid activity took place with different composition of basic elements leading to various enrichments. Further, these enrichments in different stratigraphic units allows scientists to constrain the time when such deposition took place. All this evidence shows how the environment changed with time and led to the subsequent infilling of gale crater forming these deposits.

4. Hydrothermal Activity

4.1 Evidence

On Earth, there is evidence that post impact hydrothermal activity took place in large crater regions and similar activity is believed to have occurred on Gale crater (Schwenzer et al. 2012). If this is true, then mineral alterations that took place would have been due to hydrothermal activity. What evidence do we have for this? Tridymite, a low pressure, high temperature SiO_2, polymorph, was discovered by the CheMin instrument on board Curiosity rover in the Pahrump hills of the Murray formation (Yen et al. 2021). Alliteration Halos, formed by acid-sulphate alteration and silicification of the parent rock in the Murray formation. It's believed that the Tyridymide bearing region evolved due to interaction with similar hydrothermal fluids (Yen et al. 2021). The Evolved Gas Analysis(EGA) and Sample Analysis on Mars(SAM) found further evidence linking Tridymite bearing murray formation to the alliteration halos present (Yen et al. 2021). High temperature release of SO_2 found in the silica-rich, tridymite-bearing Murray formation is similar to the SO_2 release in silica-rich alteration halo in the Stimson formation. Such a SO_2 release is not found in any other Murray formation sample which is closest to the target rock(Buckskin) in the Pahrump Hills. This indicates similar sulphur bearing fluids in association with the alteration halos in stimpson formation and the tyrdimite bearing region (Yen et al. 2021).

The ChemCam data also found unique hydration signatures, the presence of Opal-A, a hydrous amorphous mineraloid in the alteration halos and high silica Murray sample (Yen et al. 2021).

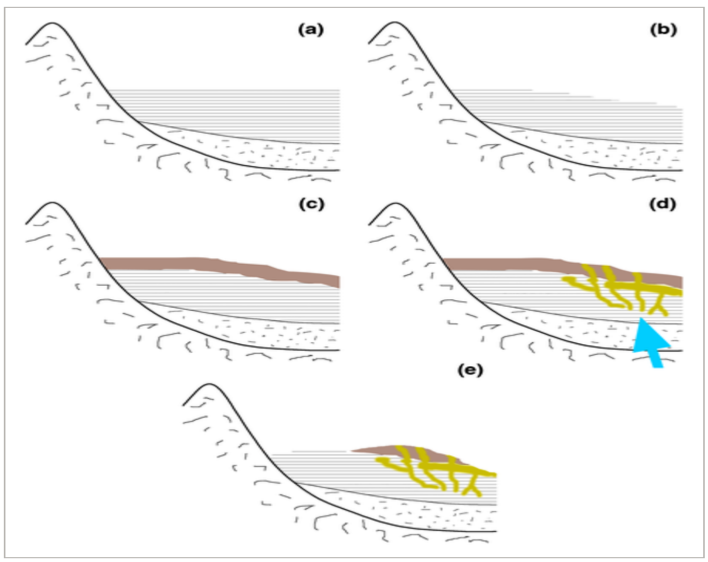
Apart from tridymite, phosphorus pentoxide(P_2O_5) also points to hydrothermal activity. Retention of P_2O_5 is an observed characteristic of terrestrial hydrothermal, acid-sulphate alteration systems and is one of the few oxides which is resistant to leaching under these conditions (Yen et al. 2021). It is believed that P_2O_5 formed due to dissolution and local precipitation as insoluble phosphates (Yen et al. 2021). High concentrations of Zn and Ge in different sedimentary lithologies across the murray formation also indicate the accumulation of hydrothermal fluids in the crater (Yen et al. 2021).

