Pathways on Mars: Preliminary Pressurized Rover Traverses from Noctis Landing, A Candidate Landing Site and Exploration Zone for Humans on Mars

Scarlett Hartzman[1,2] and Pascal Lee[1,3,4,5,6,7]

[1]Mars Institute, [2]New Rochelle High School, [3]SETI Institute, [4]Kepler Space University, [5]Ceres Robotics, [6]NASA Ames Research Center, [7]National Space Society

Corresponding authors
scarletthartzman@gmail.com, pascal.lee@marsinstitute.net

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Abstract

Preliminary pressurized rover traverse paths from a Starting Point (7.345°S, 93.016°W) near the "Noctis Landing" candidate human landing site (LS) at ~7.4°S, 93°W to nearby science and exploration target areas of interest are identified and mapped. The specific target features considered in this study are: 1) "Relict Glacier" (Target location: 7.560°S, 93.224°W); 2) "Lava Flow" (Target: 7.518°S, 93.242°W); 3) "Pink Panther Pit" (Target: 7.637°S, 92.821°W); 4) "Dragon Pits" (Central Target: DP3 at 7.229°S, 92.552°W); 5) "Noctis Caldera" (Target: 7.442°S, 94.459°W); 6) Oudemans Crater (Target: 9.753°S, 91.836°W); and 7) Syria Planum at Layl Cavus (Target: 10.372°S, 98.750°W), Malam Cavus (Target: 11.451°S, 98.256°W), and "Noc Pit" (Target: 13.642°S, 97.075°W). While pressurized rovers are anticipated to have a conventional *absolute never-exceed slope*, S_{ANE}, of 20°, the traverse paths identified here are generally kept below an *operational maximum slope*, S_{OMAX}, of 13° (slope beyond which a detour is warranted if practical), with an *operational never-exceed slope*, S_{ONE}, limited to a conservative 17° (slope beyond which an alternate route is required). This paper presents the first detailed mapping of pressurized rover traverses on both local and regional scales on Mars, accounting for specific science and exploration targets, topographic obstacles and slopes, and terrain roughness. The traverse paths found suggest that the "Noctis Landing" LS is associated with an Exploration Zone (EZ), including a Primary EZ 100 km in radius centered on the LS and wider EZs extending out to several hundred kilometers, that would give access by pressurized rover to a wide variety of high-priority science and exploration targets, both locally and regionally.

Abbreviations, Acronyms, and Initialisms

ACT	Applied Coherent Technology
ARC	Ames Research Center
ATV	All-Terrain Vehicle
CRISM	Compact Reconnaissance Imaging Spectrometer for Mars
CTX	Context Camera
DP	Dragon Pit
EVA	Extravehicular Activity
EZ	Exploration Zone
EZ1	Exploration Zone 100 km in radius
EZ2	Exploration Zone from 100 km to 200 km in radius
EZn	Exploration Zone from (n-1)00 km to n00 km in radius
HCP	High-Calcium Pyroxene
HiRISE	High Resolution Imaging Science Experiment
HMP	Haughton-Mars Project
IAU	International Astronomical Union
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LCP	Low-Calcium Pyroxene
LER	Lunar Electric Rover
LS	Landing Site
LRV	Lunar Roving Vehicle
LTD	Light-Toned Deposit
LTV	Lunar Terrain Vehicle
MGS	Mars Global Surveyor
MOC	Mars Orbital Camera
MOD	Mars Odyssey
MOLA	Mars Orbiter Laser Altimeter
MRO	Mars Reconnaissance Orbiter
NASA	National Aeronautics and Space Administration
PPP	Pink Panther Pit
RMS	Root Mean Square
SANE	Absolute Never-Exceed Slope
SMG	Speed Made Good
SOMAX	Operational Maximum Slope
SONE	Operational Never-Exceed Slope
SP	Syria Planum
THEMIS	Thermal Emission Imaging System

Note on Nomenclature

All Mars surface features and locations with provisional names (not yet approved by the IAU) are shown in quotes. “Noctis Volcano” is the provisional IAU-recommended designation for the structure identified by Lee & Shubham (2024a,b).

