OPINION & DISCUSSION

# Presence of hydrocarbons on Mars: A possibility

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## ABSTRACT

There exists a fair degree of geological similarity between the internal structure of Mars, its orbital cycle, and axis tilt with that of Earth. The early plate tectonics along with subaerial volcanism have emitted oxygen as evident in the geological history of Earth during the Archaean–Proterozoic transition. The ancient Valles Marineris equatorial rift basin of Mars could have resulted because of lithospheric dynamics. The associated large-scale transtensional strike-slip during the Late Amazonian Period further implies manifestation of possible plate tectonics on Mars.

The presence of the earliest organic species, 3.7 billion years ago, had been established on Earth. The presence of lake and ocean and evidence of glaciation infer probable evolution of life in early Mars. The depositional morphology like alluvial fans, debris flow fans, deltas, and lacustrine fans implies possible sedimentation processes active on early Mars.

Organic matters on Mars could be in situ or could have been delivered by meteorites. The presence of organic molecules of benzene and propane in 3-billion-year-old rock samples has been evidenced in Gale crater. Deposition of source rock and subsequent decomposition of organic matter could have generated hydrocarbons in early Mars. A comparative geological phenomenon between Meso-Neoproterozoic petroleum geology of Earth and the equivalent Amazonian and older periods has been analyzed in the light of the envisaged hydrocarbon generation and entrapment on early Mars. Possible martian petroleum systems of the ancient Valles Marineris rift basin and crater-induced basins including prevalence of gas hydrate and abiotic origin of methane have been studied.

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## INTRODUCTION

There lies a greater similarity of the evolution history of Mars, its interior, presence of the possible epeiric sea or epicontinental sea, early plate tectonics, associated mountain building, and rock stratigraphy with that of our Earth. Based on the impact crater densities, the martian geological time scale has been divided into Pre-Noachian (4.5–4.1 Ga), Noachian Period (4.1–3.7 Ga), Hesperian (3.7–3.0 Ga), and Amazonian (3.0 Ga to present) with decrease in density of meteorite impact during the Amazonian Period (Tanak, 1986). The evolution of planet Mars started during the Pre-Noachian (4.5–4.1 Ga), and there seems to have been an initiation of topographical manifestation of the northern lowlands and the southern highlands during this period. During the Noachian Period (4.1–3.7 Ga), ephemeral lakes might have formed in basins and craters along with a shallow ocean in the northern lowlands. Possible favorable conditions could have been prevalent for evolution of life during this period. The Early Noachian witnessed impact-basin formation such as Utopia, Hellas, Argyre, and Isidis with volcanism. The volcanism with lava flow continued through the Hesperian (3.7–3.0 Ga) and gradually decreased in the Amazonian Period (3.0 Ga to present). The Early Hesperian witnessed the Valles Marineris rifting with the giant Tharsis volcano. Active fluvial activities have been observed from the Late Hesperion through the Amazonian periods. Episodic glaciation, gully formation, and polar layered deposits have been observed during the Amazonian Period (Carr, 2012).

The history of biological evolution on Mars could have been attributed to either in situ phenomenon or from outside by meteoritic collisions. The initial development of biological instinct is broadly influenced by geochemical phenomena because it has been observed on Earth since Proterozoic (2.5 billion yr) time. Mars and Earth have similar $^{12}C/^{13}C$ and $^{16}O/^{18}O$ ratios. The excess of $^{13}C$ in the martian atmosphere over $^{12}C$ could be an indicator of ancient biotic activities (Rothschild and DesMarais, 1989).

The biogenic remains, amorphous organic matter, and algal filaments associated with the Proterozoic strata have generated hydrocarbons. The Meso-Neoproterozoic petroleum system has been established in various basins of the world with hydrocarbons trapped within the basement-controlled structures (Padhy, 1995, 1997). The Pan-African tectonism of the Neoproterozoic age (1000–540 Ma) witnessed the deposition of salt-anhydrite, carbonate, and sandstone in different basins of North Africa, Siberia, and Asia (Gulf, Oman, China, Pakistan, India) and Australia (Craig et al., 2009).