4.2 Development of the system

All the aforementioned evidence properly points to a hydrothermal system that developed in the following way (Yen et al. 2021):

1. Impact creates a subsurface network of fracture and future fluid conduits
2. Sedimentation from intermittent lakes formed by overflowing water from mount sharp and the rims of the crater build the Murray formation
3. Subsurface fluids interact with heated rocks pushing hydrothermal fluids and vapours up through the fractures.
4. Such activity took place multiple times with different temperature gradients resulting in the chemical compositional variability seen all over the Murray formation.

Figure 4 shows the same in a simplified way.



Conceptual scenario for the development of silica-rich material through hydrothermal activity at Gale crater: (a) Deposition and lithification of Murray formation sediments in Gale crater, (b) erosion of Murray formation, (c) deposition and lithification of Stimson formation sandstone, (d) hydrothermal alteration episode (influx of fluids depicted by blue arrow) creating alteration halos in the Stimson and Murray formation rocks and a silica-rich horizon in the Murray formation at the base of the Stimson, (e) further erosion exposing silica-rich Murray rocks.

(Figure 4. Yen et al. 2021)

This is the most accepted hypothesis for hydrothermal activity, however, inconsistencies remain and alternate hypotheses can be formulated for the formation of these minerals. Inconsistencies include the absence of tridymite in silica-rich alteration halos found in the Stimson sandstone (Yen et al. 2021).Tridymite forms in its thermodynamically stable field of >870ºC, transport of hydrothermal fluids might lose heat due to conductive heat loss (Yen et al. 2021). Understanding the rate of heat flow, intensity of the heat source and conductive heat loss to the surrounding conduit/fracture wall will provide a more detailed image of how the mineral alteration process for the formation of tridymite worked (Yen et al. 2021).

5. Presence of Organics

5.1 Sample Regions

The search for habitable environments in the solar system and beyond is the key area of research in astrobiology. With the number of past, present and future planned missions, Mars is a high priority target. Missions such as the viking and Mars pathfinder showed that despite the hostile conditions on Mars, past environmental conditions were conducive for the existence and development of life (Szopa et al. 2020). Making the discovery of possible habitability of life as one of its main missions, Curiosity rover made Gale crater its laboratory. Curiosity rover took 21 measurements from four different solid rock samples drilled from the Rocknest aeolian deposits, Yellowknife bay and Pahrump hills. The four solid samples are named Rocknest(RN), Cumberland(CB), John Klein(JK) and Confidence Hill(CH). Several chlorine-bearing hydrocarbons were released upon heating the RN sample indicating an oxychlorine phase such as hydrated Calcium perchlorate ($Ca(ClO_2)_4.nH_2O$) (Freissinet et al. 2015). Even though the chlorine in chloromethane was derived from the Martian oxychlorine phase; the source of carbon however, is argued to be terrestrial (Freissinet et al. 2015).

5.2 Organic preservation and issues

5.2.1 Preservation site

Going further down to the lower stratigraphic unit of the Yellowknife Bay lies the sheepbed formation. Here, Curiosity rover drilled the JK and CB samples which contained smectite clay. It has been known that terrestrial phyllosilicates like smectite transport and protect organic compounds when deposited under rapidly reducing chemical conditions, indicating that sheepbed mudstone contains mineralogy suitable for preserving organics (Freissinet et al. 2015). This is further proved by studying the exposure history of CB. Destruction or transformation of organics can take place when exposed to oxidants present in the regolith or by UV and ionising radiation; energetic cosmic rays can further degrade organic compounds in the top 2m of the surface (Freissinet et al. 2015). On carrying out analysis of cosmic-ray produced gases(noble gas isotopes) in the CB sample (Farley et al. 2014) found out that CB was exposed for 78 ± 30 Myrs. This is consistent with the geomorphology of Gillespie sandstone formation which created a ledge over the sheepbed mudstone near the CB sample, causing this shaded region to receive a relatively lower level of cosmic radiation as compared to the surrounding martian environment (Szopa et al.2020). Low exposure to cosmic radiation further enhances the preservation of organic compounds in this region. Further, (Szopa et al. 2020) believe that detection of organics can be enhanced by thermal analysis methods if Curiosity can reach the enriched sulphur layer on Mount Sharp, as sulphates could be the most efficient minerals to protect organic molecules. However, certain issues exist with this idea and are discussed below.

