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Assessing Potential Mars Landing Sites Based on Groundwater-Induced Hydrated Mineralogy and Geomorphology

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Abstract: As the thorough exploration of Mars H2O, identifying the existence of a Martian biosphere becomes imperative. This paper discussing hydrated minerals on Mars offers a critical pathway to assessing its past habitability and potential subsurface biosphere. This study presents a multi-criteria evaluation of three candidate landing sites—Danielson Crater, Aram Chaos, and southwest Arabia Terra—selected for their scientific relevance to aqueous processes and their compliance with engineering constraints for future surface missions. Using integrated datasets from CRISM, HiRISE, MOLA, and other orbital instruments, the analysis emphasizes morphological diversity, mineralogical signatures, and preservation potential. Danielson Crater is identified as the most favorable site, combining well-preserved stratigraphy with strong evidence of phyllosilicate-rich layered deposits. This framework can serve as a reference for future Mars exploration missions targeting signs of past groundwater activity and habitability.

Keywords: Mars, Hydrated Minerals, Habitability, Landing Site Selection, Danielson Crater, Aram Chaos, Arabia Terra, Subsurface Water.

Disciplines: Earth Sciences. **Subjects:** Geology.

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1 INTRODUCTION

Mars has long been the focus of planetary exploration due to its geological complexity and the presence of features suggestive of a wetter past environment. Data from multiple rover and orbiter missions—including those from NASA and ESA—have confirmed the existence of ancient basaltic crusts, widespread sedimentary formations, and topographic depressions containing hydrated minerals such as phyllosilicates and sulfates, , especially during the Noachian periods(Poulet et al., 2005)[1]. These findings provide evidence of Mars dynamic interactions with water on Martian surface or subsurface. In the cold era, the Martian surface has been highly inhospitable, yet the Martian subsurface harbors the potential for a extensive microbial biosphere. It is plausible that water may has rised from the lower ground, modifying and solidifying surface deposits, potentially preserving indicators of subsurface habitability(Grotzinger et al., 2012). Investigating the habitability of the Martian subsurface holds the key to gaining vital insights into the geochemical processes during the early stages of the Martian history and contributes an indispensable element to the myth of Earth's geology[2]. Thus, identifying locations that record such geographical processes is critical for following Mars' mission focusing on its early geochemical history[3]. The goal of this study is to assess and compare three candidate sites for future Mars lander missions based on both engineering feasibility and scientific merit. The evaluation integrates high-resolution satellite imagery and spectral data, focusing on hydrous mineral content, geomorphic preservation, and rover-accessible terrain. The methodology and findings are broadly applicable to upcoming missions such as the European Space Agency's ExoMars or NASA's MSR lander component[4].

The simulating spacecraft is set to land within a landing ellipse measuring approximately 20 x 25 km, providing the capacity to conduct comprehensive investigations in the fields of geology, mineralogy, geochemistry, and astrobiology. It is equipped with a sample collection and in situ analytical system designed to obtain crucial samples for the lab analyzation, facilitating the search for and assessment of habitable environments. The parameters of the rover will be applied as one of the criteria for assessing whether the location can be reached[5].

In the following paragraphs, section 2 describes the site selection methodology and datasets used; Section 3 presents detailed profiles of the three shortlisted sites; Section 4 discusses comparative scientific value; and Section 5 concludes with recommendations for future landing site

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considerations[6].

2 METHODOLOGY

2.1 Overview

Based on the design of future rover(seen Fig, 1 as reference), the landing site selection process for future Mars surface missions should balance scientific priorities with rigorous engineering constraints. Scientifically, ideal candidates should provide access to sedimentary records formed through groundwater interaction, which may preserve potential signatures. Geographic constraints—such as slope, elevation, surface rock abundance, and thermal properties—must ensure safe entry, descent, and landing (EDL), as well as enable efficient surface operations(Golombek et al., 2012)[7].

This study adopts a multi-criteria assessment framework adapted from previous Mars Science Laboratory (MSL) landing site selection processes. The approach integrates satellite datasets (e.g., HiRISE, CRISM, MOLA) and GIS-based terrain analyses to narrow down viable targets[8].