By analyzing the petroleum systems of Earth during Meso-Neoproterozoic (1600–540 Ma) time, it is envisaged that Earth analogous early hydrocarbons might have been generated and preserved in ideal locales like the ancient Valles Marineris rift and crater-induced basins. The concept of gas hydrate petroleum system could be another promising resource on Mars, including abiotic methane generated as a fractionation product of magma crystallization, serpentization, and by the Fischer–Tropsch-type (FTT) process.

## MESO-NEOPROTEROZOIC PETROLEUM SYSTEM ON EARTH

The Proterozoic Period is characterized by crustal stabilization and the evolution of cratonic basins. Theories on early Proterozoic plate movement and Proterozoic rift system have been envisaged based on plume-activated lithospheric activities (Wynne-Edwards, 1976; Hoffman, 1980; Kröner, 1983). The presence of microbes as old as between 3.77 to 4.29 billion yr has been evidenced in rocks in Canada. The Neoproterozoic Period can be broadly divided into preglacial Neoproterozoic petroleum systems (1000–750 Ma) and postglacial petroleum systems of 750–600 Ma (Craig et al., 2009).

The tectono-sedimentation of the Proterozoic rift systems is characterized by the deposition of sedimentary rocks. The Neoproterozoic Period witnessed episodically related Pan-African rift tectonics with deposition of stromatolitic carbonate, sandstone, anhydrite, and shale. Generally, the Proterozoic carbonates are developed in the form of ramps in extensional and foredeep set-ups and in the form of the rimmed shelf in more-stable thermally subsiding basins (Grotzinger, 1989). During the intervening warm period, there had been photosynthetic activity and cyanobacterial metabolism that resulted in oxygenation of the atmosphere (Young, 2013). The stromatolites biota assemblage infers the presence of the late Proterozoic shallow sea platformal shelf environment. The stable carbon (–0.14 to 4.5) and oxygen (–0.4 to –15.9) isotopic compositions of subcrop late Proterozoic age infer predominance of nearshore environment.

The presence of hydrocarbons in the Proterozoic, particularly in the Meso-Neoproterozoic age, has gained wider importance. The stromatolitic carbonate corresponds to a global Meso-Proterozoic event with special reference to the depositional and environmental aspects. Stromatolites, biogenic remains, amorphous organic matter, and algal filaments associated with Proterozoic strata, on deep burial, have contributed to the generation of hydrocarbons. The Meso-Neoproterozoic witnessed a bioevent with an exposition of Ediacara fauna, spiny acritarchs. The presence of the most ancient hydrocarbons in the Warrawoona Group (>3.46 Ga) of Pilbara basin, Australia, and in the Witwatersrand Super Group (~2.85 Ga) of Kaapvaal Craton, South Africa, has been documented (Buick et al., 1998). The oldest live oil (1.36–1.28 Ga) has been found in McArthur basin (Craig et al., 2009). The evidence of terrestrial microbial mats in siliciclastic rocks dates back to 2.75 Ga (Paleoproterozoic) of fluvio-lacustrine sediments of the Hardey Formation of the Pilbara craton in Western Australia. The world's oldest significant hydrocarbon source rocks are the shungite deposits (2.0 Ga) in the Lake Onega region of Arctic Russia (Craig et al., 2013). The Proterozoic source rock extracts and oils are characterized by relatively high abundances of monomethylalkanes, alkylcyclohexanes, and methylalkylcyclohexanes and very low abundances of acyclic isoprenoids, including pristane and phytane. This infers presence of cyanobacteria as the dominant source of organic matter during the Proterozoic time (Craig et al., 2013).

The occurrence of hydrocarbons has been observed in the Meso-Neoproterozoic strata of Lena-Tunguska basin, Siberia (Meyerhoff, 1980); Bohai and Sichuan basins, China (Korsch et al., 1991); Taoudeni basin of North Africa (Villanueva et al., 2016); Sao Francisco basin of Brazil (Bruno et al., 2009); Amadeus and McArthur basins, Australia (Muir et al., 1980); Eastern Flank province of southern Oman (Grantham et al., 1988); and Vindhyan basin of India (Naik et al., 1991; Padhy, 1997; Verma et al., 2002). Primarily sandstone and limestone constitute the reservoir rocks, and hydrocarbons are accumulated in structurally controlled traps with shale and evaporite acting as effective seal rocks.