5.2.2 Issues with sulphur preservation

Heat-based methods of chemical analysis present a complication to the detection of organics on Mars. On decomposition of perchlorate and chlorates, atomic oxygen is released which oxides organics (Lewis et al. 2015). Sulphur decomposition creates similar challenges to organic preservation during pyrolysis. The sulphate ion decomposes to sulphur trioxide and then, at higher temperatures, sulphur dioxide and atomic oxygen (Lewis et al. 2015). Most sulphates decompose at temperatures greater than 600^{o} C however, iron and aluminium sulphates begin to decompose at temperatures similar to those used for analysis of macromolecular organic pyrolysis (Lewis et al. 2015). Curiosity found small amounts of jarosite, a member of alunite supergroup with the general formula $AB_3(TO_4)_2(OH)_6$, in Gale crater (Léveillé et al. 2015; Lewis et al. 2015). In jarosite, the general formula is characterised by having Fe^{3+} in the B site and sulphur occupying the T site whereas, site A can be occupied by K^+,Na^+,H_3O^+,NH_4^+,Pb^+ and Ag^+(Lewis et al. 2015). Variation of cations in A and B influences decomposition temperature as shown in table 1.

TABLE 1. TEMPERATURE AT WHICH THE SULFATE ION BEGINS TO DECOMPOSE TO GIVE SULFUR DIOXIDE DURING THERMAL DECOMPOSITION OF DIFFERENT SULFATE SPECIES

Mineral	*Formula*	T *at which sulfate decomposition begins (°C)*	*Decomposition atmosphere*
Jarosite	$KFe_3(OH)_6(SO_4)_2$	501[a]	Nitrogen
Natrojarosite	$NaFe_3(OH)_6(SO_4)_2$	555[a]	Nitrogen
Hydronium jarosite	$H_3OFe_3(OH)_6(SO_4)_2$	557[b]	Nitrogen
Ammonium jarosite	$NH_4Fe_3(OH)_6(SO_4)_2$	510[c]	Nitrogen
Plumbojarosite	$Pb_{0.5}Fe_3(OH)_6(SO_4)_2$	531[a]	Nitrogen
Argentojarosite	$AgFe_3(OH)_6(SO_4)_2$	548[d]	Nitrogen
Alunite	$KAl_3(OH)_6(SO_4)_2$	610[e]	Air
Natroalunite	$NaAl_3(OH)_6(SO_4)_2$	590[e]	Air
Hydronium alunite	$H_3OAl_3(OH)_6(SO_4)_2$	680[e]	Air
Ammonium alunite	$NH_4Al_3(OH)_6(SO_4)_2$	660[e]	Air
Ferric sulfate	$Fe_2(SO_4)_3$	494[f]	Nitrogen
Aluminum sulfate	$Al_2(SO_4)_3$	580[f]	Nitrogen
Lead sulfate	$PbSO_4$	759[a]	Nitrogen
Magnesium sulfate	$MgSO_4$	780[f]	Nitrogen
Sodium sulfate	Na_2SO_4	1100[g]	Nitrogen
Calcium sulfate	$CaSO_4$	1200[h]	Nitrogen

(Table 1: Lewis et al. 2015)

Sulphate minerals commonly found on Mars include Iron sulphates such as jarosite and ferric sulphate which on pyrolysis break down their sulphate structures releasing oxygen into the pyrolysis chamber (Lewis et al. 2015). On carrying out experiments, (Lewis et al. 2015) observed a large peak of CO_2 on decomposition of jarosite impling that organic carbon is being combusted. Terrestrial sulphates have been shown to be associated with organic compounds and therefore analysing sulphate minerals on Mars is a must. Fortunately, the majority of sulphates have a high decomposition temperature ,which varies as well, as seen above, allowing for preliminary mineralogical analysis using suitable thermal extraction methods which can minimise their negative effects (Lewis et al. 2015). If better thermal analytical methods are developed then a better extraction of organics can be carried out giving us more detailed and accurate information of their formation, transformation and preservation.

