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Perspective View of Hydrology on the Martian Surface

Talal Ahmed*[1], Tooba Nayab[1] and Minahil Saeed[1]

[1] *Earthocity Science Hub, Earthocity, Islamabad, Pakistan.*

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ABSTRACT

The discovery of water ice within craters at the Martian North Pole has provided unprecedented insights into the planet's hydrology and climatic history. High-resolution images from the Mars Reconnaissance Orbiter (MRO) have revealed extensive ice deposits in these craters, some spanning several kilometers, offering a detailed perspective of Mars' frozen reservoirs. These ice layers, preserved under a thin dust cover, present a unique opportunity to study ancient climatic conditions and the planet's potential to support life. This paper examines the morphology and distribution of these polar ice deposits, their implications for understanding Martian hydrology, and their significance for future exploration missions. The stability and purity of the ice suggest it has been preserved for millions of years, potentially holding valuable records of past climate variations. Furthermore, the presence of accessible water ice is crucial for human exploration, providing essential resources for sustained missions. The study of these ice-filled craters not only enhances our knowledge of Mars' geologic and climatic history but also paves the way for future endeavors aimed at exploring and possibly colonizing the Red Planet.

1. INTRODUCTION

Mars, commonly known as the "Red Planet," has fascinated scientists and researchers for many years because of its potential to support life and its Earth-like geological characteristics. One of the most exciting recent discoveries is the presence of water ice within craters at the Martian north pole. These ice deposits provide valuable insights into the planet's climatic history and have significant implications for future human exploration [1]. The discovery of water ice on Mars has transformed our comprehension of the planet's hydrology and its potential to sustain life. High-resolution images from orbiters like the Mars Reconnaissance Orbiter (MRO) have offered breathtaking views of craters at the Martian north pole, uncovering extensive deposits of water ice [2].

High-resolution images from the MRO have provided detailed views of craters at the north pole of Mars, revealing stratified deposits of water ice [3]. These craters, which can span several kilometers in diameter, display strikingly bright ice layers that stand out against the darker surrounding regolith. It is believed that these ice deposits are remnants of ancient climatic conditions, preserved beneath a thin layer of dust and regolith that protects them from sublimation [4].

The presence of water on Mars has intrigued scientists since the 17th century, following early observations of the planet's polar ice caps by astronomers. Contemporary exploration, especially with the use of orbiters and landers, has significantly advanced our knowledge of Martian hydrology. The Mars Reconnaissance Orbiter (MRO) has played a crucial role in identifying and studying water ice deposits on the planet [2]. Author in [1] report that high-resolution images from the MRO have uncovered substantial ice deposits within craters at the Martian north pole, offering essential information about the planet's water ice reservoirs [1].

The geological and climatic history of Mars can be inferred from analyzing these ice deposits. Author in [2] observed that the stratification and purity of ice layers within these craters indicate periods of deposition and climatic variation, potentially spanning millions of years. These findings are supported by [3], who utilized radar soundings to detect subsurface ice deposits, suggesting that Mars once had a significantly different climate capable of supporting large

*Corresponding author:
E-mail address: Talal Ahmed <ttalal.pg@gmail.com>.
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volumes of water [3]. The preservation of water ice on Mars is made possible by the planet's frigid temperatures and thin atmosphere [5]. [4] emphasized that the ice in the polar regions is frequently covered by a thin layer of regolith, which serves as an insulating layer, preventing sublimation. This protective covering is essential for the long-term stability of the ice deposits, enabling them to act as records of ancient Martian environments [4].

A particularly significant crater, around 80 kilometres in diameter, reveals a cross-section of ice layers that indicate periods of deposition and climatic variation. The depth and purity of these ice deposits suggest they have remained stable for millions of years, potentially offering valuable insights into Mars' climatic history [3]. The investigation of Martian hydrology involves examining the distribution, movement, and phase transitions of water on the planet. Understanding these aspects is essential for deciphering Mars' climatic history, evaluating its capacity to support life, and planning future exploration missions [2]. Water ice is widely found in the polar regions of Mars, where it forms both permanent ice caps and seasonal frost. The northern polar cap, mainly made up of water ice, undergoes seasonal changes in size, expanding and contracting throughout the year [6]. Radar observations from orbiters have identified large subsurface ice deposits, with some extending several meters deep. These deposits are especially important in mid-latitude areas, where they are covered by a protective layer of soil [2]. There is evidence indicating that liquid water might occasionally flow on Mars surface. Seasonal dark streaks known as Recurring Slope Lineae (RSL) are thought to result from briny water flows, although their precise characteristics are still a matter of discussion [7].

