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RESEARCH ARTICLE

Megatsunamis and microbial life on early Mars

Hadi Veysi

Geology Department, Faculty of Earth Science, Shahid Beheshti University, Tehran, The Islamic Republic of Iran
Author for correspondence: Hadi Veysi, E-mail: hadiveysi1374@gmail.com

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Abstract
It is currently believed that early Mars had a vast and shallow ocean, and microbial life may have formed in it, albeit for a short geological time. The geological evidence indicates that during the existence of this ocean, large collisions occurred on the surface of Mars, which led to the formation of megatsunamis in its palaeo-ocean. Previous research has reported on the effects of tsunami waves on microbial ecosystems in the Earth's oceans. This work indicates that tsunami waves can cause changes in the physico-chemical properties of seawater, as well as tsunami-affected land soils. These factors can certainly affect microbial life. Other researchers have shown that there are large microbial communities of marine prokaryotes (bacteria and archaea) in tsunami-induced sediments. These results led us to investigate the impact of tsunami waves on the proposed microbial life in the ancient Martian ocean, and its role in the preservation or non-preservation of Martian microbial life as a fossil signature.

Contents

Introduction

In addition to eroding and changing the topography of the coast and seafloor, tsunami waves also affect marine ecosystems. These waves can demolish coral reefs, coastal vegetation and mangroves, benthic and infauna invertebrates and even vertebrates such as fish and amphibians (Masuda *et al.*, 2016).

Nevertheless, the impact of a tsunami is not limited to macroscopic marine life, and it also affects microorganisms. So far, few studies have been conducted on the impact of tsunami events on marine microbial ecology (Bhattacharyya *et al.*, 2014; Somboonna *et al.*, 2014; Makino *et al.*, 2019). The results of these studies mainly indicate that tsunami-induced sediments have more microbial communities of prokaryotes (bacteria and archaea) than non-tsunami-affected sediments (Somboonna *et al.*, 2014).

Another group of researchers found that the ingression of tsunami waves in land soils increased soil salinity, and affected microbial communities in the soil (Bhattacharyya *et al.*, 2014).

Some studies have shown that tsunami waves alter the physico-chemical properties of seawater (including oxygen level, light penetration depth, nutrient content, salinity and water turbidity) (Satpathy *et al*., 2008; Haldar *et al*., 2013; Bhattacharyya *et al*., 2014; Somboonna *et al*., 2014; Kakehi *et al*., 2017). These changes can definitely affect the microbial life in the sea.

Studies of the geology of Mars have suggested the possibility of a shallow and vast ocean in the past (Mahaney *et al*., 2010; Iijima *et al*., 2014; Billings, 2016; Costard *et al*., 2017, 2019; Di Pietro *et al*., 2021).

The possibility of primary microbial life in this ocean has also been considered (Goetz *et al*., 2016; Cabrol, 2018; Joseph *et al*., 2020; Becker, 2021). However, there are still many questions about the ocean and microbial life on early Mars that need further investigation.

The Red Planet has experienced numerous large and small collisions in the past. The effects of these collisions are evident all over the planet. Some of these collisions, such as the Lomonosov crater, are thought to have occurred when there was a vast and shallow ocean in the northern plains.

The collision of these large objects in the northern palaeo-ocean of Mars has certainly caused megatsunamis, and some researchers claim that there is evidence of tsunami-induced sediments on the surface (Billings, 2016; Witze, 2016; Costard *et al*., 2017, 2019; Stanley, 2020; Di Pietro *et al*., 2021). Because tsunami waves on Earth affect marine microbial communities, the effect of Martian megatsunamis on the ancient microbial life on this planet is not unexpected. For this reason, we have addressed this issue in this study.

Many researchers today cautiously discuss about the Martian palaeo-ocean and its shorelines, and despite some geological evidence, the issue of the existence of an ocean on early Mars remains in debate (Schmidt *et al*., 2022).

Using geomorphological mapping, Context Camera (CTX), High-Resolution Imaging Science Experiment (HiRISE) and Thermal Emission Imaging System (THEMIS) in the southeast of the Acidalia Planitia (northwest of the Arabia Terra), and the Chryse Planitia, some researchers have claimed that there are geomorphological features of tsunami-induced sediments on Mars. They claim that these sedimentary features are related to two megatsunamis from large collisions in the Martian palaeo-ocean that occurred 3.4 billion years ago (Iijima *et al*., 2014; Rodriguez *et al*., 2016; Costard *et al*., 2017).

In this study, we investigate the effect of collision-induced megatsunamis on possible microbial life in the ancient Martian ocean, assuming the presence of an ocean in the northern plains, and the presence of microbial life in it.