5.3 Hydrocarbon detection and identification

Reaction between oxychlorine and reduced organic carbon from the sheepbed formation led to the discovery of chlorobenzene and several dichloroalkanes (C_2,C_3,C_4) (Freissinet et al. 2015). SAM Gas Chromatography Mass Spectrometer(GCMS) detected Trichloromethylpropane (TCMP) and isomers of Dichlorobenzene(DCBZ) when the data was compared to the National Institute of Standards and Technology(NIST) Mass Spectrometry(MS) Library (Figure 5) (Szopa et al. 2020). Isomers of dichlorobenzene confirmed by SAM included 1,2-DCBZ, 1,3-DCBZ and 1,4-DCBZ. Along with these SAM also detected 1,2- dichloropropane, 1,1-dichlorobutane and 1,2-dichlorobutane.

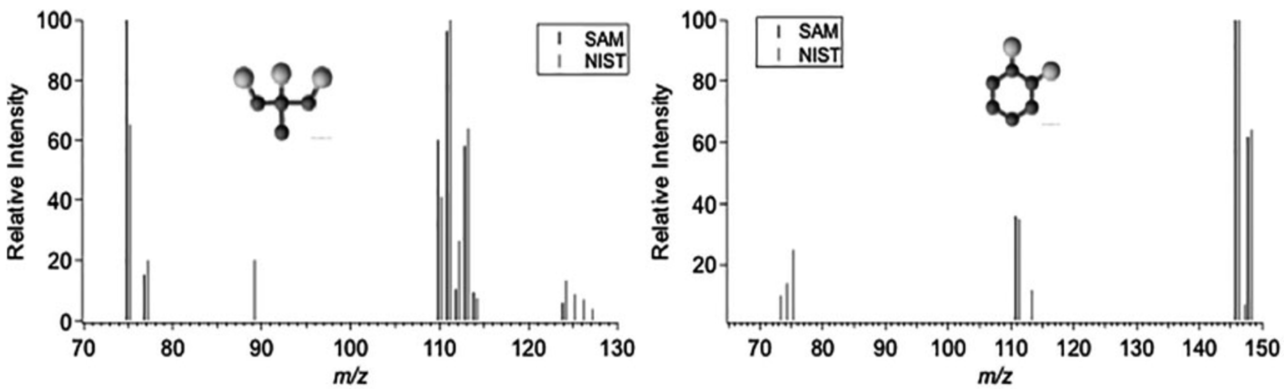


FIG. 2. Normalized mass spectra of 1,2,3-trichloro-2-methylpropane (left) and 1,2-DCBZ (right) from SAM CB-5 sample plotted against National Institute of Standards and Technology (NIST) MS library reference spectrum. The similarities in the respective mass spectra give a high confidence in the identification of the molecules. Isomers of DCBZ produce very similar mass spectra under SAM MS analytical conditions. Only the 1,2-DCBZ spectrum is presented in this figure as an example. DCBZ = dichlorobenzene; MS = mass spectrometer; SAM = Sample Analysis at Mars.

(Figure 5: Szopa et al. 2020)

5.4 Source of Organic Carbon

Meteoritic infall is believed to be a source of organic carbon (Szopa et al. 2020). It is assumed that meteoritic organics could have reacted with Martian perchlorates during pyrolysis to produce the aromatic carbon detected by SAM in the CB sample (Szopa et al. 2020). To test this hypothesis (Szopa et al. 2020) created a sample of Murchison carbonaceous Meteorite with calcium perchlorate and olivine to simulate the presence of silicates. On pyrolysis, using temperatures similar but a bit higher than those used in SAM pyrolysis, (Szopa et al. 2020) detected mono and multiple chlorobenzenes using GCMS. Further, the trace element inventory of the Sheepbed mudstone is consistent with the meteoritic hypothesis (Freissinet et al. 2015). Alkyl components present in CB samples could act as precursors for Dichloroalkanes detected in sheepbed mudstone (Freissinet et al. 2015). More indepth research will be needed to figure out other possible sources of organic carbon but interplanetary organic material as a source of organic carbon on Mars cannot be rendered false.