2. METHODOLOGY

The north and south polar layered deposits (NPLD and SPLD, respectively) are layered domes of dusty water ice several kilometres thick that record climatic variation, probably over timescales of 105 to 109 years, in a similar way to terrestrial ice caps [21]. The current research utilizes satellite images sourced from various space agencies. To acknowledge the image rights, credits are provided at the bottom of each image and mentioned in the captions. The primary agencies credited for the images used in this study are the National Aeronautics and Space Administration (NASA, USA), the European Space Agency (ESA), and Arizona State University (USA). The methods used for obtaining different resolution images and spectral channels are followed by Multi orbital digital terrains model (DTM), Mars Orbital Camera (MOC) and the Mars Orbiter Laser Altimeter (MOLA). The current methodology is based on the morphological distribution of the polar ice deposits on the north polar regions i.e. Planum Boreum and Circum polar units. The morphological distribution is characterized by the stratigraphic units given below, MRO technology is used in identifying the layered deposits of ice at poles. Detailed spectral analysis is provided by MOLA, while SHARAD is used for obtaining the sequences and outflow channels detection. The Morphology and distribution is characterized by distribution analysis on Martian poles followed by the morphological evidence and thickness, the current phase of the study is observed by Mars Global Surveyor's Mars Orbiter Laser Altimeter. The phase of conducting analysis on present reservoirs and their outflow channels is followed by a distribution analysis of outflow channels and terrains; the current phase of the study is observed using MOC, and scabland features are marked through DTM. The study of geomorphological and geological features including north and south pole ice distributions is followed by the distribution pattern of the ice caps and processes induced by geological evidences. The current phase of study is observed using MOLA, MOC. (Fig. 1) depicts the flow work analysis of the current study.

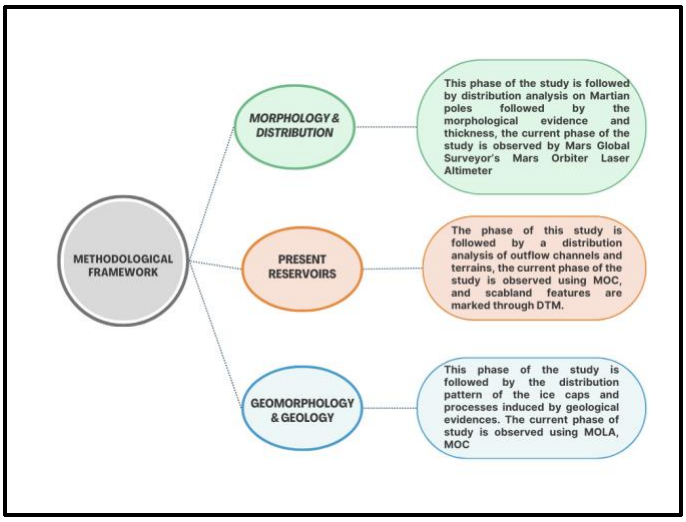

Fig. 1. Methodological framework

3. ANALYSIS

3.1 Morphology and Distribution

The shape and structure of polar ice deposits on Mars provide essential insights into the planet's climatic and geological past. These deposits are mainly located in craters and polar layered deposits (PLDs) at both poles, with more extensive and accessible reserves found in the northern region. Detailed imaging from the Mars Reconnaissance Orbiter (MRO) and radar data has offered comprehensive views of these ice reserves [8].

Ice deposits within Martian craters, particularly in the northern polar area, frequently display a layered structure consisting of alternating ice and dust layers. This stratification indicates periods of deposition that are likely influenced by climatic cycles associated with changes in Mars' axial tilt and orbital dynamics [2]. The craters vary greatly in size, with some measuring several kilometers across, and the ice layers contained within them can reach thicknesses of several meters [1].

Because of Mars low atmospheric pressure, liquid water can only persist briefly in the lowest areas. Water ice makes up the bulk of the two polar ice caps, and if the southern polar cap were to melt, it could inundate the planet's surface with up to 11 meters of water. Additionally, the permafrost layer extends from the poles down to about 60° latitude [9]. Subsurface radar measurements from instruments such as SHARAD (Shallow Radar) aboard the MRO have identified significant buried ice deposits, especially in mid-latitude areas. These ice layers are protected by a thin regolith covering, which helps insulate them and reduces sublimation. The thickness and quality of these ice deposits indicate that they have remained stable for long periods, serving as important records of Mars' environmental history [3]. Large amounts of water ice are believed to be stored within Mars' extensive cryosphere. Radar observations from Mars Express and the Mars Reconnaissance Orbiter have identified considerable ice deposits at both polar regions and mid-latitudes. Furthermore, the Phoenix lander successfully collected samples of water ice from the Martian surface at shallow depths. (Fig. 2) illustrates the interaction of planetary atmospheres with ice deposits, which record climatic variations in their stratigraphy. Both Earth and Mars experience Milankovitch cycles, significantly influencing the distribution of stable ice. Glacial flow and volcanic activity impact ice on both planets, though at varying rates. However, it's important to note key differences: Earth's ice caps interact significantly with oceans, a dynamic absent on Mars. Additionally, Mars features seasonal CO_2 ice caps, which condense a substantial portion of its atmosphere. The red lines mark the locations of topographic profiles, while the gray shading in the north polar profiles highlights areas where topographic data may be unreliable [7].

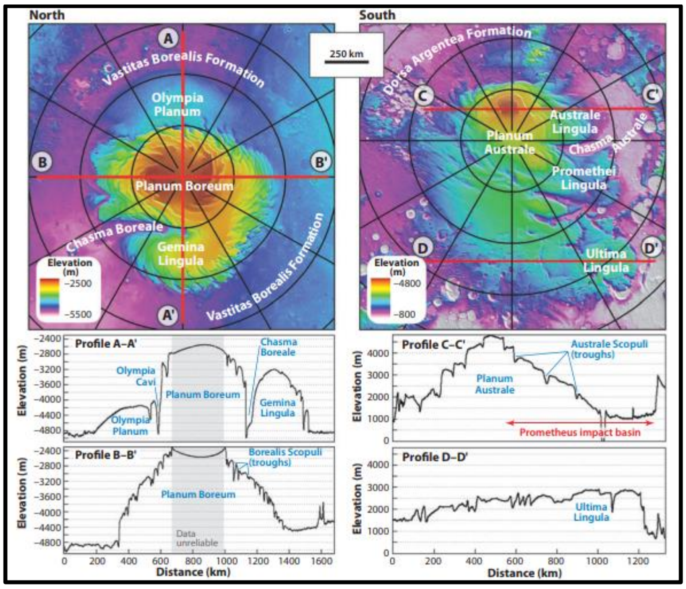

Fig. 2. Regional MOLA topographic maps depict the north (left) and south (right) polar regions at a consistent scale