Postglacial Neoproterozoic–Early Cambrian petroleum systems on the Peri-Gondwana are characterized by fault-bounded rift basins filled with organic-rich shale deposited during postglacial transgression. The sedimentary sequences of Bikaner–Nagaur basin, Potwar basin of Pakistan, Hormuz Group of Gulf, and Huqf Group of Oman (Gorin et al., 1982) are deposited under a semiarid to arid climate. The salt basins along the primeval Proterozoic rift lie closely parallel to the Afro-Asian plate margin (Piper, 1983). The synrift carbonate-evaporate deposit of Bikaner–Nagaur basin is well correlated with the salt range of Punjab basin and Hormuz of Gulf basin (Padhy and Singh, 1998). The carbonate-evaporite assemblage could be related to periodical cut off from the open sea (Tucker, 1991). The tectono-depositional system of Bikaner–Nagaur and the Himalayan foreland basins (Krol, Spiti, Zanskar, Kashmir, Kumaon) of northern and northwestern parts of India exhibit a possible southeastern extension of the Proterozoic rift system (Peters et al., 1995; Padhy, 1997). The presence of bitumen within the Neoproterozoic sequence in the central cratonic basins of India has rendered some interesting insight into the envisaged oldest petroleum occurrences (Padhy, 1997; Padhy and Yalamurty, 2002).

The Neoproterozoic–Early Paleozoic witnessed a shallow marine environment all through the northern part of the Gondwana. The preglacial Neoproterozoic petroleum systems on the Peri-Gondwana Margin are largely restricted to cratonic shield in the form of sag basins filled with conglomerate, stromatolitic carbonate, quartzitic sandstone, and shale. The black shales containing organic matter of algal, filamentous cyanobacterial sheaths, and amorphous organic matter constitute the source rock. Biological markers, namely isoprenoids, steranes, tricyclic terpanes, and gammacerane, are found in 1.7-billion-yr-old Jixian strata of Tuanshanzi formation, north China, and the geochemical characteristics indicate deposition of the sediments in marine carbonate environment (Peng et al., 1998).

## MARS PLATE TECTONICS, CLIMATE, AND BIOLOGICAL EVOLUTION

Earth has been witnessing a phenomenon of active plate tectonics that periodically recycle the crust and the upper mantle under convective motion. There has also been evidence of the prevalence of plate tectonics on Earth during the Precambrian time. Generally, when the mantle is subjected to the convective motion, plate movement occurs by heat exchange between the core and the mantle. The spatial distributions of petroleum-rich provenances are broadly associated with the extensional, compressional, and poly-phase tectonic set-ups through geological time on Earth. The core is composed of a convective liquid outer core and a solid inner core rich in iron, nickel, and sulfur. Martian crust is thicker than that of Earth. The mantle is subject to convective motions that contribute to possible plate movements.

Ancient landforms, magmatic complexes, mountain ranges, and typical tectonic grains have been interpreted in the light of early plate tectonism on Mars (Dohm et al., 2001). Rift systems along with intrusive related (volcanic) tectonics have occurred around south of the central part of Valles Marineris, including Warrego Valley during the Late Noachian to the Early Hesperian, and the troughs are characterized by outflow of channels (Dohm et al., 1998).

Mars has a linear volcanic zone, which is envisaged as a typical manifestation of plate tectonics (Yin, 2012). The tectonic model has been interpreted by analyzing the high-resolution thermal emission imaging system, context camera, and High Resolution Imaging Science Experiment images across two trough zones: Ius Chasma in the west and Coprates Chasma in the east along the linear Valles Marineris rift system along the martian equator (Yin, 2012). The Ius-Melas-Coprates trough zone is characterized by left-slip transtensional deformation (>2000 km in length with >100 km in total slip) during the Late Amazonian time, younger than 0.7 Ga, although the tectonic grains might have existed during the Noachian Period (Yin, 2012). The structural assemblages comprised northeast extensional and northwest-trending compressional structures. It is analogous to Earth's Dead Sea fault system (Yin, 2012), which represents a typical plate boundary.