2.2 Engineering constraints

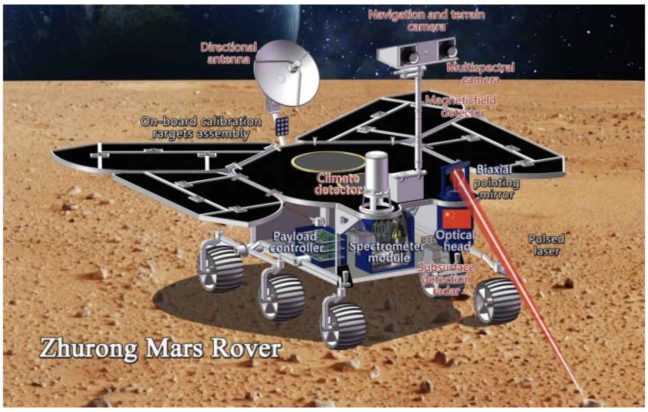

Fig 1, Example of an Up to date Mars Rover - Zhurong(Wan, 2021)

The following engineering parameters(Golombek et al., 2012) were imposed to ensure mission viability:

2.2.1 Altitude:

To satisfy the EDL(ie, entry, descent, and landing) process, the elevation of candidates should below -0.5 km, ensuring enough atmosphere and margin to safely slow the rover[9].

2.2.2 Geographical Location:

To optimize energy usage for scientific activities in colder conditions, the latitude range is restricted to ±30°. This avoids polar regions and areas with intermittent shallow ice, addressing planetary protection concerns and ruling out ground ice within flat surfaces.

2.2.3 Topography and Slopes:

To ensure the stability and navigability during and after EDL, slopes with lengths from 1 ~ 10 km should be < 5 degrees. For slope lengths < 1 km, slopes must be between 5 ~ 15 degrees. At small slopes several meters long, it should be < 15 degrees. In extreme conditions, slopes < 30 degrees are negotiated, but the operational performance would be significantly impacted.

2.2.4 Landing Ellipse:

The ellipse, approximately 25 x 20 km with an east-west azimuth, ensures aero-maneuvering accuracy. Four ellipses with azimuths of 90, 100, 110, and 120 accommodate flexible launch dates.

2.2.5 Rock Abundance:

Landing regions must be devoid of rocks taller than 0.55 m to prevent damage to the rover's lower pan. The probability of encountering such rocks in a randomly sampled 4 m^2 area should be less than 0.5%. Additionally, scattered rock debris on the planet's surface should not exceed 7%.

2.2.6 Load-Bearing Surface:

Preferred surfaces have an albedo < 0.25 and thermal inertia > 100 J m^2 K^1 s^0.5 to avoid dust-dominated areas that lack load-bearing capacity. Sites with extreme temperature variations may hinder surface operations due to energy redirection for rover thermal maintenance.

2.3 Science Criteria

Following the groundwater model, the initial occurrence of upwelling is proposed to have taken place in deep basins. A rising groundwater table would have played a crucial role in modifying and solidifying available sediments within these upwelling zones[10]. In the northern hemisphere of Mars, there are 95 huge impact basins (diameter >40 km) with substantial depths (rim-base depth > 2 km). About 80% of these basins are attributed to the Noachian era, predating the anticipated onset of upwelling activities (Michalski et al., 2013). These conditions guide the following science criteria。

2.3.1 General criteria:

a. The geological features should date back to > 3.6 Ga, representing Mars' early period, pre to late Noachian and early Hesperian.

b. Abundant morphological and mineralogical evidence pointing to long-standing aqueous activity, with extensive sedimentary outcrops.

c. Even distribution of outcrops across the landing ellipse to enhance the rover's chances of reaching them.

d. Minimal dust coverage, relevant to albedo and thermal inertia.

2.3.2 Specific criteria:

a. The existence of 1) subaqueous sediments or 2)

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hydrothermally altered rocks.

b. All known active life requires liquid water. The existence of minerals indicating past aqueous traces, for example, phyllosilicates, carbonates, sulfates, etc.

c. Determination of Noachian to Early Hesperian age, depending on assessing stratigraphic relationships and/or crater counts.