3.2 Present Reservoirs

Direct observations have verified the existence of visible water reservoirs on Mars, which include atmospheric water vapor, water ice in the atmosphere, seasonal surface ice deposits, and permanent ice at the polar caps [10]. Of the four water reservoirs, the Martian polar caps are the largest. Recent topographic data from the Mars Global Surveyor’s Mars Orbiter Laser Altimeter indicate that, with a high ice-to-dust ratio, the water ice in Mars' northern and southern polar caps could correspond to a global water layer approximately 22 to 33 meters thick [11]. Besides the observable water reservoirs on Mars, there is considerable evidence indicating the existence of concealed water reservoirs, which are likely to have a total mass much larger than the currently visible ones [9].

Likely sources for this phenomenon include the Martian atmosphere. Through a process known as deliquescence, surface salts can absorb atmospheric water vapor, incorporating it into their crystal structures. When these crystals warm up, they dissolve, creating a liquid mixture that is then pulled downhill by gravity. Other potential explanations include the presence of an underground aquifer or a buried ice field that melts with the changing seasons (but the Martian ice cap itself is not melting). In (Fig. 3) blue areas, found at high northern and southern latitudes, indicate higher amounts of water ice, while orange areas signify lower concentrations. White squares indicate the sites of small, recent impact craters that have uncovered water ice near the Martian surface. Red squares denote likely locations of chloride deposits, which may have formed from the evaporation of saline water. Blue squares highlight the sites of Mars' "seasonal seeps," believed to be influenced by briny water activity.

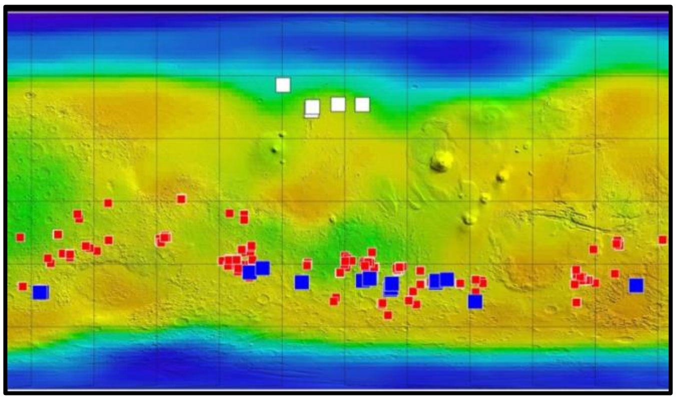

Fig. 3. Present Reservoirs on the Martian surface. The background colors on this map represent concentrations of subsurface water. Shot taken by (*NASA/JPL*)

3.3 Geomorphology and Geology

The north pole of Mars showcases an intricate geomorphological and geological landscape influenced by hydrological processes. A key feature is the polar ice cap, primarily made up of water ice and topped with a seasonal layer of carbon dioxide ice. This ice cap experiences dynamic changes over the course of the Martian year, with fluctuations in size and coverage driven by seasonal temperature variations and atmospheric conditions [12]. The geology beneath the Martian north pole shows signs of ancient fluvial activity, indicating past hydrological processes involving liquid water. Structures such as valley networks, channels, and outflow channels point to significant water flow in the area's geological history [13].

The term "channel" describes a specific category of Martian landforms defined by trough-like structures that indicate significant fluid flow along their bases. Notably, outflow channels emerge from areas of extensive collapse known as "chaotic terrain." These Martian outflow channels are immense, reaching widths of up to 150 km and extending over 2,000 km in length. Their discovery revealed bedforms and morphological characteristics akin to those found in the Channeled Scabland, a landscape in the northwestern United States shaped by catastrophic flooding during the Pleistocene glaciation [13].

At their largest scale, the outflow channels showcase extensive anastomosing patterns, interspersed with elevated areas or "islands" of terrain that predate the flooding events. These channels are characterized by low sinuosity and high width-to-depth ratios, exhibiting notable flow expansions and constrictions, crossings of divides, hanging valleys, and erosion influenced by structural features shown in Fig. 4. Detailed observations reveal significant streamlining of the residual uplands, along with longitudinal grooves, inner channels, cataract complexes, scablands, and bar complexes [10].