The presence of syntectonic and intraformational soft-sediment structures in Upper Amazonian strata infers the presence of surface water along with the drainage deflections during the development of the left-slip transtensional faulting (Yin, 2012). The transtensional structural framework infers a rift with rift-fill sediments, akin to a rift basins of Earth. It is presumed that subcrustal deformation might have taken place, and plate tectonic activity, albeit, at a slower rate, might have prevailed on Mars.

The pace of biological evolution is well matched with the rates of tectonic and surface processes over geological time as evinced by Bjornerud (2018). Subduction of the oceanic crust releases water, and it is evident that subaerial volcanism has led to increasing oxygen levels in the atmosphere as observed during the Archaean–Proterozoic geological transitional time on Earth (Kump and Barley, 2007). A possible carbon cycle has been triggered by the weathering process. The carbon cycle perturbation could lead to carbon sequestration, resulting in methane hydrate release under extreme cold followed by the extreme warm climate and thus releasing biogenic (photosynthetic fixed) carbon. It is envisaged that the manifestation of the carbonate–silicate cycle of Earth could be a near possibility on Mars because of incipient subduction and volcanism resulting in emission of carbon dioxide. There could be initial nonoxygen producing (anoxygenic) stromatolite forming microbes on Mars as observed in the Early Archaean cherts in Isua and Warrawoon rocks of southwestern Greenland (Westall and Folk, 2003).

The dust cloud from asteroid collisions might have trigged the life on Earth (Schmitz et al., 2019). Meteorite impact on the surface of Mars could have facilitated possible biodiversity. The iron-rich dust in the proto-ocean (iron fertilization) could be one of the prime factors for plankton production. The presence of hematite on Mars' surface also infers a process of probable oxygen bonding with the ancient iron-rich ocean. Recent scientific data infer the probable presence of ancient ocean in the northern plains and adjacent to the southern highlands on Mars (Max et al., 2013). It is estimated that the martian surface had been covered by the primordial ocean to the tune of 36%–75% (Mohamed, 2015).

Certain mineralogical occurrences indicate an aqueous process that our Earth has undergone in the geological past. Analogous mineralogical assemblages have been seen on Mars, also. The presence of minerals such as serpentine (the hydrous magnesium mineral) has been inferred from Arsia Chasma on Mars (Jain and Chauhan, 2014). Presence of phyllosilicates and carbonates from Capri Chasma regions (Jain and Chauhan, 2015) based on Mars Reconnaissance Imaging Spectrometer for Mars has been proved. This further infers water-associated alteration or weathering processes might have occurred on Mars terrain in the geological past. The present surface alteration leading to the planet's red color is because of anhydrous ferric oxide.

Earth geology reveals that the Proterozoic terminal phase witnessed glacio-marine/turbidity deposits along with carbonates, chert, and phosphorite. Evidence of glacial features has been postulated in the volcanic province in Alba Patera (Sinha and Murty, 2013a) within the pole-facing craters (45°N to 39°N) and in the Protonilus Mensae areas of Mars (Sinha and Murty, 2013b). The oldest occurrence of glaciation on Mars dates back approximately 1 billion yr ago (Levy et al., 2007). The midlatitude glaciers on Mars have been dated to millions of years (Baker and Head, 2015).

## ENVISAGED PETROLEUM GEOLOGY OF MARS

The conventional petroleum system that prevailed on Earth is characterized by the basic elements and processes of petroleum geology. The basic elements comprise source, reservoir, seal, and overburden rock. The important processes include trap formation and generation-migration-accumulation. The critical time of migration of hydrocarbons and effective entrapment within the porous and permeable reservoir give rise to commercial hydrocarbon deposits. Based on the geology of Mars and keeping in view the hydrocarbon distribution in the Meso-Neoproterozoic on Earth, possible prevalence of the martian petroleum system has been envisaged and discussed below.

## PLATE BOUNDARY AND ANCIENT RIFT

Although the present active plate tectonics, like Earth, are not prevalent on Mars, they might have been active in early Mars. The variation in crustal thickness (~32 km in the north versus ~58 km in the south) (Golombek and Phillips, 2009) along with the left-slip transtensional fault system between the northern lowlands and southern highlands might be attributed to lithospheric stress balancing. It is interesting to note that the regional structural fabric and the associated thrust faults, normal faults, and folds are attributed to plate tectonics and the crustal deformation of Mars. The structural set up of the Valles Marineris is envisaged to be in close resemblance with the petroliferous basins along the primeval Proterozoic rift system.