Characteristics of tsunami wave propagation in the palaeo-ocean of Mars

Due to the low gravity of Mars, the height of the tsunami waves caused by the large collisions in the northern plains was more than the common terrestrial tsunamis. Because the topography of Mars has changed a lot since the disappearance of the palaeo-ocean, it is impossible to calculate with certainty the propagation characteristics of megatsunami waves on the surface of Mars, and there is a significant error in this regard. However, it appears that the velocity of the megatsunamis waves attained 20 m s^{-1} in the vicinity of impact craters, and 16 m s^{-1} near the shoreline (Iijima *et al*., 2014). Megatsunamis are also estimated to be up to 120 m high, and 570 000 km^2 area (Billings, 2016; Drake, 2016; Sumner, 2016).

Distribution of proposed microbial life in the Martian palaeo-ocean

In terrestrial oceans, microbial life is found in the tidal flat, continental margin, oceanic trench, abyssal plain and in the vicinity of mid-ocean ridges (Fig. 1). Nevertheless, the topography of the ancient Martian ocean floor in the Vastitas Borealis basin does not appear to be similar to the topography of the Earth's oceans' floor. This could be due to the lack of plate tectonics on early Mars (Yin, 2012; Costard *et al*., 2019). For this reason, geomorphological features such as mid-ocean ridges or

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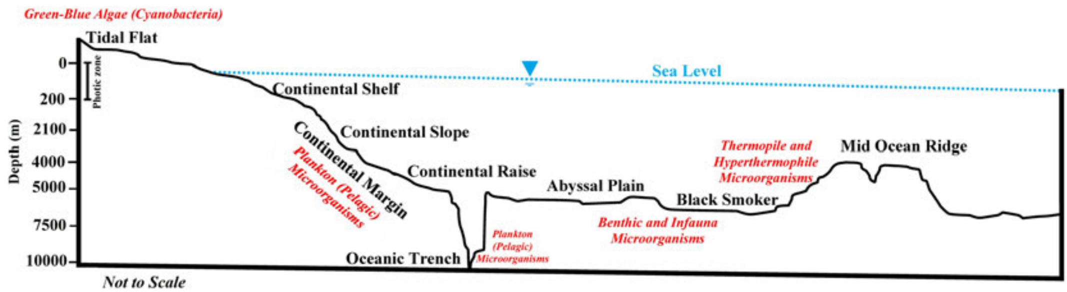

Fig. 1. *General topography of the Earth's oceans' floor and the distribution of microbial life in its various zones.*

oceanic trench do not appear to have formed on the Martian palaeo-ocean floor. As a result, the topographic structure of the Martian palaeo-ocean floor must have been simpler than that of Earth's oceans. Nevertheless, at least there should be zones such as the continental margin, and abyssal plain. Of course, large and numerous collisions have caused severe changes in the topography of the palaeo-ocean floor (Fig. 2).

In various parts of the simple topography of the Martian ocean floor, microbial life could have lived in the abyssal plain as a benthic (or infauna), or alongside black smokers. Some of the possible microorganisms may have been pelagic (planktonic), and living on the continental margin. Others, such as cyanobacteria (green-blue algae), could have lived in the tidal flat of the palaeo-ocean. Of course, it is claimed that there was no spring tide in the ancient Martian ocean (Iijima *et al.*, 2014). In this case, cyanobacterial colonies may have formed in the vicinity of the shore.

In this study, we consider a situation similar to the Earth's oceans' floor for the distribution of microbial life in the ancient Martian ocean, and assume that the proposed microbial life in the Martian palaeo-ocean near the shore, in the form of planktonic on the continental margin, and existed in the form of benthic and infauna on the Martian ocean floor.

Effect of megatsunamis waves on microbial life in the Martian palaeo-ocean

When a Tsunami wave base encounters the oceanic basin floor, it can displace the whole of life forms on the floor, inside sediments, pelagic and even in the tidal flat or shore moving them far distances from their initial location (Robinson and Bernard, 2009). Some microorganisms can remain in the palaeo-ocean after the occurrence of megatsunamis. In this case, the change in the physico-chemical properties of seawater (such as salinity, oxygen level, light penetration depth or photic zone and nutrient content) due to the tsunami waves (Satpathy *et al.*, 2008; Haldar *et al.*, 2013; Bhattacharyya *et al.*, 2014; Somboonna *et al.*, 2014; Kakehi *et al.*, 2017), can create an extreme environment suitable for the growth of extremophile microorganisms (such as halophiles). But some other microorganisms that would not be compatible with increasing salinity, decreasing temperature or increasing seawater turbidity, would be eliminated.

Life in tsunami sediments and preservation of microbial fossils

Suitable sediments for microbial fossilization

Microbial life does not readily undergo fossilization, and large amounts of clay deposits are required to preserve them as a fossil. For instance, on the Earth, fossils of microorganisms such as Ediacaran period bacteria are well preserved due to their presence in clayey covers. As a result, these clay deposits on Mars can also provide a suitable environment for the preservation of microbial fossils (Joel, 2016).