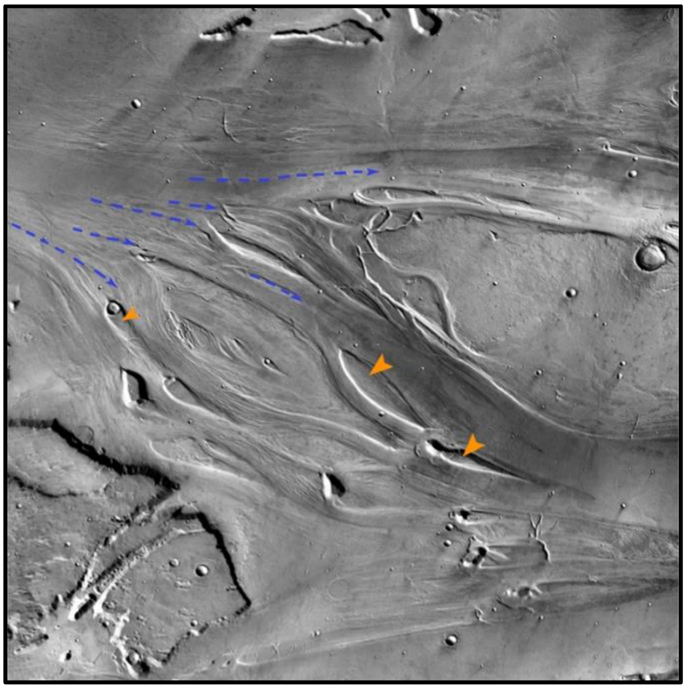

Fig. 4. Blue arrows indicate the direction of water flow within these outflow channels. Streamlined islands, marked in orange, formed around obstacles, such as a small crater on the center-left

The Planum Boreum materials have been classified into several units shown in tables (1-3), including the residual ice cap and the regions containing the north polar basal unit (BU) along with the sand dunes [23] as shown in (Fig. 5). The majority of the traditional North Polar Layered Deposits (NPLD) in (Fig. 6) are represented as a single unit, notable for its laterally continuous layers that exhibit variations in brightness, roughness, and slope where they are exposed. While MOC imaging data of the NPLD layer exposures indicated layering down to the resolution limit, the higher-resolution HiRISE data has fully resolved even the thinnest layers, revealing them to be only decimetres thick [21].

The Polar Layered Deposits (PLDs) have long been believed to consist primarily of atmospherically deposited dust and water ice [21]., with the distinct layers resulting from variations in the mixing ratio of these components. However, the presence of buried CO_2 ice and CO_2 clathrate hydrate has been ruled out as significant constituents based on thermal [23] and mechanical strength considerations [24]. The areas of the PLDs not covered by the residual ice caps exhibit an orange-brown color, similar to other dust deposits on Mars (e.g., Fig. 6a), which is commonly interpreted as a dust layer formed by the sublimation of ice-rich material [22]. Recent hyperspectral data from the CRISM instrument have detected water ice in the layered exposures of the NPLD at the head of Chasma Boreale [21]. MARSIS radar transparency data provide strong constraints on the bulk composition of both PLDs, indicating that the northern [21]and southern [22] deposits are composed almost entirely of water ice, with upper dust volume fractions of 2% and 10%, respectively. SHARAD data also indicate similar transparency for the NPLD [18] but do not penetrate to the base of the SPLD [22], possibly due to a wavelength-dependent effect such as volume scattering from pervasive fracturing.

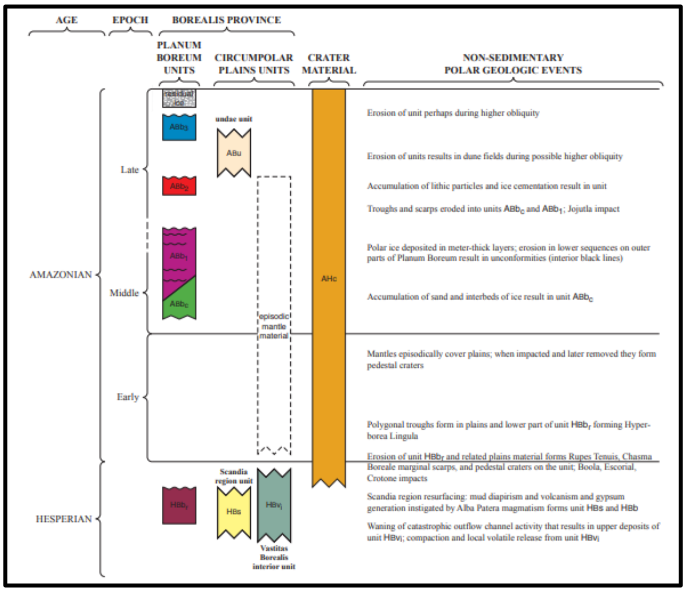

Fig. 5. General Stratigraphy of Planum Boreum

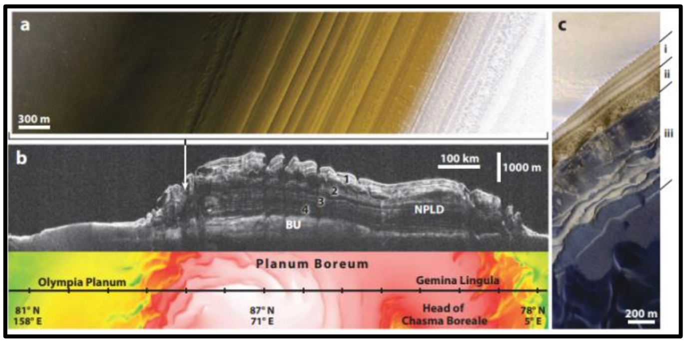

Fig. 6. North polar stratigraphy as captured by HiRISE imaging and SHARAD radar data