6. Possibility of life

Presence of water, organics and a rich source of hydrothermal energy forms a perfect habitat for life to evolve and develop. Finding organics doesn't necessarily mean the presence of life as abiotic sources can lead to the creation of organic carbon as discussed above. No direct evidence of life has been found on Mars yet, but if life did exist then what type of life would it be? Microbial life is known to survive in the most remote and inhospitable regions on Earth, broadening our understanding of the limits of microorganisms (Sielaff et al., 2019). Certain habitats and regions on Earth act as analogs to Martian conditions and help us understand how life might survive.

6.1 Rio Tinto and Haughton impact crater as an analog

Rio Tinto in southwestern Spain is an important analogue as it has a similar geochemical hydrological system as that would have been present in the Noachian time (Marlow et al., 2011). The Mars Astrobiology Research and Technology Experiment (MARTE) carried out a search for evidence of cryptic life in the subsurface region of a fractured Paleozoic volcano sedimentary deposit near the source waters of the Rio Tinto River. They found acidic and neutral subsurface solutions and core samples revealing microbes attacking pyrite (Fernández et al. 2008). These subsurface alteration mechanisms in Rio Tinto may be similar to subsurface weathering of the Martian crust and provide insights into the possible (bio)geochemical cycles taking place in underground habitats in early Mars volcanic regions (Fernández et al. 2008). This applies to Gale Crater as the post impact environment would have been similar with deep hydrothermal conduits and fractures running along the entire crater floor and rim.