2.3.3 Secondary qualifying criteria:

a. Morphological evidence suggesting standing bodies of water (deltaic deposits, shorelines, etc.).

b. Collections of secondary minerals from various geological epochs.

c. Evidence of former water ice, glacial activity, or related deposits.

2.4 Data and Software

All CRISM and HiRISE images were downloaded from Mars Orbital Data Explorer (https://ode.rsl.wustl.edu/mars/index.aspx) and from Arizona LPL website (http://hirise.lpl.arizona. edu/). MOLA/CTX mosaic/Albedo data sets can be found in project folder given. The final candidate sites were all compiled using **ArcGIS Pro** for mapping and overlaying. Further detailed footprints and global overview were accessible via **Google Mars Pro[11]**.

3 SUMMARY OF CANDIDATE SITES

3.1 Overview

The three final candidate sites were selected following the application of engineering constraints and geological filters. Based on figure 2, regions acceassible are roughly divided into two blocks, East and West. It is important to note that different-colored regions represent different epochs of the Martian surface, with deep purple indicating the Noachian period, while other colors correspond to the Early Hesperian and subsequent periods. Our three candidates mentioned in the article are all located in the deep purple section on the western side[12]. All three are situated in the ancient terrains of western Arabia Terra, which represents one of the oldest preserved crustal regions on Mars. These sites are located in areas with clear indications of hydrous mineralogy, varied stratigraphy, and morphological features possibly formed by past groundwater activity[9].

Based on geospatial overlays using MOLA topography, CRISM/OMEGA mineral maps, and thermal inertia datasets, the candidate locations were identified as: Danielson Crater, Aram Chaos, Southwestern Arabia Terra Basin

FIG 2, REGIONS THAT HAS BEEN SELECTED AFTER OVERLAYING SATELLITE DATA SETS AND APPLYING SPECIFIED ENGINEERING PARAMETERS, MEETING THE FUNDAMENTAL ENGINEERING CONSTRAINTS. (PRODUCED BY ARCGIS PRO)

At the same time, three candidates are also located within the highlighted white boxs on the Odyssey map and CRISM/OMEGA map, as shown on Fig 3 and 4.

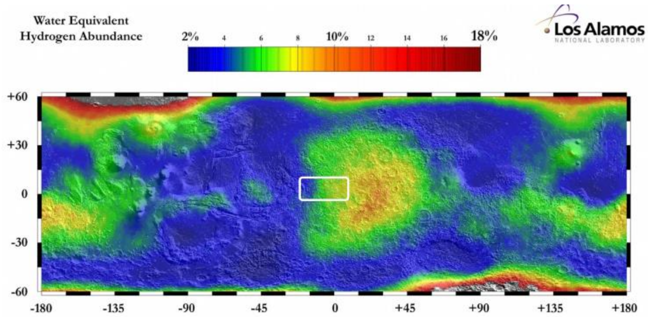

Fig 3, the image above depicts the distribution of subsurface water on Mars as revealed by the Neutron Spectrometer aboard the Mars Odyssey spacecraft, NASA.

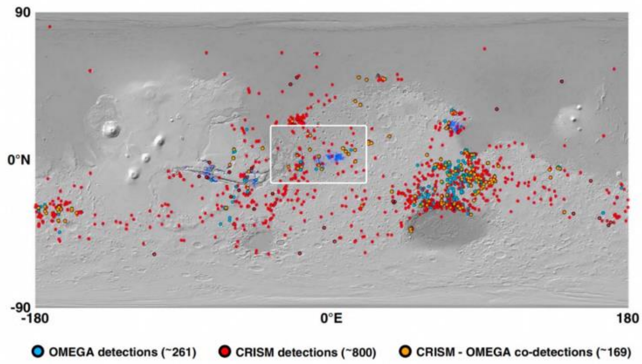

FIG. 4, GLOBAL OVERVIEW OF MARTIAN HYDROUS TRACE IS PRESENTED.

Each point signifies the location where hydrous minerals have been identified, with CRISM detections in red, OMEGA detections in blue, and instances where both instruments detected show in orange. Dark blue areas highlight OMEGA mappings in specific regions, including Sinus Meridiani (Carter et al., 2013).