1. Introduction

“Noctis Landing” is a candidate landing site/exploration zone (LS/EZ) for the human exploration of Mars originally proposed at 6.49°S, 92.45°W (Lee et al. 2015a,b) during NASA’s *First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars* (Bussey & Hoffman 2016). EZs were originally defined as 100 km radius areas around landing sites within which human exploration activities, and in particular pressurized rover traverses, would focus (Bussey & Hoffman 2016). In this paper, following Shubham et al. 2019, we define the first 100 km radius area as the “Primary Exploration Zone” or EZ1, the area beyond EZ1 out to 200 km radius as EZ2, the area beyond EZ2 out to 300 km as EZ3, etc. Based on the assumption that the search for signs of life would be a driving science priority in the human exploration of Mars, “Noctis Landing” was chosen because it allows access to the monumental canyons of Valles Marineris to the east, which present an extensive stratigraphic record to search for signs of past life, and access to Mars’s giant volcanoes in Tharsis to the west, which present many caves to search for signs of extant life (Lee et al. 2015a,b).

The “Noctis Landing” candidate human LS was subsequently relocated from 6.49°S, 92.45°W to 7.4°S, 93°W, 61 km to the southwest from the original site, for the following combination of reasons (Heineman & Lee 2024): a) a “Relict Glacier” that might still harbor buried H_2O glacier ice was identified at 7.55°S, 93.25°W, 75 km southwest of the original “Noctis Landing” site (Lee et al. 2023); b) the “Relict Glacier” is associated with adjacent terrain interpreted as a vast (~5000 km^2) field of volcanic rootless cones, suggesting a possible large repository of shallow buried ice beyond the “Relict Glacier” itself (Lee & Shubham 2024); c) establishing a permanent base on Mars—accompanied by a versatile mobility capability—is key to enabling long-term scientific exploration and permanent human presence on the planet (Lee 2022, 2024) and given that goal, being able to access H_2O as an in-situ resource would be critical; d) Eastern Noctis Labyrinthus was recently identified as an ancient, deeply eroded giant volcano, provisionally designated “Noctis Volcano”, centered at 7.35°S, 94.55°W with a diameter of ~450 km (Lee & Shubham 2024) and encompassing the “Noctis Landing” LS, significantly increasing the scientific value of the site; e) a fresh-looking lava flow was also identified adjacent to the “Relict Glacier”, within the perimeter of the Noctis Volcano, suggesting the volcano remained active until recently. The coexistence of a sustained source of volcanic heat throughout Martian history and the potential presence of H_2O at shallow depth makes “Noctis Landing” a prime LS/EZ for astrobiology and studies of Mars’s evolution through time (Lee & Shubham 2024a,b). Thus, the new “Noctis Landing” LS was chosen to optimize both potential access to H_2O and major science opportunities.

A previous study had identified potential long-range pressurized rover traverse paths from the original “Noctis Landing” LS site to the giant volcanoes of Tharsis (Arsia Mons, Pavonis Mons, and Ascraeus Mons) and to Olympus Mons, destinations located 1000 kilometers and more away, *i.e.,* EZ10 and beyond (Visaya & Lee 2019). The present study, using the relocated “Noctis Landing” LS, considers closer target areas of interest (EZ1 to EZ5), and uses more advanced data visualization and mapping tools, to produce more detailed preliminary pressurized rover traverse paths taking into account specific science and exploration targets, topographic obstacles and slopes, and terrain roughness.

2. This Study

In this study, we identify and map possible paths for future crewed pressurized rover traverses from a starting point chosen at 7.345°S, 93.016°W near the new “Noctis Landing” LS (Heinemann & Lee 2024) to several key science and exploration target areas of interest within the “Noctis Landing” exploration zones EZ1 to EZ5, *i.e.*, out to 400-500 km away from the LS. **Figure 1** shows a regional context map for this study in which the Noctis volcano and areas covered by **Figures 2 through 7** are outlined.