Another compositional constraint is provided by the density of the SPLD, derived from analysis of the gravitational anomaly associated with Planum Australe. Independent analyses by [15] yielded consistent bulk densities of 1,220 and 1,271 kg/m³, respectively. The corresponding dust volume fraction depends on the assumed dust density but is likely around 15%. Although water ice dominates both PLDs, the reported dust content in the SPLD is consistently higher. While the bulk composition of the PLDs is becoming better understood, significant uncertainty remains regarding compositional variation across individual layers. SHARAD data reveal distinct reflections (Fig. 6b), which may correspond to layers or packets of layers observed in visual datasets. [20] applied the methodology of [22] to link SHARAD reflections to composition. The thinnest layers of the NPLD visible in HiRISE data are approximately 10 cm thick. For SHARAD to detect reflections from such a layer, it would need to contain at least 10% dust. Thicker layers, such as 1 meter thick, could be detected with lower dust concentrations, around 2%. Both PLDs are incised with troughs and scarps, which exhibit a spiraling pattern (Fig. 2) and expose internal layers (e.g., Fig. 6a). The formation of these features is likely related to a feedback mechanism between slope and ablation [23].

Although several fluid-flow mechanisms have been suggested to account for these features, cataclysmic flood events, similar to those that formed the Channeled Scabland, provide the most thorough explanation. However, important differences exist due to Mars' distinct environmental conditions, such as lower gravitational forces, much reduced atmospheric pressure, and consistently subfreezing temperatures compared to Earth. These Martian conditions significantly affect sediment transport processes, cavitation, ice formation, debris flow, and the potential for large-scale ice interactions within the channels [2].

Geological features found within Martian craters indicate that Mars had periods of warmer and wetter conditions in its history, likely allowing for the formation of crater lakes across extensive areas of the surface. This theory is supported by various lines of evidence, including mineralogical, sedimentological, and geomorphological studies. Some scientists even suggest that large portions of the planet's low-lying northern plains may have been covered by an ocean several hundred meters deep, although this idea is still debated within the research community [10]. The discovery of specific minerals, such as hematite and goethite both of which form in the presence of water add to the evidence that liquid water once existed on Mars surface. Higher-resolution analyses by the Mars Reconnaissance Orbiter have refuted some earlier data thought to indicate ancient water basins and flows. In (Fig. 7) of a fluvial channel system located at latitude 7.9°N and longitude 205.8°W, south of Cerberus Rupes (MOC Image M21-01914). the fluvial channel shows the the scene spans approximately 4 km across, revealing a complex network of anastomosing channels and streamlined uplands. These features illustrate a history of differential fluid erosion on layered bedrock, leading to the formation of terrace levels and abandoned spillways. Additionally, regularly spaced rib-like bedforms, with wavelengths of about 60 meters, are observed transverse to the direction of fluid flow within some channels. These characteristics strongly suggest the influence of large-scale water flow. Notably, the absence of impact craters on the flood- scoured surfaces indicates that this flow occurred relatively recently in Martian geological history.

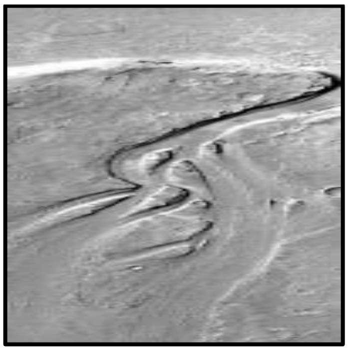

Fig. 7. The high-resolution Mars Orbiter Camera (MOC) (*Image courtesy of Malin Space* Science *Systems*).

Recent findings have strengthened the evidence for past water presence on Mars. The Opportunity Rover discovered gypsum, suggesting historical water activity on the planet. Additionally, [14] reported that the upper mantle of Mars contains water levels similar to those on Earth, ranging from 50 to 300 ppm, which could amount to enough water to cover Mars to depths between 200 and 1,000 meters. The Curiosity Rover also detected hydrated minerals, likely calcium sulfate, in rock samples and identified subsurface water content of up to 4% at depths of 60 cm during its exploration of the Glenelg terraina [15].

Additionally, the existence of polygonal terrain in the northern polar region of Mars indicates the impact of ground ice and permafrost processes. These polygonal patterns, akin to those observed in Earth's periglacial areas, suggest the presence of subsurface ice and the influence of thermal contraction and expansion [16]. The geomorphology and geology of Mars northern polar region provide important insights into the planet's hydrological history and the influence of water on its surface features. Fluvial landforms, periglacial formations, and ice deposits all indicate historical water-related processes, deepening our understanding of Martian hydrology and the potential for habitability on the Red Planet [2].

The northern pole of Mars is predominantly shaped by the extensive North Polar Layered Deposits (NPLD), which consist of alternating layers of water ice and dust accumulated over millions of years. These layers serve as a historical archive of Mars' climate, akin to the ice caps found on Earth. The region's surface is characterized by spiral troughs, thought to be formed through a combination of sublimation, wind erosion, and potential glacial activity. These troughs reveal the underlying layers, providing valuable insights into Mars' past environmental conditions [16].

In addition to these features, the northern pole is home to a seasonal polar ice cap made mostly of carbon dioxide ice, which sublimates during the Martian summer and recondenses in the winter. Beneath this seasonal layer is a residual water ice cap that remains intact throughout the year. The geomorphology of this area is further influenced by dunes, impact craters, and possibly volcanic activity, all contributing to the diverse and ever-changing landscape of Mars' northern polar region [16].