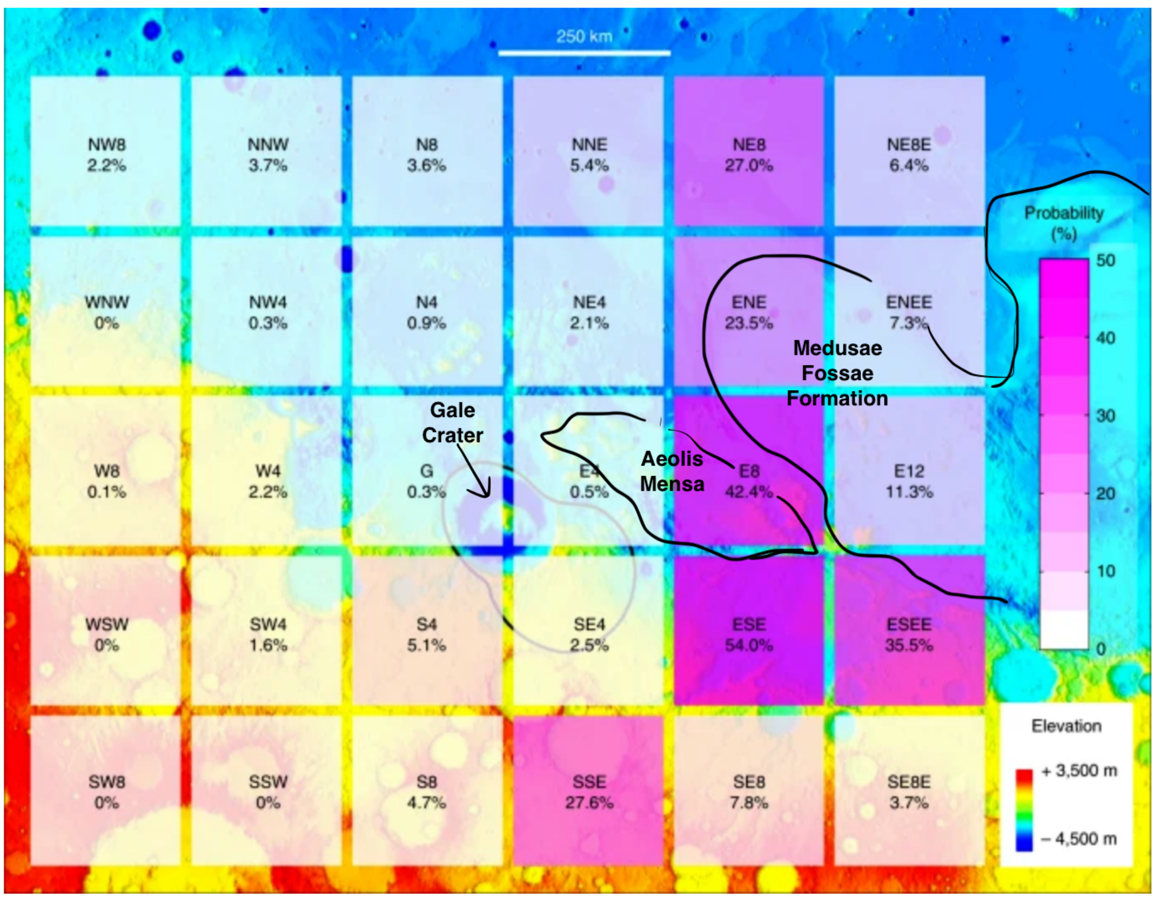
The Eocene Haughton impact crater, located on Devon Island in the Canadian High Arctic Archipelago, provides a useful analogue site to study post impact sulphate deposits containing microbial life (Brolly et al. 2017). (Brolly et al. 2017) infer that shocked gypsum is more suitable for microbial colonisation which is analogous to many martian craters including Gale. Gypsum has been discovered in Gale crater and the possibility of life existing in similarly shocked gypsum cannot be negated. For the Euro 2020 ExoMars mission (Brolly et al. 2017) conducted experiments to distinguish between Gypsum with different degrees of habitability using Raman spectroscopy. However, they concluded by saying that Raman spectroscopy could not make that big of a difference between shocked and unshocked gypsum. This shows the limits of such an analytical method. Analysis using Raman spectroscopy needs to be improved or better methods need to be devised to analyse such biotic indicators.

6.2 Methane

6.2.1 Source and evidence

The presence of methane on Mars has been intensively debated. In situ observation of Methane spikes was made by Curiosity rover, which was confirmed by the firm detection of 15.5 ± 2.5 ppb by volume of methane in the Martian atmosphere above Gale Crater on 16 June 2013, by the Planetary Fourier Spectrometer onboard Mars Express (Giuranna et al. 2019). Many sources of methane exist, however terrestrial analogs on Earth indicate that subsurface accumulations in the form of clathrates, zeolites and reservoir rocks are the most plausible ones on Mars (Giuranna et al. 2019). Drill samples from the laminated mudstone on the Jura point indicated strong X-ray diffraction spectral absorption peaks as observed by CheMin to be consistent with collapsed smectite along with other phyllosilicates including zeolite (Tu et al. 2021). To figure out the source region (Giuranna et al. 2019) divided the study region of Gale crater and Medusae Fossae formation into 30 possible emission sites for their model. Using the results from their model they created a probability map as shown in figure 6 below. The model indicates a possible source of methane to be lying east and south east of the Gale crater. Blocks E8 contains the Aeolis Mensae which is in close proximity to the Medusae Fossae formation where shallow bulk ice is proposed to exist (Giuranna et al. 2019). Permafrost is the best seal for trapping methane. Faults along the Aeolis Mensae are deep rooted and may stretch all the way into Gale crater through which methane migrates and is released episodically (Giuranna et al. 2019). There are both biotic and abiotic origins of Methane, therefore the presence of methane points to habitability and may be a sign of life. If the source is biotic, then what kind of life can exist?