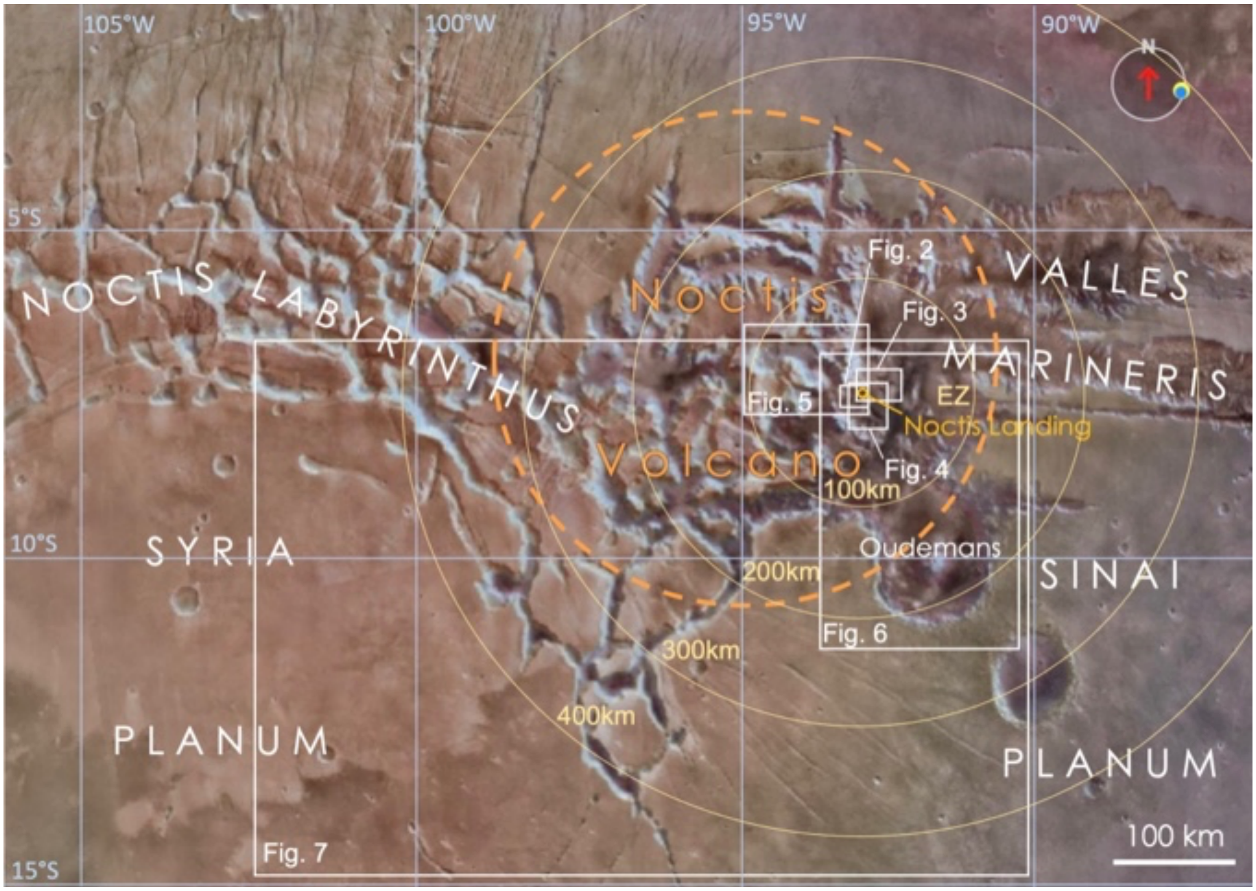

Figure 1. Noctis Landing LS/EZ Context Map. *Shown are the outline of the Noctis Volcano (orange dashed circle) (Lee & Shubham 2024b), the location of the "Noctis Landing" candidate human landing site (LS) (Heinemann & Lee 2024), concentric exploration zones around the LS out to 400 km in range (yellow solid circles), and the outlines of Figures 2 through 7 in this paper (white rectangles). Note that the Primary Exploration Zone, EZ1 (first circle out to a range of 100 km from "Noctis Landing", as well as all areas shown in Figures 2 through 5, are encompassed within the perimeter of the Noctis Volcano. Background image: NASA Viking Orbiter and Mars Reconnaissance Orbiter CTX mosaic.*

The specific features targeted in this study are:

1) "Relict Glacier" – a light-toned deposit (LTD) approximately 4 x 6 km in size, presenting the morphologic traits of a glacier (Lee et al. 2023);

2) "Lava Flow" – a 2 x 10 km fresh lava flow, *i.e.,* presenting a low albedo (indicating little alteration) and a sparsely cratered surface (indicating limited exposure to impacts) adjacent to the "Relict Glacier" (Lee & Shubham 2024, Shubham & Lee 2024);

3) "Pink Panther Pit" – a 10 km-long closed depression interpreted as a crustal ice-loss collapse feature or thermokarst (Shubham & Lee 2024a,b, Lee & Shubham *in prep.*)