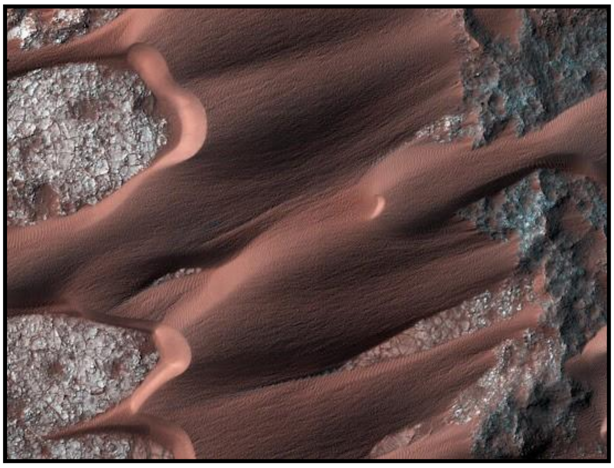

Fig. 8. Hydration and mineralization on the Martian surface adjacent to dunes. Source (*ESA*).

4. DISCUSSIONS

The distribution and structure of polar ice deposits play a crucial role in understanding Martian hydrology. The presence of large, stable ice reserves suggests that Mars has endured extended cold periods, facilitating ice accumulation and retention. The layered composition of ice within craters and polar layered deposits (PLDs) indicates that the planet has experienced various climatic cycles, likely influenced by fluctuations in its axial tilt and orbital characteristics [2]. Additionally, the behavior of water on Mars is shaped by its chemical and thermodynamic properties, as well as the planetary environment [17].

Due to low surface temperatures, water on Mars exists mainly in condensed forms, resulting in an extremely dry atmosphere that cannot transport substantial amounts of water seasonally. Today, liquid water is unstable on Mars, as it would rapidly evaporate or freeze in colder areas [6]. Observations from the Viking landers and the Thermal Emission Spectrometer (TES) on the Mars Global Surveyor indicate that atmospheric water vapor peaks at about 100 precipitable microns during the northern summer, while remaining below 15 microns during other seasons. The dynamics of water vapor are influenced by sources and sinks, atmospheric thermal structure, dynamics, and aerosols. It is still unclear whether the observed seasonal water vapor cycle achieves annual equilibrium [18]. Mars Express has investigated the Medusae Fossae Formation (MFF), uncovering massive deposits that reach depths of up to 2.5 km. While initial observations left the composition uncertain, recent studies have shed new light on these deposits (Fig. 9). According to Thomas Watters from the Smithsonian Institution, "Our re-examination of the MFF using advanced data from Mars Express's MARSIS radar shows that the deposits are even thicker than previously thought, reaching up to 3.7 km. Notably, the radar signals align with what we expect from layered ice and resemble those from Mars's polar caps, which are known to be rich in ice" [19]. If melted, the ice within the MFF could generate a global water layer ranging from 1.5 to 2.7 meters deep, making it the largest water reservoir identified in this region of Mars, comparable in volume to Earth's Red Sea [7].

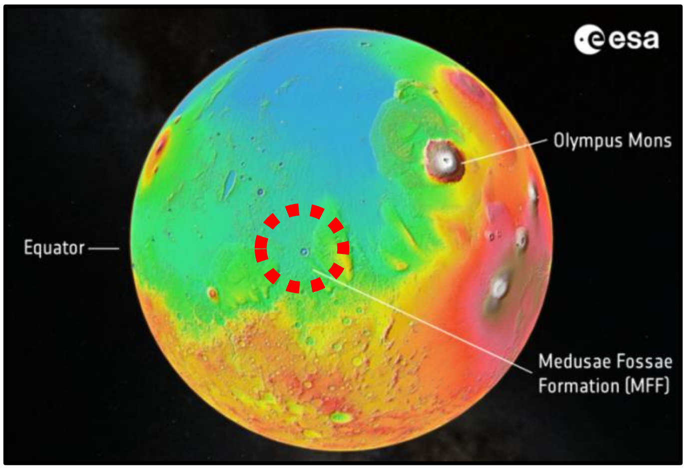

Fig. 9. The Medusae Fossae Formation (MFF), *located* near the equator, is a fascinating region characterized by massive wind-sculpted deposits.

The Medusae Fossae Formation (MFF) on Mars, situated at the interface of the planet's highlands and lowlands, is made up of wind-sculpted deposits that extend for hundreds of kilometers and rise several kilometers in height. These formations are likely the largest individual source of dust on Mars and represent some of the most extensive deposits on the planet [19]. Recent studies utilizing radar data from Mars Express have uncovered a significant amount of water ice beneath the dry surface layer of the Medusae Fossae Formation. The upper layer, consisting of dust or volcanic ash, is estimated to be between 300 and 600 meters thick and overlays ice-rich deposits that can reach up to 3,000 meters deep. If the dust layer is 300 meters thick, the total volume of water ice in the MFF is estimated to be around 400,000 km³, which could create a global ocean approximately 2.7 meters deep if melted. In contrast, if the dust layer is 600 meters thick, the ice volume is estimated at 220,000 km³, enough to form an ocean about 1.5 meters deep [20]. In (Fig. 10) the blobs transition from blue around the edges to green, yellow, orange, red, and finally white towards the center. A scale at the bottom labeled 'Potential Ice Thickness' ranges from 0 meters (dark blue) to 3000 meters (red-white).