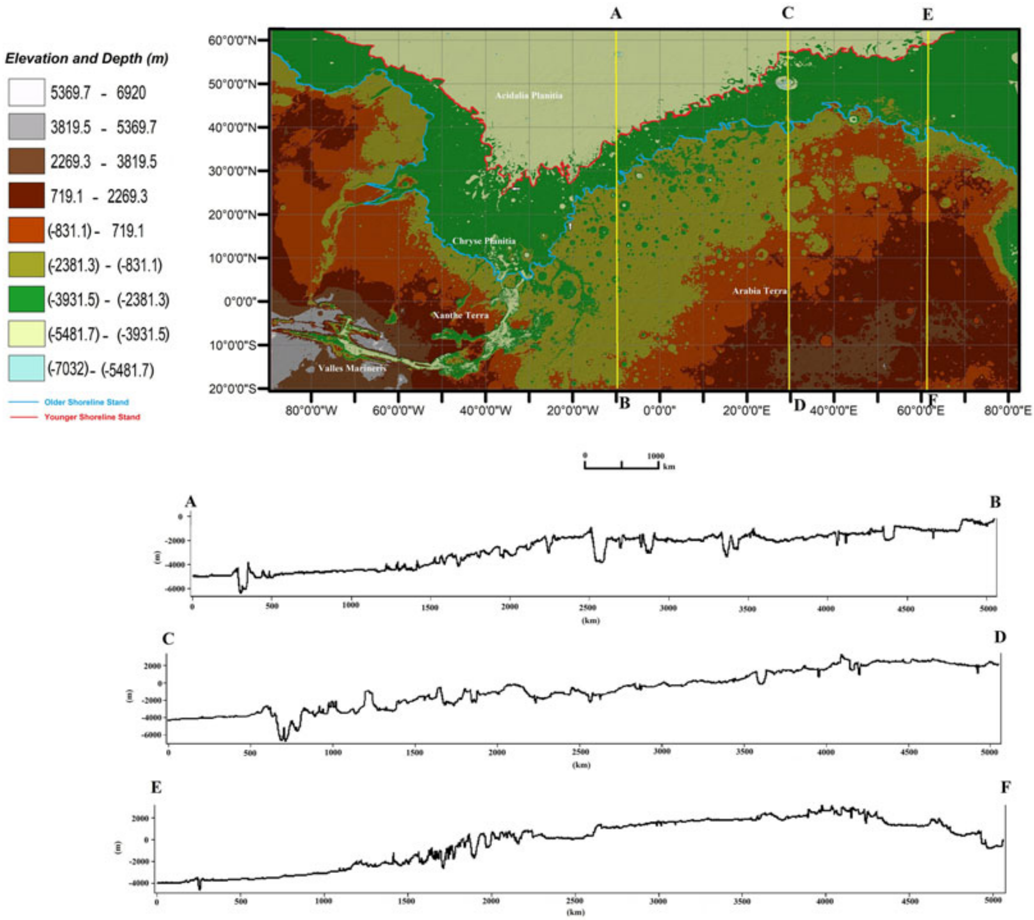

Fig. 2. Proposed oceanic basin for the ancient Martian ocean at Vastitas Borealis and its possible shorelines. The proposed ancient ocean floor topography is not similar to the Earth's oceans' floor, which could be due to the lack of plate tectonics on early Mars and the effects of large collisions. Produced via MOLA digital elevation models (460 m pixel^{-1}), in Esri's ArcGIS® 10.2 software (http://www.esri.com/software/arcgis). Credit: MOLA Science Team, MSS, JPL, NASA.

Preservation of microbial fossils in sediments caused by Martian megatsunamis

Thumbprint terrains

Thumbprint terrains are part of the geomorphological features of the Martian megatsunamis, discovered by geomorphological mapping, CTX and THEMIS imaging in the southeast of the Acidalia Planitia (northwest of the Arabia Terra), and the Chryse Planitia. Due to the high albedo of thumbprint terrains, they appear to be coarse-grained and made of sand, gravel and rock fragments (Costard *et al.*, 2017; Di Pietro *et al.*, 2021) (Fig. 3).

Because tsunami waves carry large volumes of marine sediments and seawater into mainlands, there is definitely marine microbial life in tsunami sediments (Somboonna *et al.*, 2014). Nevertheless, in tsunami-induced thumbprint terrain deposits due to an abundance of coarse-grained sediments and deficiency of clay particles, the chances of preserving marine microbial life as a fossil for billions of years are very low.