4) "Dragon Pits" – a cluster of smaller closed depressions also interpreted as crustal ice-loss collapse features (Shubham & Lee 2024a,b, Lee & Shubham *in prep.*);

5) "Noctis Caldera" – the summit remnant caldera of the Noctis Volcano (Lee & Shubham 2024a);

6) Oudemans Crater – a 120-125 km wide impact structure presenting in its central uplift well-preserved sections of Valles Marineris stratigraphy laid flat;

7) Syria Planum at Layl Cavus, Malam Cavus, and "Noc Pit", three cavi (pits/caves) with a wide variety of hydrothermal deposits on their flanks and floors, in a region prone to dust storm activity (Lee & Shubham *in prep*, and refs therein).

3. Approach

3.1 Data

The present study examined several Mars data sets, primarily: a) high resolution visible imaging from NASA's Mars Reconnaissance Orbiter (MRO) Context Camera (CTX) and High Resolution Imaging Science Experiment (HiRISE) with spatial resolutions of ~6 m/px and ~0.3 m/px, respectively; b) terrain elevation and slope data from NASA's Mars Global Surveyor (MGS) Mars Orbiter Laser Altimeter (MOLA) with a standard horizontal map resolution 463 m/px; and c) surface roughness data at cm to m scale from NASA's 2001 Mars Odyssey (MO) Thermal Emission Imaging System (THEMIS), usually expressed as root mean square (RMS) slope at 10 cm to 1 m scale. The data were examined and analyzed via three Mars data visualization and mapping tools: ACT NASA Mars QuickMap, NASA ARC/JPL Mars Trek, and Google Mars.

3.2 Operational Constraints

Two key operational constraints were considered for path planning in this study: 1) obstacle avoidance; and 2) steep slope avoidance.

Obstacle avoidance. Obstacles range in size from regional-scale obstacles (*e.g.*, large craters, mountain ranges, canyon systems, tectonic fault networks) to local-scale obstacles (*e.g.*, boulders, cliffs, dunes, hummocks, steps, and rough areas). Among local-scale obstacles, Mars surface terrain features, whether positive or negative in relief, that are likely to exceed a pressurized rover's ground clearance—assumed to be 1 m—must be avoided. Considerable experience with obstacle avoidance in traverse planning and implementation exists from rover missions on the Moon and Mars, and also from terrestrial expeditions across rocky deserts and polar regions viewed as planetary exploration analogs (*e.g.*, Lee 2010, 2015).

In the "Noctis Landing" EZs, the main large-scale obstacles are associated with several-meter-tall dune fields occupying low-lying and otherwise relatively flat areas, and chaotic hummocky terrain forming the floor of the Noctis Volcano's monumental collapse zones. The canyons of Noctis Labyrinthus beyond those in Eastern Noctis Labyrinthus, which form part of the Noctis Volcano, are also interpreted as large-scale collapse features resulting from crustal ice loss (Lee and Shubham*, in prep.*).

Dunes are ubiquitous on Mars. They originate as unconsolidated accumulations of windblown sand which migrate across the landscape over time. Still, many dunes on Mars, if not most, eventually become inactive and possibly cemented (*e.g.*, Parteli & Herrmann 2007). The morphology of dunes depends on sand supply and wind regime (*e.g.*, Lee & Thomas 1993). While it is anticipated that pressurized rovers will be designed to tackle any dune on Mars, the taller ones ranging from 10 m to 640 m in height (Lorenz et al. 2015) and those with steeper slopes, *i.e.*, with slip faces ranging from 20° to 33°, represent obstacles that should be avoided and circumvented. In normal operations, a conservative approach to limiting trafficability risks and tilted configurations of the rovers will be to avoid any dune taller than the diameter of the rover's wheels (~1 m), and/or wider than the rover's wheelbase (~3 m), if possible.

Chaotic hummocky terrain, especially in the Noctis Volcano's mega-collapse zones, presents formidable local-scale obstacles. While some obstacles are clearly apparent by the discrete positive relief they present, others appear blanketed by sand or dust, which could make them treacherously hazardous. Traverse paths across such areas are planned to conservatively follow the shallowest contiguous slopes (as revealed in MOLA data), the smoothest (least rough) surfaces (as revealed in THEMIS thermal inertia data), and minimal local and large-scale obstacles (as revealed in CTX and HiRISE imaging).