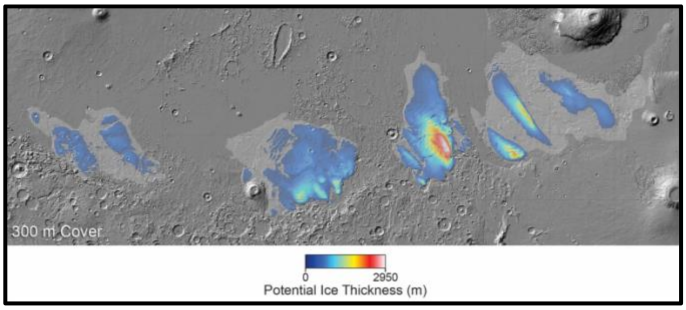

Fig. 10. A grey planetary surface featuring coloured blobs is displayed., showing potential *ice* thickness. Source *(ESA).*

5. FUTURE IMPLICATIONS

The availability of accessible water ice on Mars is crucial for upcoming exploration missions. Water is essential for human survival, and having it on Mars could significantly reduce the need to transport supplies from Earth. This would lower mission costs and allow for longer, more sustainable stays on the Martian surface [5]. Besides providing drinking water, the ice can be processed to generate oxygen for breathing and hydrogen for fuel, supporting life support systems and propulsion for return missions. Therefore, the polar regions, rich in ice deposits, are ideal candidates for future human landing sites [8].

Additionally, studying these ice deposits can deepen our understanding of Martian geology and climate. By drilling into the ice layers and analyzing their composition, researchers can uncover insights into past climatic conditions and the planet's potential to support life. This research is also vital for the search for microbial life, as subsurface ice could offer habitats shielded from harsh surface conditions [3].

6. CONCLUSION

Exploring Martian water ice, especially at the north pole and within the Medusae Fossae Formation (MFF), has greatly improved our understanding of Mars' hydrology, geological history, and potential to support life. High-resolution imagery and radar data from missions like the Mars Reconnaissance Orbiter and Mars Express have uncovered extensive, stable ice deposits that provide valuable insights into the planet's climatic history. These findings suggest that Mars has undergone significant climatic fluctuations, with episodes of warmer, wetter conditions capable of sustaining large bodies of water.

The existence of water ice on Mars is not only important for scientific research but also vital for future human exploration. Accessible ice deposits can supply essential resources such as drinking water, oxygen, and hydrogen for fuel, minimizing the need to transport supplies from Earth and enabling longer, more sustainable missions. As a result, the polar regions, rich in ice deposits, are ideal candidates for future landing sites.

Moreover, studying these ice deposits will enhance our understanding of Martian geology and climate, providing insights into the planet's potential to support microbial life. Analyzing the composition of ice layers through drilling can uncover ancient climatic records and inform the search for signs of past or present life. Overall, ongoing research and exploration of Martian ice deposits are crucial for unraveling the planet's climatic history, evaluating its habitability, and preparing for human missions to Mars. These efforts will not only expand our knowledge of the Red Planet but also lay the groundwork for future exploration and potential colonization.

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Table 1. Planum Boreum Units.

Unit Name	Unit Symbol	Definition	Covers/ Forms	Structural Geology	Lithology	Age
Planum Boreum 3 unit	ABb_3	Forms as many as 6 to 8 layers each several meters thick of moderately high or variable albedo having knobby margins and diffuse interlayer boundaries; moderate surface ice abundance	Covers most of Planum Boreum, including some pole-facing trough walls, and scattered outlier mesas of Olympia, Abalos, and Tenuis Mensae. Mostly thinly mantled by bright residual ice	Local unconformities occur within unit. Locally cut by grabens and pits along low ridges and scarps above western Olympia Rupēs	Nearly pure water ice with small dust concentration except for thin surficial dust lags; likely undergoing thermokarst degradation and eolian erosion, particularly on unit margins	Late Amazonian
Planum Boreum 2 unit	ABb_2	Forms low-albedo material; layers evident in places; low ice abundance. As much as several tens of meters thick	Covers parts of floors and slopes of Chasma Boreale, Olympia Cavi and Rupēs and nearby troughs, and margins of Gemina Lingula east of Chasma Boreale	Variably hummocky and bumpy surface. Locally includes possible cut-and-fill structures	Dusty to sandy eolian mantle derived largely from planum boreum cavi and rupēs units	Late Amazonian
Planum Boreum 1 unit	ABb_1	Finely layered, high-albedo in upper part and moderate-albedo in lower part; moderate ice content. Locally exceeds 1000 m in thickness. Includes bright horizontal reflectors and local discontinuities in SHARAD radar data	Forms much of upper Planum Boreum and scattered patches in the surrounding plains; exposed mainly in southward-facing scarps; unit may exceed 1500 m thickness near north pole. Exposures typically include sequences of dozens to hundreds of even layers mostly meters thick (interrupted by a few prominent, thicker layers)	lower sequences polygonally fractured. Local internal unconformities commonly with dark surfaces, particularly in lower, outer parts of Planum Boreum. Marked by arcuate patterns of troughs and undulations and dissected by Chasma Boreale. Sparsely cratered by impacts tens to a few hundred meters in diameter. Displays cross-hatched fracturing within 10 to 12 kilometers of 43-km-diameter Udzha crater	Atmospherically precipitated and transported ice and dust perhaps deposited during episode of overall lower obliquity and originating from lower latitude sources; alternating layers may result from cyclic climatic and depositional conditions. Glacial deformation not apparent but brittle contraction cracks and possible subsurface faults beneath troughs evident. Exposed surfaces may be partly covered by dust mantle	Middle to Late Amazonian
Planum Boreum cavi unit	ABb_c	Dark and light even to irregular layers typically meters thick; local cross bedding; overall low water ice abundance. Locally reaches a couple hundred meters in thickness	Lines lower, steep walls of Olympia, Boreum, and Tenuis Cavi, northern Olympia Planum, Chasma Boreale, and depression in western Abalos Mensa.	Light-toned layers typically form prominent ledges marked by polygonal fractures spaced meters apart, whereas dark layers less fractured and more friable and disaggregated into dark soils, ripples, and dunes	Poorly indurated sandy weathered basalt fines deposited by wind, interbedded with ice-rich layers. Sandy material may originate from erosion of planum boreum rupēs and scandia units. Occurrence may be spotty, within former wind-sheltered hollows carved within planum boreum rupēs unit. Perhaps generated during a mostly high-obliquity epoch	Middle to Late Amazonian
Planum Boreum rupēs unit	HBb_r	Evenly layered; >20 layers total exposed, each ~10 to 100 m thick; likely high ice content. Diffuse and moderately reflective in MARSIS and SHARAD data. Locally 1000 m thick along Rupes Tenuis	Forms much of the basal section of the main lobe of Planum Boreum, particularly along Rupes Tenuis and lower parts of Olympia Rupēs and Cavi; also forms low (~300 m thick) Hyperborea Lingula plateau	Layer margins commonly form knobs and rounded, concave-upward plates. Superposed by several multi-kilometerdiameter craters including Boola and Crotone	Ice-laden, fine-grained deeply eroded but presently indurated deposits. Generally undeformed except for polygonal graben network that cuts lower section of unit making up hyperborea lingula and hyperboreus labyrinthus	Early to Late Hesperian