## SEDIMENTATION

The martian sedimentary rocks could be mainly mafic in composition because the provenance is primarily the basaltic rock. The ancient sedimentary deposits on Mars may be dominated by impact-generated debris sheets, breccias, and so on. The possible aqueous transport systems in the form of valley network fluvial channels have been active during the Late Hesperian–Early Amazonian time, although it becomes dry and dusty at present. The mass-flow, traction, and suspension transports could have also taken place. Stratified deposits and stacked pattern of sedimentation have been observed. The Hesperian lake sediments in Gale crater and the Amazonian periglacial sediments were deposited during the cold climate. The rock might have undergone diagenesis by chemical and physical weatherings. The presence of clay minerals, sulfate, carbonate, evaporate, or other hydrous minerals have been inferred. Various depositional morphologies like alluvial fans, debris flow fans, deltas, lacustrine fans, eolian bedforms, and duststone deposits on Mars have been interpreted (Grotzinger and Milliken, 2012).

## ORGANIC MATTER AND SOURCE ROCK

The source rock refers to the organic-rich sediments deposited primarily under anoxic conditions. The stromatolites of organic origin dating back to 3.7 billion yr ago have been found on Earth (Watson, 2016). The presence of stromatolites infers an intertidal mudflat environment (Logan et al., 1964). The presence of organic molecules of benzene and propane of 3-billion-yr-old rock samples in Gale crater has been observed from the sample taken by the Curiosity rover (Chang, 2018). Medium- to long-chain hydrocarbons, $C_{10}$–$C_{12}$ alkanes, have been detected in Gale crater, and these could act as important biosignatures (Miller et al., 2016; Freissinet et al., 2019). Thiophene is a heterocyclic compound with the formula $C_4H_4S$. Microbial thiophene production occurred on early Mars under ideal conditions. Thiophene detected on Mars by the Curiosity rover could be of biotic or abiotic origin (Heinz and Schulze-Makuch, 2020).

Organic matters on Mars could be in situ or could have been delivered by meteorites or interplanetary dust. The organic shale deposited within the Valles Marineris rift could act as a good source. The high geothermal heat and deep burial of the organic matters under anoxic conditions might have facilitated the generation of oil and gas on Mars. Subsequently, it might have expelled from the fine-grained source rock and migrated updip through the carrier bed, fault, or fractures to the reservoir rocks and accumulated in suitable traps with effective seal rock capping over it. Lacustrine shale could be a potential source rock. The Gale crater might be a vast salty lake, and the salt-loving methanogenic archaea-type microorganisms could be the potential biological source of methane (Schulze-Makuch, 2019).

## RESERVOIR ROCKS

The Meso-Neoproterozoic rift-fill lithology constitutes a suite of conglomerate-sandstone-carbonate-stromatolite-shale. Stratal geometries associated with progradation of shoreline and deltaic sediment wedges have been observed in Melas Chasma and Eberswalde Crater (Grotzinger and Milliken, 2012). From the interpretation of the morphological manifestation on Mars, the presence of sedimentary rocks has been envisaged with a probable fair degree of porosity and permeability. Impact-induced tectonism might have enhanced the secondary porosity (joints, fractures, etc.). The active fluvio-valley system during the Late Noachian to the Amazonian Period could have deposited terrigenous sediments as rift fills and crater fills.

## SEAL ROCK

The deposition of evaporite could have taken place in Earth analogous salt basins on Mars and could have acted as a seal. The intraformational rift-fill shale could also act as an effective seal.

## RIFT-FILL AND IMPACT-RELATED TRAPS

The oil and gas deposits could be preserved in the ancient traps associated with the rift tectonics or in the crater-induced basins. The Valles Marineris could be a promising rift basin analogous to that of the Archaean–Proterozoic basins of Earth. The martian surface has witnessed impact-related structures through the Noachian–Hesperian time with less intensity during the Amazonian Period. These craters are widely seen in the northern lowlands and the southern highlands. Impact-induced fault-bounded structural traps could be ideal locales of methane accumulation (Oehler and Etiope, 2017). This could be analogous to the crater-related structural traps, central uplifts, and updip crater rims found in North America. It is interesting to note that some of the impact-induced structures of Phanerozoic age, such as Ames structure, Oklahoma, and the Red Wing Creek structure of Williston basin, yielded hydrocarbons (Barton et al., 2009). Even fracturing during serpentinization may enhance secondary porosity and constitutes important reservoir rocks.