Steep slope avoidance. Slope is an essential consideration for EVA, both on foot and in rover operations (Iqbal et al. 2024). A slope of ~20° represents a typical limit based on the slope requirements and/or performance for i) the Apollo Lunar Roving Vehicle (LRV) (NASA 2002, Iqbal et al. 2024) which was designed for up to 25° slopes (Boeing 1972), but with 20° as an empirical operating limit (NASA 1972); ii) the Lunar Chariot (Harrison *et al.* 2007); iii) the Lunar Electric Rover (LER) designed for up to 35° slopes (Pedersen et al. 2011); iv) the Artemis Lunar Terrain Vehicle (LTV) designed for up to 20° slopes (NASA 2021); and v) the JAXA-Toyota Lunar Cruiser pressurized rover designed for up to 20° slopes (JAXA 2025).

Consistent with the above typical limit, we consider in this study a pressurized rover restricted to an *absolute never-exceed slope,* S_{ANE}, of 20°. Traverse paths, however, must be chosen to minimize slope. We adopt here a conservative *operational never-exceed slope,* S_{ONE}—a slope beyond which an alternate route must be sought—of 17°, and a safer *operational maximum slope,* S_{OMAX}—a slope beyond which an alternate route should be sought if practical—of 13°. In situations where exceeding 17° slopes is the only viable solution, the *absolute never-exceed slope*, S_{ANE}, of 20° serves as the ultimate limit since slopes of 17° to 20° would be acceptable to tackle only in emergencies.

3.3 Path Planning

The Starting Point common to all traverse paths identified in this study, located at 7.345°S, 93.016°W and at an elevation of +353 m, was selected as a flat and relatively dune-free area ~ 1 km NW of the "Noctis Landing" LS at ~7.4°S, 93°W, and ~0.5 km NE of a potential habitat area at -7.351°S, 93.019°W. The traverse planning strategy adopted in this study entails the following five key steps:

1) draw a bee line between the Starting Point and target end point to establish an initial shortest "as the crow flies" traverse direction;

2) identify key waypoints to reach along or on either side of the bee line - *e.g.*, science targets, terrain landmarks (at large and local scales), and narrow trafficable passages such as corridors, passes, and interdune valleys;

3) identify optimal departure or approach paths at the Starting Point and target end points, and at the key waypoints along the way, taking into account the obstacle avoidance and steep slope avoidance operational constraints from Section 3.2;

4) establish path segments connecting consecutive waypoints, taking into account the same operational constraints as in 3);

5) iterate between steps 3 and 4 as needed until an acceptable traverse path is obtained.

It should be noted that the selection of paths avoiding large-scale obstacles, and minimizing slope and terrain roughness, is not only critical for nominal pressurized rover operations, but also for any EVA (extra-vehicular activity) in which astronauts would have to "hike" on foot, go on local vehicular excursions using ATVs (all-terrain vehicles), or other unpressurized rovers. Also, in general, when faced with either rough terrain or a field of large dunes to transit under normal exploration operations, rough terrain is considered a better path option, provided it is trafficable, mainly because rough terrain obstacles are more predictable, whereas dunes have less predictable bearing strength and slope stability. Also, rocky terrain generally presents greater science opportunities, in particular for sampling, than dunes.

4. Results

Preliminary pressurized rover traverse paths from the Starting Point to a total of seven targets were identified and mapped. All traverse paths identified remain at or below the conservative S_{ONE} = 17° *operational never exceed slope* limit. The traverse paths are presented in the following subsections. **Table 1** summarizes the location, elevation, and distance from the Starting Point of the various destinations and waypoints considered in this study.

Table 1: "Noctis Landing" Traverse Starting Point, Targets, and Waypoints.