3.1.1 Danielson Crater

Location	Latitude (N)	Longitude(E)	Approx MOLA elevation(km)	Target
between Meridi	7.93N	353E	Deepest crater floor:	Even layered deposits,

ani Planum and Arabia Terra			~−3400 m crater rim: ~−1400 m of absolute elevation	Phyllosilicates

Findings from the Mars Opportunity mission offer evidence supporting the notion that the formation of hematite in Meridiani Planum was driven by an aqueous mechanism. The hematite in this region predominantly comprises spherules identified as concretions, believed to have weathered out from a sulfate-rich outcrop. The presence of cross-bedding textures within the outcrop, as observed by Squyres et al. (2004), suggests subaqueous deposition. It is plausible that the development of hematite concretions occurred through post-depositional aqueous alteration of the outcrop[13]. (Glotch & Christensen, 2005)

Adjacent to Meridiani Planum, Arabia Terra is characterized by its low elevation, high albedo, and a densely cratered terrain. It constitutes the largest expanse of ancient cratered crust in the northern hemisphere of Mars, with crater densities indicating a predominantly Noachian age. The characteristics of Arabia Terra closely align with the conditions proposed by the groundwater model (Hartmann, 2005)[14].

The exact coordinates of Danielson Crater, next to Meridiani Planum and Arabia terra, are 7.93N 7.11W. This is a complex and quite representative impact crater, which holds an ellipsoidal shape of about 62 × 53 km. Danielson crater contains one of the best-preserved layered sediments of an impact basin on Mars surface, covering more than the 70% of the crater's floor. Visually, it displays an transition between light-toned and dark-toned layers, forming a stair-stepped stratal geometry that is prevalent across the crater's surface.(Baioni et al., 2014) The deep position of the crater and its location at a significant decline in regional topography indicate that this basin can be a proper candidate for investigating groundwater activity[15].

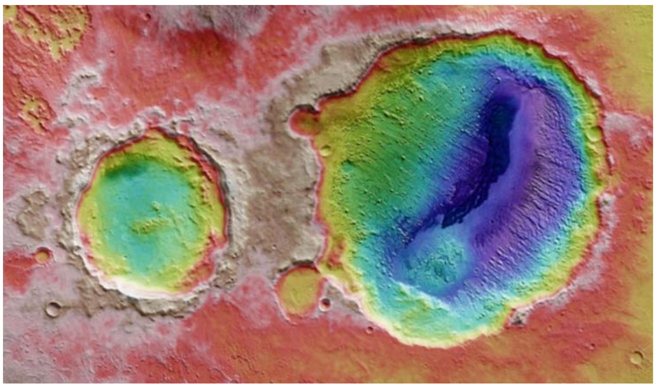

FIG 5, DANIELSON AND KALOCSA TOPOGRAPHY, SHOWN ON ESA WEBSITE

3.1.2 landing site information

Considering the engineering constraints, it possesses sufficient space to accommodate a landing ellipse of 25x20km dimensions. The landing ellipse suggested is located at 7.4N 6.89E. From high-resolution CTX images, we may observe that the northern part of Danielson, where the landing ellipse is located, is predominantly covered by light-colored material.

Based on CRISM data, intense phyllosilicates with Al and mild phyllosilicates with Fe and Mg are likely present which suggest possible aqueous alteration. According to D. Baioni, this region also underwent multiple episodes of ice melting in subsequent epochs, as evidenced by the presence of both glacial-like and fluvio-glacial landforms. Except for geomorphology characteristic of water and possibly ice, wind erosian is also present here. The question of whether the water originates from precipitation or fluvio-glacial activities or upward movement of groundwater requires further analysis. Currently, the last assumption is preferred. Danielson Crater, in general, appears to be a suitable candidate for a Mars mission.