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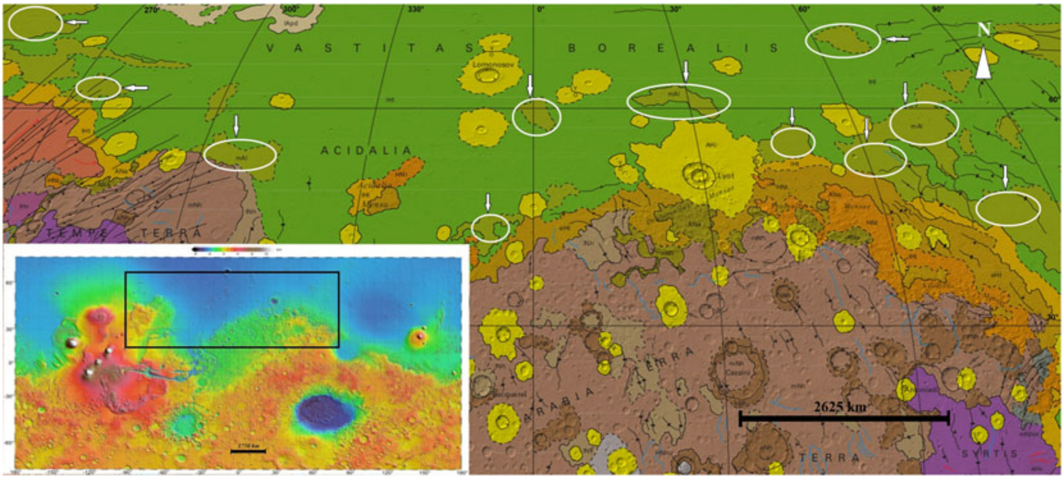

Fig. 3. *Distribution of tsunami-induced thumbprint terrain deposits in the northern plains, on the geological map of Mars. Courtesy of USGS, 2014 (at a scale of 1 : 20 000 000).*

Boulder fields and ice-rich lobes

HiRISE images show large metre-sized boulders on the northern plains of Mars. Numerous boulder fields have been identified at the Gusev crater, Isidis and Elysium Planitia (Golombek *et al*., 2003, 2008; Iijima *et al*., 2014; Rodriguez *et al*., 2016) (Fig. 4). Some of these bouldery sediments have accumulated concentrically around the impact craters, and upon the proposed marine terraces of the palaeo-ocean (Fig. 5). For this reason, many researchers have suggested that these bouldery sediments are caused by megatsunamis waves (Iijima *et al*., 2014; Rodriguez *et al*., 2016) (Fig. 6).

Two individual megatsunamis appear to have occurred in the ancient Martian ocean about 3.4 billion years ago, a few million years apart. The first megatsunami caused by a collision occurred in a liquid ocean, and caused the boulder rocks to scatter on the surface of Mars. Nevertheless, the second megatsunami occurred in a frozen ocean (due to the cooling of the Martian climate), scattering ice-rich lobes on the surface of the Red Planet (Drake, 2016; Rodriguez *et al*., 2016; Sumner, 2016; Di Pietro *et al*., 2021). Some impact craters on the northern plains, such as the Lyot crater (48°33′42.7″N, 18°12′46.7″E), have the ice-rich ejecta from the second megatsunami (Di Pietro *et al*., 2021).

Considering the sedimentological properties required to preserve microbial fossils, it is clear that microorganisms transferred from the ancient Martian ocean have no chance of preservation in boulder fields on the northern plains. Considering that life can survive in frozen oceans and snowball terrestrial planets (or moons) (Sutherland, 2022), the ice-rich lobes from the second megatsunami in the frozen ocean of Mars can preserve microbial life.

Tsunami palaeo-lakes on Mars

Martian palaeo-lakes that formed in impact craters are mainly of glacial, fluvial, rainfalls and groundwater rise origin (Hargitai *et al*., 2018; Zhao *et al*., 2020; Boatwright and Head, 2021).

In lacustrine environments, phyllosilicate clays and evaporite sediments are abundant, which is a suitable sedimentological property for the preservation of microbial fossils (Anderson, 2012; Zhao *et al*., 2020).

Nevertheless, there was another group of palaeo-lakes on Mars that were fed directly by tsunami waves (Drake, 2016). That is, the craters that are older than the megatsunamis, and existed near the proposed shorelines at the time of the megatsunamis occurrence.