Site	Coordinates		Elevation	Roving Distance From Starting Point
Starting Point	7°20'41"S, 93°00'59"W	7.345°S, 93.016°W	+353 m	0 km
"Dodo Crater"	8°51'S, 92°36"W	8.85°S, 92.6°W	+2082 m	11.66 km
DP1	7°23'17"S, 92°34'12"W	7.388°S, 92.570°W	-166 m	28.24 km
DP2	7°21'25"S, 92°37'30"W	7.357°S, 92.625°W	-584 m	DP1+4.65 km
DP3	7°13'44"S, 92°33'07"W	7.229°S, 92.552°W	-389 m	DP1+12.58 km
DP4	7°09'54"S, 92°37'30"W	7.165°S, 92.625°W	-616 m	DP3+8.67 km
DP5	7°10'55"S, 92°39'36"W	7.182°S, 92.660°W	-477 m	DP3+12.00 km DP4+5.78 km
DP6	7°07'01"S, 92°35'13"W	7.117°S, 92.587°W	-463 m	DP3+10.28 km
DP7	7°13'23"S, 92°28'59"W	7.223°S, 92.483°W	-575 m	DP3+4.37 km
"Iceland Junction"	7°28'26"S, 93°10'59"W	7.474°S, 93.183°W	+796 m	15.38 km
"Lava Flow"	7°31'05"S, 93°14'31"W	7.518°S, 93.242°W	+1142 m	20.76 km
Layl Cavus	10°22'19"S, 98°45'00"W	10.372°S, 98.750°W	+3693 m	601.99 km
"Layl Ramp"	9°32'46"S, 98°19'12"W	9.546°S, 98.320°W	+6335 m	522.25 km
Malam Cavus	11°27'04"S, 98°15'22"W	11.451°S, 98.256°W	+5162 m	616.59 km
"Malam Ramp"	11°43'34"S,98°20'13"W	11.726°S,98.337°W	+6678 m	592.91 km
Noc Cavus	13°21'50"S, 96°40'41"W	13.364°S, 96.678°W	+2650 m	N/A
"Noc Pit"	13°38'31"S, 97°04'30"W	13.642°S, 97.075°W	+6616 m	740.16 km
Noctis Caldera	7°26'31"S, 94°27'32"W	7.442°S, 94.459°W	+6364 m	147.84 km
Noctis Landing	7°21'00"S, 93°00'00"W	~7.35°S, 93.0°W	+320 m	0.6 km
Oudemans Crater	9°45'11"S, 91°50'10"W	9.753°S, 91.836°W	+2217 m	189.26 km
PPP Ramp	7°44'24"S, 92°37°48"W	7.740°S, 92.627°W	+38 m	40.35 km
PPP Vista Point	7°34'23"S, 92°52'59"W	7.573°S, 92.883°W	+709 m	20.71 km
Pink Panther Pit (PPP)	7°38'13"S, 92°49'16"W	7.637°S, 92.821°W	-500 m	54.84 km
"Relict Glacier" (Feature)	7°33'S, 93°15'W	7.55°S, 93.25°W	+1.4 km	N/A
"Relict Glacier" (Target)	7°33'36"S, 93°13'26"W	7.560°S, 93.224°W	+1391 m	22.11 km
"Sinai Junction"	9°04'37"S, 92°25'12"W	9.077°S, 92.420°W	+2229 m	131.61 km
SP1	8°27'58"S, 92°37'08"W	8.466°S, 92.619°W	+1102 m	92.32 km
SP2	7°54'11"S, 95°06'18"W	7.903°S, 95.105°W	+7415 m	326.35 km
SP3	9°53'20"S, 97°24'43"W	9.889°S, 97.412°W	+7138 m	456.57 km
SP4	9°32'46"S, 98°19'12"W	9.546°S, 98.320°W	+6339 m	528.00 km

4.1 Traverse to "Relict Glacier"

The "Relict Glacier" is a 4 x 6 km light-toned deposit (LTD) located at 7.55°S, 93.23°W and presenting a wide range of morphologic traits characteristic of terrestrial glaciers, in particular crevasse fields—including linear, splaying, circular, and tic-tac-toe crevasses—moraine bands, thrust planes, and foliation, that have led to this LTD being interpreted as the remains of a glacier (Lee et al. 2023). The LTD's surface material is not H_2O ice, which would be thermodynamically unstable at this low latitude on Mars. Instead, this LTD is composed mainly of *jarosite*, a hydroxylated sulfate which, on Mars, may result from the interaction of H_2O with basalt—a common volcanic material on Mars—in an acidic and oxidizing but low water-to-rock ratio environment (Shubham & Lee 2021,2024, Lee et al. 2023). Lying stratigraphically above the jarositic LTD are volcanic pyroclastic deposits rich in low-Ca pyroxene (LCP) (Shubham & Lee 2024). It is suspected that H_2O glacier ice is still preserved underneath the jarosite crust, the latter having formed in this case by chemical interaction between an acidic pyroclastic deposit and H_2O glacier ice (Shubham & Lee 2021). A high priority objective for a crewed mission to "Noctis Landing", or for a robotic precursor mission, would be to determine where H_2O ice might still be found in the "Relict Glacier", examined for possible biosignatures, and extracted as a resource.