## PETROLEUM SYSTEM

The linear trough zones of the Valles Marineris were developed along the Late Noachian–Early Hesperian tectonic fabric and was later reactivated by left-slip transtensional faulting during the Late Amazonian time (0.7 Ga or younger). This rift system could be the Neoproterozoic equivalent of hydrocarbon province on Mars. Broadly, three petroleum systems have been envisaged.

## AMAZONIAN AND OLDER PETROLEUM SYSTEM

The organic source rock deposited in the ancient Valles Marineris rift basin might have generated hydrocarbons under high heat flow during early Mars. During the Late Amazonian Period, the transtensional structures associated with wrench tectonics could be the potential locales of hydrocarbon deposits. The ancient rifts elsewhere on Mars and traps associated with the crater-induced basins could be the areas for hydrocarbon deposits.

## GAS HYDRATE PETROLEUM SYSTEM

Methane could be biogenic or thermogenic in origin and is later sequestered as hydrate under suitable pressure and temperature conditions. Episodic glaciations occurred on Earth during the Neoproterozoic age. The massive methane release and the deposition of the cap carbonates could be attributed to the gas hydrate destabilization (Kennedy et al., 2001). It is presumed that there could be an analogous geological scenario on Mars.

Gas hydrate is composed of water and methane gas, and it remains in stable condition under high pressure and low temperature. Methane and methane as clathrate hydrate or gas hydrate could be present on Mars (S. Padhy, unpublished results). In severe cold climate, water might have converted into permafrost (water-ice cryosphere) or subsurface ice. The ground ice and the envisaged remnant ocean in the lowlands could act as permafrost seals for the entrapped methane (Oehler and Etiope, 2017). Methane on Mars could be biotic (methanogenic microbes) or abiotic in nature. It may be associated with ancient Mars or of the recent time. The northern lowlands of Mars, the Acidalia and Utopia basins, could be potential areas for methane deposits (Oehler and Etiope, 2017).

Methane seepages or gas vents could occur because of destabilization of gas hydrate. Methane generated at depth could migrate through fracture networks, along the updip permeable beds or unconformity surfaces. The physico-chemical characteristics of gas hydrate formation on Mars could be analogous to that of Earth. Methane as gas hydrate might have been deposited within or below the martian cryosphere. The shallowest depth of hydrate stability could be 15–30 m beneath the martian surface, and the base could be in the range of 5–20 km depth (Johnson et al., 2012).

The vents might be in communication with the methane gas that lies beneath the gas hydrate stability zone. It migrates up through the conduits such as faults and joints. The rate of release of gas from the near-subsurface deposits could be attributed to seasonal variation (high during summer) (Mumma et al., 2009). There could be a fair chance of the presence of groundwater on Mars because water is required for biotic or abiotic production of methane. As for evidence of ground ice, ice-melt–like features have been seen on Mars.

Recently the diurnal variation and microseepages of methane flux at Gale crater have been studied (Moores et al., 2019). During the night, because of decrease in convection, the relative increase in methane build-up near the surface is observed. However, at dawn, the convection intensifies, resulting in dilution of the methane content in the atmosphere.

## UNCONVENTIONAL (NONBIOGENIC) PETROLEUM SYSTEM

The presence of methane on Mars has been proved. The abiotic methane generation could constitute an important unconventional petroleum system. Methane might have generated in an unconventional way as the fractionation product of magma crystallization. Geothermal reactions could also generate methane.