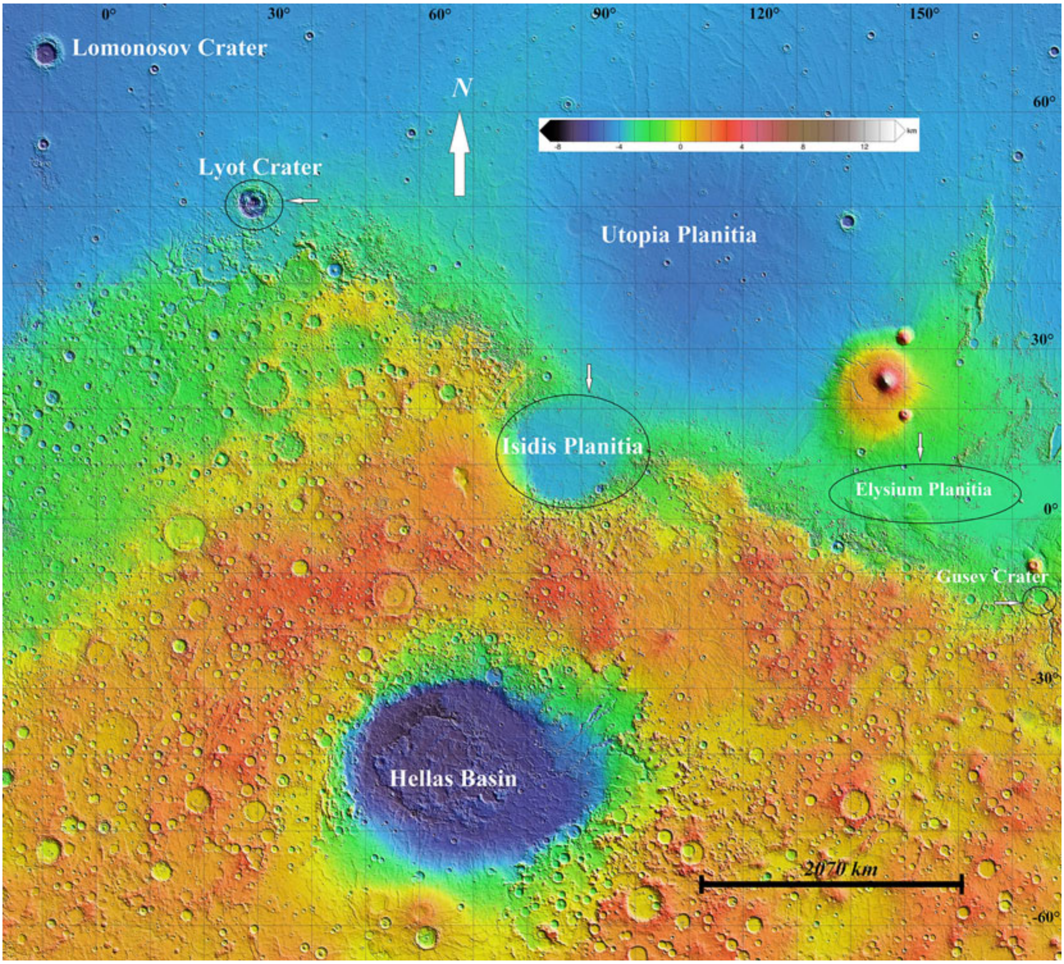

Fig. 4. Distribution of boulder fields in the northern plains within the Gusev crater, Isidis and Elysium Planitia. The ice-rich ejecta resides in Lyot crater. Image via Mars Orbiter Laser Altimeter (MOLA). Courtesy of NASA GSFC.

In this case, some of the impact craters near the Chryse Planitia, which are older than the mentioned megatsunamis (3.4 billion years ago), could have been tsunami-induced lakes or pools, which foster the marine microbial life and preserve the fossil signatures.

Another group of tsunami palaeo-lakes can be formed indirectly from runoffs due to outflow channels caused by tsunami waves on mainlands (Boatwright and Head, 2021).

Some impact units in the vicinity of Chryse Planitia are older than the Early Hesperian, which was more than 3.56 billion years ago. There are more than seven impact craters near the proposed shorelines in the Chryse Planitia older than the Early Hesperian. The mentioned megatsunamis occurred roughly 3.4 billion years ago; as a result, craters near the Chryse Planitia that are approximately the age of Early Hesperian or older, may have been tsunami lakes in the past (Fig. 7).

Conclusion

Considering the effect of terrestrial tsunamis on marine ecosystems, including microorganisms, and the discovery of some geological evidence of megatsunamis on early Mars, Martian megatsunamis could have influenced the proposed microbial life in the ancient Martian ocean.