The traverse path to "Relict Glacier" follows a dune-rippled corridor extending southwest from the Starting Point **(Fig. 2a)**. At "Little Devon Island"—a rocky outcrop with an outline reminiscent of Devon Island, the terrestrial Mars analog site in the Arctic home to the NASA Haughton-Mars Project (HMP)—volcanic rocks associated with a major regional NW-SE-trending fracture zone may be examined and sampled, and possible rootless cones may also be examined (Lee & Shubham, *in prep*.). Further southwest, at "Iceland Junction," located at 7.474°S, 93.183°W, 15.385 km from the Starting Point following the path to "Relict Glacier", is the bifurcation of the path to the SSW. The 6.73 km traverse path from "Iceland Junction" to "Relict Glacier" terminates at 7.560°S, 93.224°W, at an elevation of +1391 m, ~50 m north of the Relict Glacier's distinctive eastern crevasse field from the vicinity of which the rest of the glacier may be accessed. The "Relict Glacier" traverse comprises a total of 83 vertices, or waypoints, and covers a total one-way driven distance of 22.11 km. Along this path, slopes at ~0.1 km spatial scales vary between 1.77° and 9.79°, below our pressurized rover's *operational maximum slope*, S_{OMAX}, of 13°, and well below its *operational never-exceed slope*, S_{ONE}, of 17°.

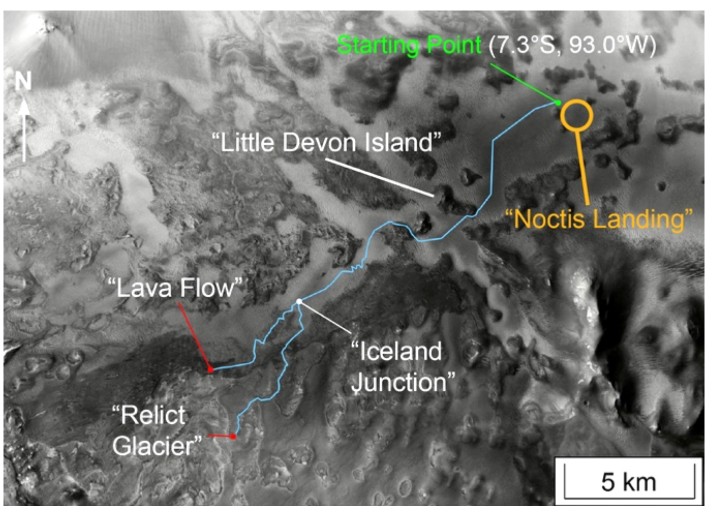

Figure 2. Traverse Paths from "Noctis Landing" to "Relict Glacier" and "Lava Flow". *These two traverse paths share a 15.385 km-long common trunk from the Starting Point at "Noctis Landing" to "Iceland Junction" via "Little Devon Island". At "Iceland Junction", the path branches off to the south for 6.73 km to reach "Relict Glacier", specifically a large crevasse field at the eastern edge of the Relict Glacier. The other branch continues to the southwest for 5.375 km to terminate at "Lava Flow".*

4.2 Traverse to "Lava Flow"

A fresh-looking lava flow with only sparse cratering is present immediately north of the Relict Glacier. The traverse to "Lava Flow" shares the same path as the traverse to "Relict Glacier" between Starting Point and "Iceland Junction" **(Fig. 2)**. At "Iceland Junction", the path to "Lava Flow" is the bifurcation branch heading further southwest. The traverse to "Lava Flow" continues for 5.375 km, eventually climbing onto the far-eastern surface of the Lava Flow and terminating at 7.518°S, 93.242°W at an elevation of 1142 m. The "Lava Flow" traverse comprises a total of 95 vertices, or waypoints, and covers a total one-way driven distance of 20.76 km. Along this path, slopes at ~0.1 km spatial scales vary between 1.87° and 10.31°, below the pressurized rover's *operational maximum slope*, S_{OMAX}, of 13°, and well below its *operational never-exceed slope*, S_{ONE}, of 17°.