Fig. 3: Probabilities estimated for the 30 emission sites.



For each grid cell, the probability of being a source location is defined as the number of release scenarios consistent with the observations divided by the sample size. Basemap as in Fig. 2.

(Figure 6 : Giuranna et al. 2019)

6.2.2 Methanogenic life

There is a possibility for the presence of methanogenic life in the early Mars environment. When hydrocarbons react with atmospheric H_2, energy is released in a range which is used by methanogenic life on Earth (McKay and Smith, 2005). Vigorous volcanic outgassing from a highly reduced early martian mantle is expected to provide sufficient atmospheric H_2 and CO_2, which caused the greenhouse effect on early Mars (Ramirez et al. 2014). (Tarnas et al. 2018) quantitatively demonstrate that radiolysis likely generated concentrations of dissolved H_2 capable of sustaining microbial communities in the subsurface of Noachian Mars (3.7–4.1 Gyr ago). Radiolytic H_2 and CH_4 derived from radiolytic H_2, can be locked in hybrid clathrate hydrates within the cryosphere and released by large impacts, volcanism, or obliquity variations (Tarnas et al. 2018). (Serrano et al. 2019) conducted experiments on two non-permafrost strains (*Methanosarcina mazei, Methanosarcina barkeri*) and three permafrost strains of methanogenic archaea, which are anaerobic chemolithotrophic microorganisms. The authors exposed them to Mars-like conditions and recorded their response and growth. Martian condition simulated include (Serrano et al. 2019):

1. Stable subfreezing temperatures (-80°C) that may occur in the martian subsurface
2. The combination of a martian regolith simulant with the chemical composition of early/late Mars under simulated martian atmospheric conditions
3. The presence of magnesium perchlorate($MgCl_2O_8$)in the culture medium.

(Serrano et al. 2019) concluded their study by presenting results that indicate that methanogens from non-permafrost environments are suitable candidates for potential life in the martian subsurface as they showed constant survival and methane production. This study supports the fact that methanogens are suitable model organisms for potential life-forms in the martian subsurface and the possibility that Mars, at present, is habitable and was in the early Noachian (Serrano et al. 2019).

6.3.3 Halophilic Heterotrophic Life

The abundant presence of perchlorate further points to another form of life. A substance poisonous to us humans but used by specific types of microorganisms to grow. In the subsurface acidic and saline conditions, halophilic heterotrophic microorganisms such as *Haloferax denitrificans* and *Haloferax gibbonsii* are known to exist on earth in lakes of the Yilgarn Craton of Western Australia (Aerts et al. 2019;Oren et al.,2014). The presence of perchlorate may even stimulate the growth of such Perchlorate and halophilic prokaryotes in the subsurface Martian environment (Oren et al.,2014).