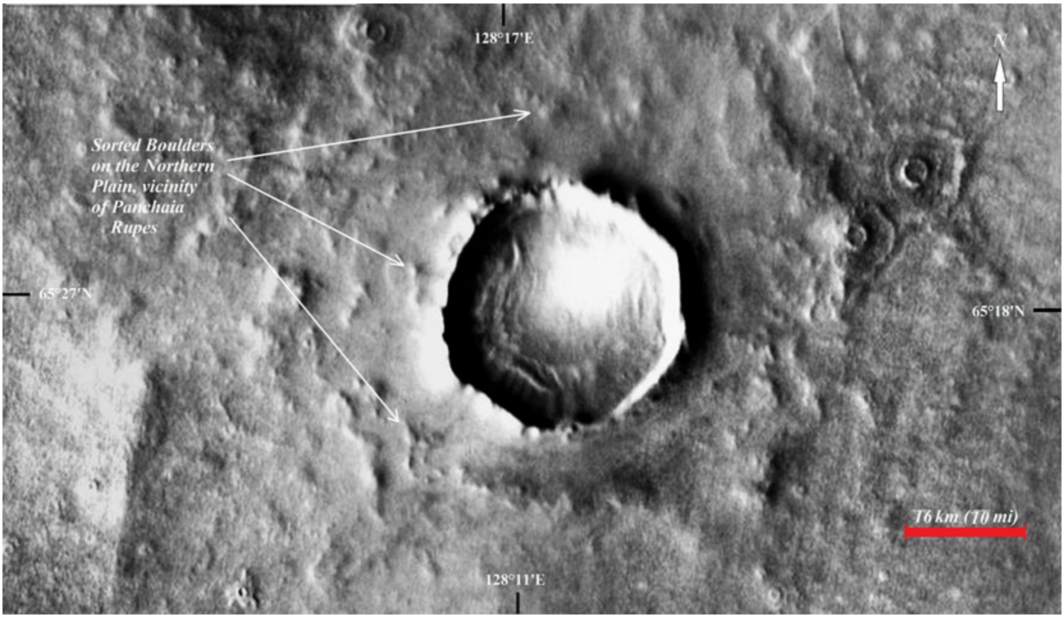

Fig. 5. *Concentrated large sorted boulders around an impact crater in the northern plains in the vicinity of Panchaia Rupes. Image via THEMIS daytime Infrared. Courtesy of NASA/JPL/Univ. of Arizona.*

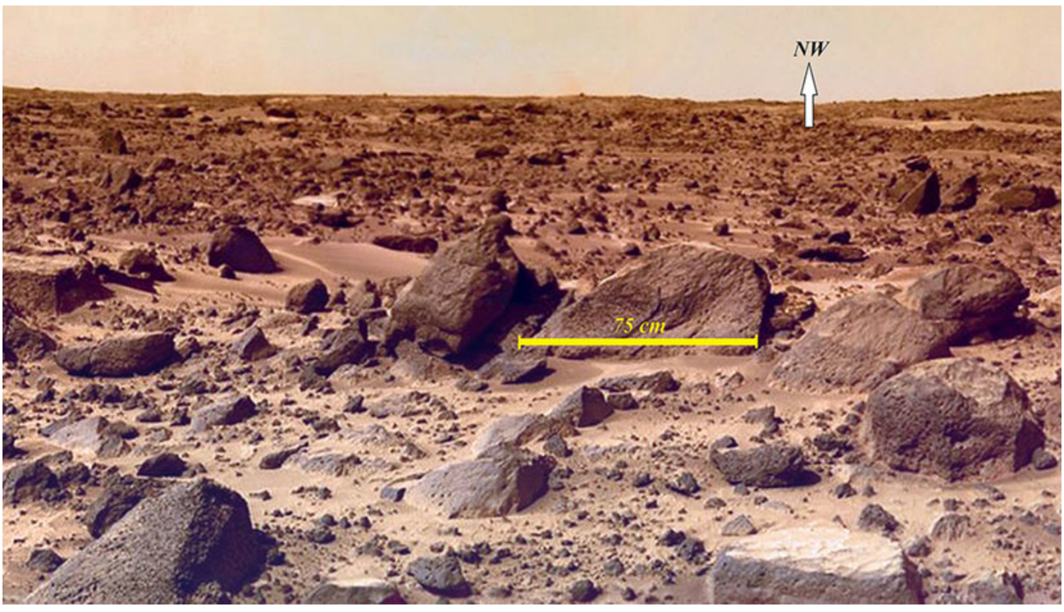

Fig. 6. *Boulder field was caused by massive torrential currents at the landing site of the Mars Pathfinder in 1997. The Ares Vallis on the northern plains (19.13°N, 33.22°W). Courtesy of NASA / JPL-Caltech/Popular Mechanics.*