			covering the base of Chasma Boreale; likely forms plateau underlying Escorial crater ejecta and perhaps material of Abalos Colles.			

Table 2. Circum Polar Plains Units

Unit Name	**Unit Symbol**	**Definition**	**Covers/ Forms**	**Structural geology**	**Lithology**	**Age**
Undae unit	ABu	Includes dunes typically tens to hundreds of meters across and tens to more than 100 m high, as well as rippled and bumpy mantle material commonly between and surrounding dunes. Low albedo in defrosted, summertime images and bright (warm) in THEMIS daytime infrared images; low ice abundance	Forms broad, irregular patches encircling much of Planum Boreum	Locally confined within subtle topographic traps and craters; more pronounced dune fields include olympia undae and other areas within and south of chasma boreale (hyperborae and abalos undae) that appear to be made up of individual and chains of barchan dune forms	High abundance of type 2 tes spectral type; omega data indicate overall signature of hydration plus gypsum concentrated on upper parts of olympia undae. Ergs of wind-blown, weathered basaltic silt and sand, locally rich in gypsum and other hydrated minerals. Originates mostly from local erosion of planum boreum cavi unit and some planum boreum 2 unit, particularly from west- to south-facing cavi-wall outcrops and buried surfaces in eastern olympia planum. Dunes largely inactive at present; likely active during higher obliquity episodes, particularly > 4–5 million years ago	Late Amazonian
Vastitas Borealis interior unit	HBv_i	Vast, moderately cratered plains-forming deposits	Typically marked by scattered higher albedo bumps ~1 to several kilometers across. South of Chasma Boreale and around western Scandia Tholi and Cavi in some of the lowest elevation plains marked by a polygonal network of shallow trough segments tens of meters deep, a few hundred to 2000-m wide and several kilometers long. Unit largely obscured by recent thin mantle deposits	Also contains scattered circular depressions up to tens of kilometers in diameter	Sediments of outflow channels that dissect highlands thousands of kilometers south of map area. Pervasively altered and deformed during late hesperian by compaction, mud volcanism, and other periglacial processes involving subsurface volatiles. Scattered bumps may be degraded, infilled crater forms	Early to Late Hesperian

Scandia region unit	HBs	Forms singular and chained subcircular to irregular complexes of domical hills of Scandia Tholi and Cavi tens to a few hundred kilometers across and tens to hundreds of meters in relief		Larger hill complexes have interior and surrounding depressions (scandia cavi) tens to hundreds of meters deep and a few narrow sinuous ridges a couple kilometers wide and tens of kilometers long. Many tholi bounded by shallow moats within surrounding, underlying vastitas borealis interior unit. Wrinkle ridges in adjacent vastitas borealis units disappear in scandia region unit. Unit largely obscured by recent thin mantle deposits	Sedimentary and cryoclastic volcanism may have formed much of unit and attendant collapse structures, perhaps instigated by alba patera magmatism. Unit may be deeply eroded	Early to Late Hesperian

Table 3. Crater Material

Unit Name	Unit Symbol	Definition	Covers/ Forms	Structural Geology	Lithology	Age
Crater material	AHc	Forms crater rims and bowls and surrounding blankets commonly elevated meters to tens of meters above subjacent units. Outcrops >15 km across mapped	Blankets vary considerably and are missing in some cases and include thin ones with ramparts and extensive, smooth, thick ones (of so-called ‘pedestal craters’).	-	Ejecta resulting from larger impacts	Late Hesperian to Amazonian