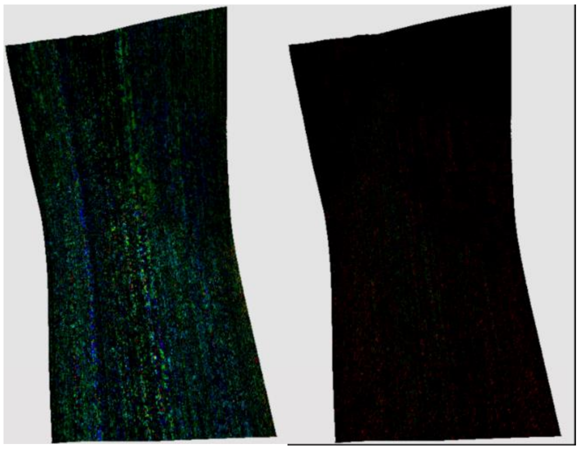

FIG 6, CRISM SPECTRUM FOR PHYLLOSILLICATES WITH AL OR FE-MG

3.2 3.2 ARAM CHAOS

Location	Latitude (N)	Longitude(E)	Approx MOLA elevation(km)	Target
Chaos Terrain	2.7N	339E	About -2000m deep	Large fractures, Phyllosilicates Grey hematite

Aram Chaos contains the second-largest known deposit of grey hematite on Mars, covering an area of approximately 5000 km^2. Hematite is a mineral that often forms in the presence of liquid water. On Mars, hematite has been

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associated with ancient water-related processes. The hematite on Mars is thought to have formed in standing bodies of water or as a result of groundwater-related processes. Aram Chaos is linked to the Ares Vallis outflow channel, suggesting the outward flow of material in the past. This correlation, along with basin morphology, the existence of easily broken sedimentary layers, and the presence of grey crystalline hematite, raises the possibility of past liquid water, both on the surface and potentially in the subsurface of this region. (Glotch & Christensen, 2005)

Two possible mechanisms have been proposed to explain the occurrence of hematite: (1) the melting of ground ice, and (2) the evacuation of magma via volcanism (Glotch & Christensen, 2005). Some researchers argue for the melting of a permafrost layer triggered by volcanic intrusion, leading to subsequent collapse. Others, such as Carr (1979) and Nummedal (1978), suggest the potential release of an aquifer in a catastrophic event if the pressure within the confined aquifer surpasses the effective lithostatic pressure, or in the event of intense earthquakes. Despite the specific mechanism, it seems probable that subsurface water played a role during the formation of most chaotic terrains.

Upon further comparions, realizing that the hematite in Aram Chaos does not match the spectral charatceristics of magnetite-derived (ie, volcanically derived) hematite and considering the evident basin morphology of Aram Chaos, it is indicative of the subaqueous deposition of the layered units. In this case, studying hematite deposits at Aram Chaos seems to be a rational choice to understand the ancient groundwater conditions on Mars and provides insights into the planet's potential subsurface habitability. (Glotch & Christensen, 2005)

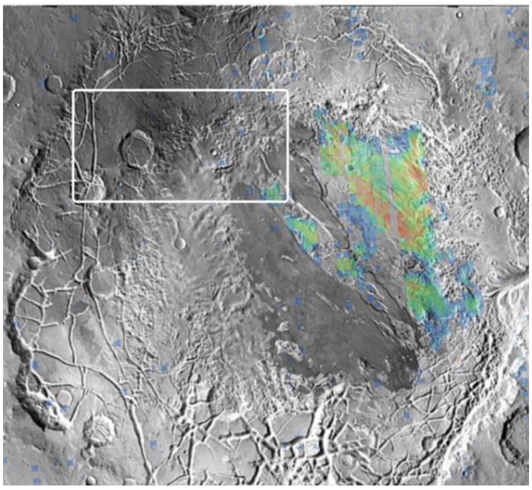

Fig 7, Overview of Aram Chaos: abundant of Hematite gathers at the upper portion of the crater; The region highlighted is the detectable location. (Glotch & Christensen, 2005)

- **Landing Site Information**

Our selected landing ellipse locates at 22.37W 4.13N. The surrounding characteristics encompass an uneven floor topography, substantial slumped and angled blocks reaching dimensions of up to tens of kilometers, and frequently occurring large arcuate fractures extending into the surrounding plains (Sharp, 1973). Based on CRISM data, intense phyllosilicates with Al and phyllosilicates with Fe and Mg are likely present which further prove the aqueous activities. Taking into consideration the unfavorable rock abundance, the center of the ellipse can only be positioned in the northern dark region of the crater. Contemplating autonomous movement to the exploration site post-landing [16].