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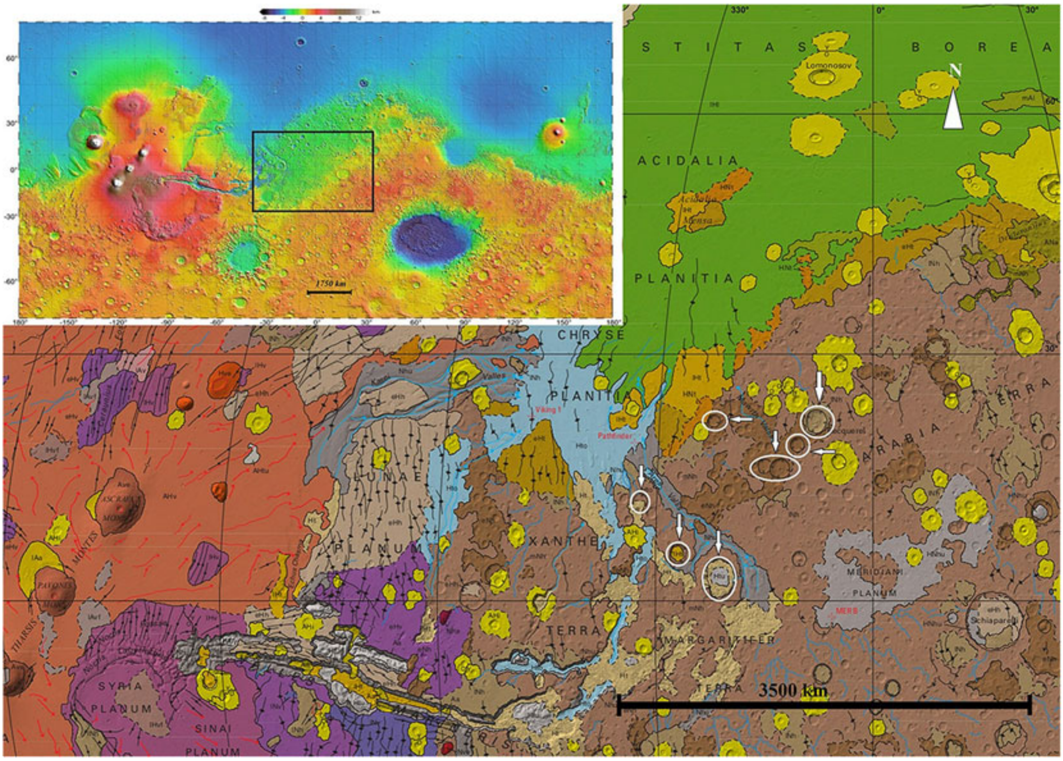

Fig. 7. Some impact craters near the Chryse Planitia are older than the Early Hesperian, which may have been tsunami lakes in the past, that have bred marine microbial life, and preserved it as a fossil. Courtesy of USGS, 2014 (at a scale of 1 : 20 000 000).

Changes in the physico-chemical properties of seawater, and the transfer of microbial life into soils and crateric lakes on the mainlands of early Mars, were among the effects of tsunami waves on microbial life of the Martian palaeo-ocean.

Tsunami waves have also been implicated in the preservation or non-preservation of fossil signatures on early Mars. Tsunami-induced deposits, such as boulder fields and thumbprint terrains, do not have appropriate sedimentological properties for microbial fossilization. Nevertheless, the ice-rich lobes from the tsunami in the frozen palaeo-ocean of Mars in the Early Hesperian, and the tsunami lakes in the vicinity of proposed palaeo-ocean shorelines, have good conditions for the fossilization of marine microbial life of early Mars.

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References

Anderson PS (2012) New analysis of clay deposits in ancient Martian lakes. Phys.org.

Becker R (2021) Is there life on Mars? Where is the proof. *Journal of Astrobiology* **7**, 38–75.

Bhattacharyya P, Karak T, Chakrabarti K, Chakraborty A, Paul RK and Tripathi S (2014) Did tsunami tremor jolt microbial biomass and their activities in soils? A case study in Andaman Island, India. *Environmental Earth Sciences* **72**, 1443–1452.

Billings L (2016) Giant tsunami remnants spotted on Mars. Scientific American.

Boatwright BD and Head JW (2021) A Noachian proglacial paleolake on Mars: fluvial activity and lake formation within a closed-source drainage basin crater and implications for early Mars climate. *The Planetary Science Journal* **2**, 52.

Cabrol NA (2018) The coevolution of life and environment on Mars: an ecosystem perspective on the robotic exploration of biosignatures. *Astrobiology* **18**, 1–27.

Costard F, Séjourné A, Kelfoun K, Clifford S, Lavigne F, Di Pietro I and Bouley S (2017) Modeling tsunami propagation and the emplacement of thumbprint terrain in an early Mars ocean. *Journal of Geophysical Research: Planets* **122**, 633–649.

Costard F, Séjourné A, Lagain A, Ormö J, Rodriguez JAP, Clifford S and Lavigne F (2019) The Lomonosov crater impact event: a possible megatsunami source on Mars. *Journal of Geophysical Research: Planets* **124**, 1840–1851.

Di Pietro I, Séjourné A, Costard F, Ciazela M and Rodriguez JAP (2021) Evidence of mud volcanism due to the rapid compaction of Martian tsunami deposits in southeastern Acidalia Planitia, Mars. *Icarus* **354**, 114096.

Drake N (2016) Tsunamis on Mars? Splashy claim raises eyebrows. Notionalgeographic.com.

Goetz W, Brinckerhoff WB, Arevalo R, Freissinet C, Getty S, Glavin DP and Brucato JR (2016) MOMA: the challenge to search for organics and biosignatures on Mars. *International Journal of Astrobiology* **15**, 239–250.