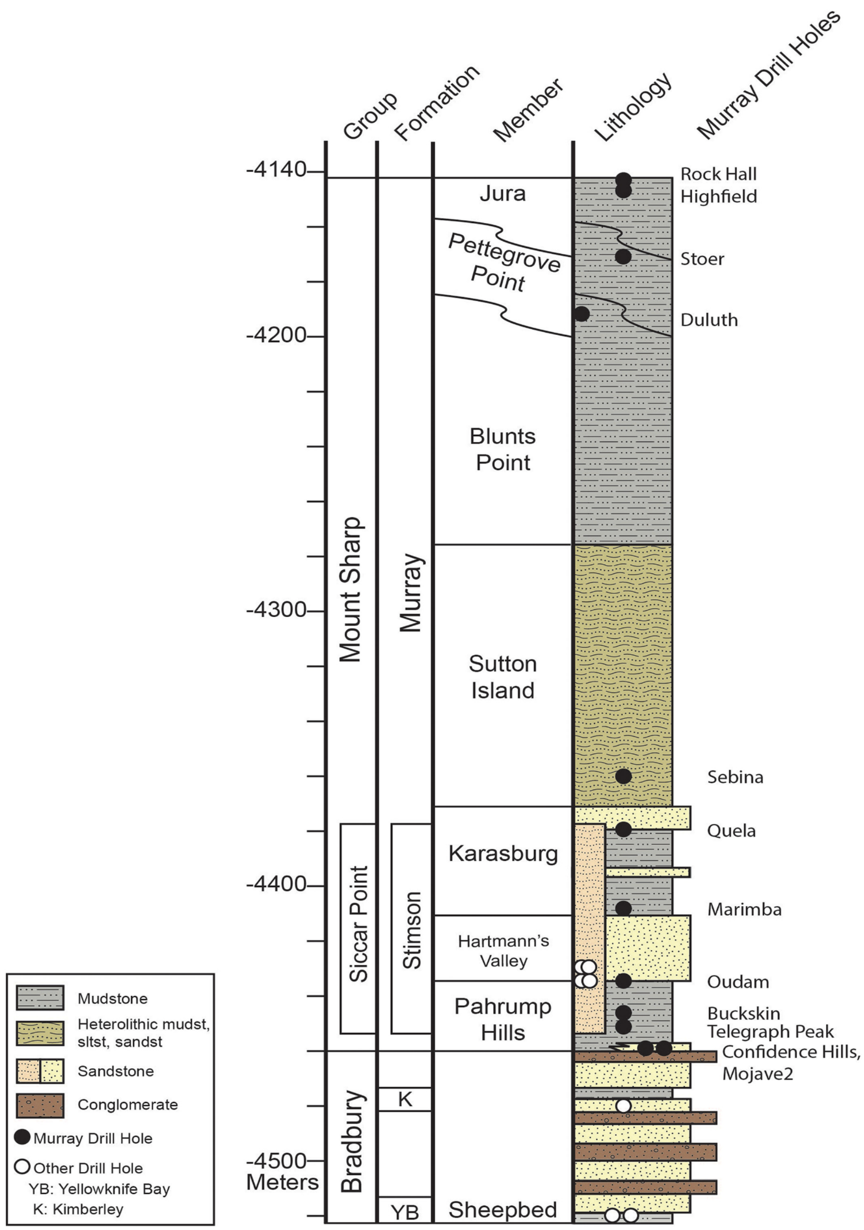
These are just some possible models of life forms that could have existed on mars and might do so today in the subsurface. Gale crater seems to be a perfect place for such forms since it contains many deep fractures and hydrothermal conduits which might provide subsurface habitat for life.

7. Conclusion

We find that Gale crater has had a rich environmental history post impact. The crater resulted in the formation of a lake filled in by an overflowing stream on the northern rim of the crater. Hydrothermal activity took place continuously since its formation and even during sediment deposition, compaction and lithification. This hydrothermal activity was very important as it was a rich source of energy for any life that may have existed and resulted in the formation of many minerals. Subsequent deposition and sedimentation in the crater captured a changing aqueous environment showing how fluxes in aqueous composition affected the mineral precipitation. Presence of organics, liquid water and dissolved nutrients provide the perfect habitat for the evolution and development of life. Over time the deposits in the Gale crater have been eroded, revealing the underlying deposits each different in composition. Till now curiosity has made many observations including that of methane and has provided the scientific community with much needed important information. Studying the Gale crater has given us an idea of the sort of experiments to carry out and surfaces to study in order to better understand the target environment. The experience from Curiosity will guide the Perseverance rover in Jazero crater where it will take samples and study the lacustrine environment.

Abbreviations

MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
IR	Infrared
CheMin	Chemistry and mineralogy X-ray diffraction
EGA	The Evolved Gas Analysis
SAM	Sample Analysis on Mars
RN	Rocknest
CB	Cumberland
JK	John Klein
CH	Confidence Hill
UV	Ultra violet
GCMS	Gas Chromatography Mass Spectrometer



(Figure 2 : 2,128 × 3,305)

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