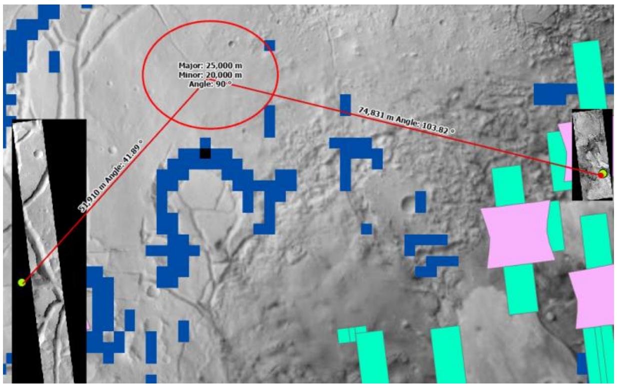

FIG 8, CTX BASEMAP WITH CRISM AND HIRISE DATA SHOWN.

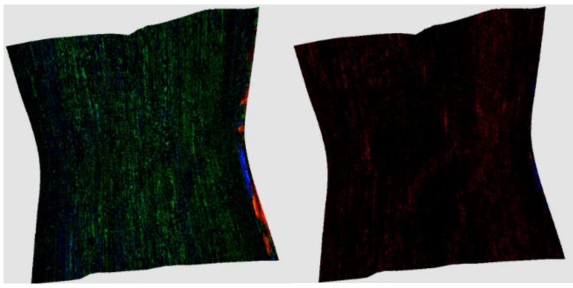

FIG 9, CRISM SPECTRUM FOR PHYLLOSILLICATES WITH AL OR FE-MG; MORE OBVIOUS FE-MG RICH CLAY MINERALS THAN THAT OF DANIELSON CRATER

3.3 SW ARABIA TERRA

Location	Latitude (N)	Longitude(E)	Approx MOLA elevation(km)	Target
Arabia Terra	7.27N	7.49E	About 1500m deep	Sand dunes, Phyllosilicates

This chosen crater, akin to Danielson Crater, shares a comparable latitude within the Arabia Terra region. In the crater's lower-left quadrant, there is an accumulation of dark material accompanied by hydrous minerals. HiRISE observations reveal a dark-toned field of barchan sand dunes in the northern part of the crater floor.

The terrestrial analogs of these dunes are readily

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identifiable, showcasing a crescent shape characterized by a steep slip face flanked by horns oriented in the downwind direction. Barchan dunes typically form under unidirectional winds and act as reliable indicators of the dominant wind direction. In this instance, the prevailing winds in this area blew approximately from north to south. In Figure 11, this wind tendency could be recognized clearly.

Composed of basaltic sand, the dunes feature smaller secondary dunes and brighter bed forms between them. The dark dunes overlay the smaller bright bed forms, suggesting a more recent formation (Shroder, 2022).

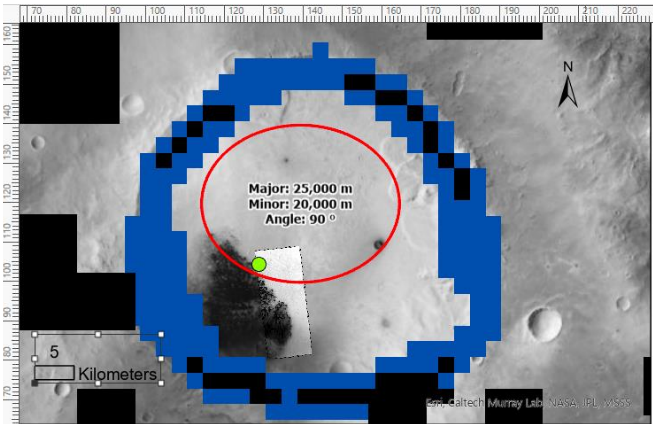

FIG 10, CTX BASEMAP WITH CRISM AND HIRISE DATA SHOWN.