Golombek MP, Haldemann AFC, Forsberg-Taylor NK, DiMaggio EN, Schroeder RD, Jakosky BM and Matijevic JR (2003) Rock size? Frequency distributions on Mars and implications for Mars exploration rover landing safety and operations. *Journal of Geophysical Research: Planets* **108**, 1–27.

Golombek MP, Huertas A, Marlow J, McGrane B, Klein C, Martinez M and Cheng Y (2008) Size–frequency distributions of rocks on the northern plains of Mars with special reference to Phoenix landing surfaces. *Journal of Geophysical Research: Planets* **113**.

Haldar D, Raman M and Dwivedi RM (2013) Tsunami – a jolt for phytoplankton variability in the seas around Andaman Islands: a case study using IRS P4-OCM data. *Indian Journal of Geo-Marine Sciences* **42**, 437–447.

Hargitai HI, Gulick VC and Glines NH (2018) Paleolakes of northeast Hellas: precipitation, groundwater-fed, and fluvial lakes in the Navua-Hadriacus-Ausonia region, Mars. *Astrobiology* **18**.

Iijima Y, Goto K, Minoura K, Komatsu G and Imamura F (2014) Hydrodynamics of impact-induced tsunami over the Martian ocean. *Planetary and Space Science* **95**, 33–44.

Joel L (2016) How did fragile early microbes become fossils? *Eos*, 97. Available at https://doi.org/10.1029/2016eo057519.

Joseph RJ, Graham L, Büdel B, Jung P, Kidron GJ, Latif K and Schild R (2020) Mars: algae, lichens, fossils, minerals, microbial mats, and stromatolites in Gale crater. *Journal of Astrobiology and Space Science Reviews* **3**, 40–111.

Kakehi S, Kamiyama T, Kaga Y, Naiki K and Kaga S (2017) Improvement in the dissolved oxygen concentration and water exchange in Ofunato Bay, Japan, after the collapse of the bay? Mouth breakwater by the 2011 Tohoku earthquake and tsunami. *Fisheries Oceanography* **26**, 114–127.

Mahaney WC, Dohm JM, Costa P and Krinsley DH (2010) Tsunamis on Mars: earth analogues of projected Martian sediment. *Planetary and Space Science* **58**, 1823–1831.

Makino A, Xu J, Nishimura J and Isogai E (2019) Detection of *Clostridium perfringens* in tsunami deposits after the great east Japan earthquake. *Microbiology and Immunology* **63**, 179–185.

Masuda R, Hatakeyama M, Yokoyama K and Tanaka M (2016) Recovery of coastal fauna after the 2011 tsunami in Japan as determined by bimonthly underwater visual censuses conducted over five years. *PLoS ONE* **11**, e0168261.

Robinson AR and Bernard EN (2009). *The Sea. Vol 15: Tsunamis*. Cambridge, MA and London, England: Harvard University Press, pp. 53–91.

Rodriguez JAP, Fairén AG, Tanaka KL, Zarroca M, Linares R, Platz T and Glines N (2016) Tsunami waves extensively resurfaced the shorelines of an early Martian ocean. *Scientific Reports* **6**, 1–8.

Satpathy KK, Mohanty AK, Prasad MVR, Natesan U and Sarkar SK (2008) Post-tsunami changes in water quality of Kalpakkam coastal waters, east coast of India with special reference to nutrients. Asian Journal of Water, *Environment and Pollution* **5**, 15–30.

Schmidt F, Way MJ, Costard F, Bouley S, Séjourné A and Aleinov I (2022) Circumpolar ocean stability on Mars 3 Gy ago. *Proceedings of the National Academy of Sciences* **119**.

Somboonna N, Wilantho A, Jankaew K, Assawamakin A, Sangsrakru D, Tangphatsornruang S and Tongsima S (2014) Microbial ecology of Thailand tsunami and non-tsunami affected terrestrials. *PLoS ONE* **9**, e94236.

Stanley S (2020) Crater, Tsunamis, and Minerals on Mars. *Wondrium Daily.*

Sumner T (2016) Ancient tsunamis reshaped Mars' landscape. *ScienceNews*.

Sutherland S (2022) Ancient asteroid impact may have triggered Mars mega-tsunami. *The Weather Network*.

Witze A (2016) Giant tsunamis washed over ancient Mars. Nature.com. Available at https://doi.org/10.1038/nature.2016.19916.

Yin A (2012) An episodic slab-rollback model for the origin of the Tharsis rise on Mars: implications for initiation of local plate subduction and final unification of a kinematically linked global plate-tectonic network on Earth. *Lithosphere* **4**, 553–593.

Zhao J, Xiao L and Glotch TD (2020) Paleolakes in the Northwest Hellas region, Mars: implications for the regional geologic history and paleoclimate. *Journal of Geophysical Research: Planets* **125**, e2019JE006196.