The methane venting could also be attributed to the product of either continuing reactions between water and basalt at subsurface or serpentinization and subsequent escape of methane from the cryosphere-hydrate system sequestration (Max et al., 2013).

$$(Fe,Mg)_2SiO_4 + nH_2O + CO_2 \rightarrow Mg_3Si_2O_5(OH)_4 + Fe_3O_4 + CH_4 \qquad (1)$$

The generation of nonbiogenic methane is hypothesized mainly from carbon from the mantle. The FTT process is a chemical reaction of hydrogenation of an oxidized form of carbon (CO or $CO_2$). Under the wide temperature range of 100°C–500°C, the mixture of carbon dioxide and hydrogen produces methane ($CH_4$).

$$(CO_2 + 4H_2 = CH_4 + 2H_2O) \qquad (2)$$

The Sabatier synthesis is considered in an aqueous solution (assuming dissolved $CO_2$ and $H_2$ phases to simulate hydrothermal conditions), but the process remains effective in a gas phase (Etiope, 2017).

On Earth, evidence of abiotic methane is occasionally seen associated with the ultramafic rocks. On Mars, carbon dioxide could be obtained from the atmosphere, by the mantle degassing process, or thermal decomposition of carbonate. The $H_2$ can be obtained from serpentinization, radiolysis, cataclasis of silicates in fault zones, or magmatic degassing (Smith et al., 2005). Dunite (typically having >90% olivine) and pyroxene, required for serpentinization, are common minerals on Mars (Oehler and Etiope, 2017). In addition to molecular $H_2$ and $CO_2$, the FTT-Sabatier reaction effectively takes place under a metal catalyst such as iron, nickel, chromium, and ruthenium. On Mars, presence of chromite with ruthenium has been inferred (Oehler and Etiope, 2017). The FTT-Sabatier reaction or $CO_2$ hydrogenation might have produced gaseous hydrocarbons on Mars. Methane might have been stored as clathrates in the subsurface of Mars.

Early Mars might have experienced relatively high heat flows and high impact intensity of craters during the Noachian age. This might have attributed to methane generation by thermogenesis as well as by FTT reactions (Oehler and Etiope, 2017).

## CONCLUSIONS

A close similarity exists in the early geological history between Earth and Mars. It is envisaged that generation of hydrocarbons might have taken place on early Mars analogous to that of the established Meso-Neoproterozoic hydrocarbon occurrences on Earth. A favorable condition of early-life production and prevalence of marine habitats on Mars might have been present, albeit today the planet is dry with a lean oxygenated atmosphere. The composition of the interior Mars, presence of linear volcanic zone, and the structural manifestation of Valles Marineris fault zone infer possible plate tectonics on early Mars, though the active plate movement and seismicity as seen on Earth are not observed on Mars. The subaerial volcanism might have facilitated release of oxygen into the Mars atmosphere millions of years ago, as evident in early Earth geological history, and in the process could have resulted in a hydrological cycle. The ancient Valles Marineris rift could have resulted because of lithospheric stress, and the associated large-scale transtensional tectonics during the Late Amazonian Period is attributed to plate movement.

Evidence of a fluvial system has been observed from the Late Hesperion through the Amazonian periods. The depositional morphologies, similar to that on Earth (like alluvial fans, debris flow fans, deltas, lacustrine fans, and eolian bedforms) have been interpreted, implying existence of an active sedimentation process on Mars.

Organic matters on Mars could be in situ or could have been delivered from outer space by meteorites. The organic shale deposited within the Valles Marineris rift could act as a good source. The Gale crater is presumed to be a vast salty lake with possible deposition of lacustrine source rock. The salt-loving methanogenic archaea-type microorganisms might have existed in mass. The high geothermal heat presumably could have facilitated the generation of hydrocarbons. It is envisaged that oil and gas deposits could be preserved within the ancient traps associated with the rift basins and in the crater-induced basins.

Based on the geology of Mars and keeping in view the hydrocarbon distribution in the Meso-Neoproterozoic age on Earth, it is presumed that an analogous martian petroleum system might have prevailed, albeit it is premature to speculate the quantity of hydrocarbons generated and preserved. It is envisaged that broadly there could be three petroleum systems on Mars. The Valles Marineris rift basin developed along the late Noachian–Early Hesperian tectonic grain is characterized by large-scale strike-slip faulting during the Late Amazonian time (0.7 Ga or younger), and it could be the Proterozoic equivalent of petroliferous rift province of Earth. Additionally, gas hydrate petroleum system holds another promising deposit.

Abiotic methane might have generated in an unconventional way, like fractionation product of magma crystallization, serpentization, or reaction of water with basalt. The FTT process could have facilitated generation of methane on Mars.

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