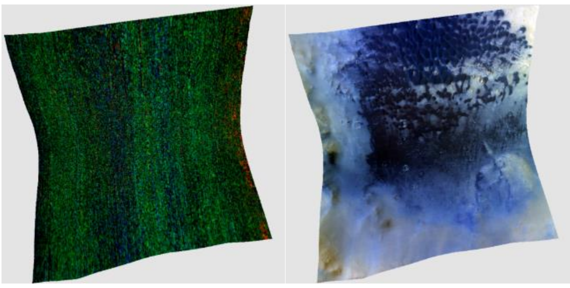

FIG 11, THE MOST INTENSE SPECTRAL REACTION IS SHOWN, INDICATING ABUNDANT EXISTENCES OF PHYLLOSILLICATES WITH AL. (LEFT); TRUE COLOR IMAGE OF THIS SAND DUNES(RIGHT), INDICATING NS WIN DIRECTION

- **Landing Information**

Our landing ellipse centers at 6.9E 7.4N, which is at the northern part of SW Arabia Terra. Figure 10 shows that the surrounding features are quite flat and smooth surface which is highy satisfying the rock abundanc limit. After landing, rover need to go to the southern sand dune to detetct the hydrous feature. This candidate holds the most obvious phyllosilicates with Al indications(Fig,11) which may prove the aqueous alternations. Aeolian activities may also contribute to the formation of this area.

4 DISCUSSION

In this section, a general ranking of the previous candidates will be provided, based on four criteria, diveristy, context, habitability, and preservation.

Mars Landing Site Science Criteria

	Danielson Crater	Aram Chaos	SW Arabia Terra
Diversity			
Multiple rock units recognized?	🟢	🟢	🔵
Well-resolved cross-sections?	🟢	🟢	🔴
Various geomorphology or mineralogic trends?	🟢	🟢	🔴
Context			
Extrapolating to regional area?	🟢	🔵	🟢
Well-resolved chronology of rock units	🔵	🟢	🔵
Habitability			
Mineralogic and geomorphic details?	🟢	🟢	🔴
H2O activities or hydrous minerals?	🟢	🟢	🟢
Preservation			
Reservation related to sedimentation period?	🔵	🟢	🔴
Is it well-preserved?	🟢	🔵	🟢

Ranking table 1, referred to Golombek et al., 2012, for 3 sites considered, with green indicates high value, red low value and blue medium value. The one with the highest ranking become the final site for 2030 Mars mission.

Danielson crater and Aram Chaos are two of the highest ranked sites based on the scientific criteria. SW Arabia Terra is deemed to possess lesser relative science merit.

From the perspectives of efficiency and the rover's endurance capacity, craters with relatively concentrated features are preferred. As shown in the overall images(Fig, xx), the rover cannot directly land in close proximity to the exploration points in order to avoid encountering excessively high rock abundance within the landing ellipse. Under this condition, the rover would need to traverse approximately 50-

70 km to reach the nearest hydrous points. In simple terms, when the evaluation results are similar, Danielson Crater is favored due to its lower hardware requirements.

5 CONCLUSION

This study presents a multi-criteria evaluation of three potential landing sites for future Mars surface missions, integrating both engineering constraints and scientific priorities. The assessment framework draws on lessons from previous Mars missions and utilizes a combination of remote sensing datasets—including CRISM, HiRISE, and MOLA—to identify terrains that not only meet safety requirements but also offer significant astrobiological and geological value.

Among the three candidates, Danielson Crater emerges as the most favorable site. Its deeply incised stratigraphy, extensive phyllosilicate-rich layered deposits, and geomorphological features indicative of long-term aqueous alteration support a strong case for the preservation of biosignatures. Additionally, it offers terrain that satisfies critical engineering parameters for landing and rover mobility. Aram Chaos also demonstrates high scientific potential, particularly in terms of mineral diversity and hydrogeological significance, but its fractured terrain presents operational risks. The southwestern Arabia Terra site, while displaying some hydrous mineral signatures and favorable surface conditions, lacks the geological diversity and preservation state seen in the other two locations.

Ultimately, the multi-parameter approach employed here underscores the importance of integrating mineralogical, geomorphic, and operational considerations in Mars landing site selection. Danielson Crater stands out as a scientifically rich and technically accessible target, and should be considered a leading candidate for future missions focused on subsurface habitability and biosignature preservation.

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The original contributions presented in the study are included in the article/supplementary material, further inquiries can be directed to the corresponding author.

CONFLICT OF INTEREST

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

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