4.3 Traverse to "Pink Panther Pit"

The "Pink Panther Pit" ("PPP") is a 20 km-long, 5 km-wide depression, interpreted as a thermokarst "megaslump", i.e., a large collapse pit resulting from the departure of subsurface ice (Lee & Shubham 2024, Lee & Shubham, *in prep.*). It is associated in its northeastern rim area with prominent deposits of polyhydrated sulfates and jarosite.

The traverse path from Starting Point to "PPP" crosses a vast, ~20 km-wide dune-covered plain with scattered volcanic outcrops, and reaches "PPP Vista Point" at 7.573°S, 92.883°W, at an elevation of +709 m, as it approaches the pit from its northern tip **(Fig. 3a)**.

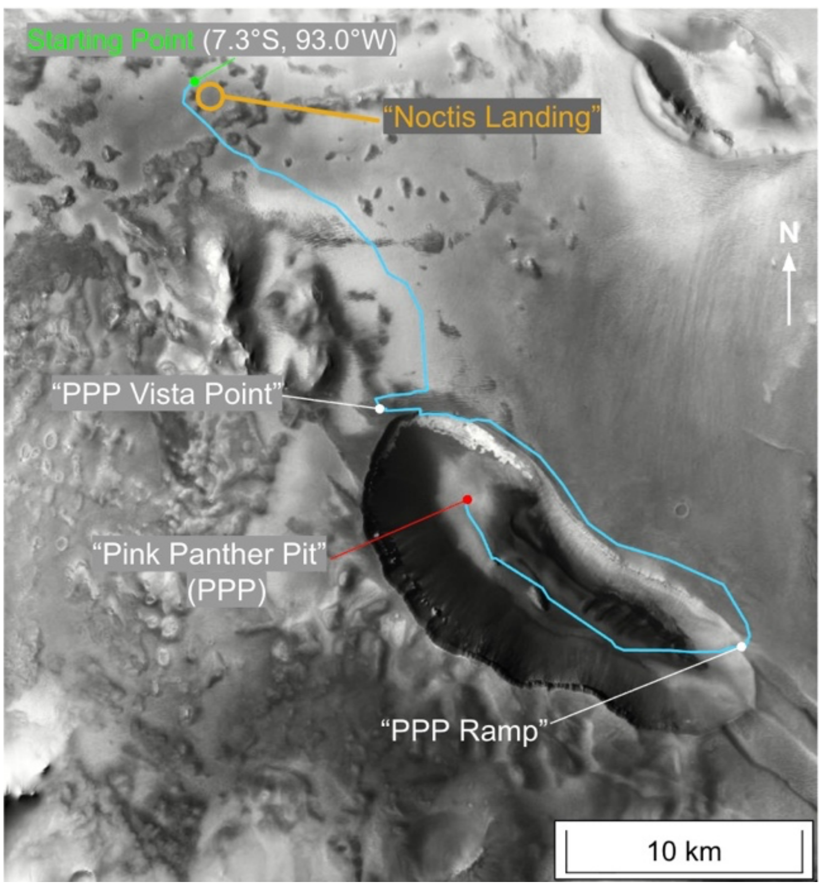

Figure 3a. Traverse Path from "Noctis Landing" to "Pink Panther Pit" ("PPP")*. The traverse path from Starting Point to the "PPP" first reaches "PPP Vista Point" where the entire length of the pit may be viewed. The path then reaches the pit's northern edge where a jarosite-rich LTD is exposed. Further south, the path reaches "PPP Ramp" via which "PPP" — the pit's sandy bottom—may be accessed.*

The path continues along the eastern edge of the pit where an LTD may be examined and sampled. The path eventually encounters a shallow ramp at "PPP Ramp", located at 7.740°S, 92.627°W and an elevation of +38 m, allowing access to the floor of the pit. The traverse ends at "PPP", the lowest point in the pit, located at 7.637°S, 92.821°W at an elevation of -500 m. The "PPP" traverse comprises a total of 74 vertices, or waypoints, and covers a total one-way driven distance of 54.84 km. Along this path, slopes at ~0.1 km spatial scales vary from 0° to 13.13° **(Fig.3b)**, close to the pressurized rover's *operational maximum slope*, S_{OMAX}, of 13°, well below its *operational never-exceed slope*, S_{ONE}, of 17°.

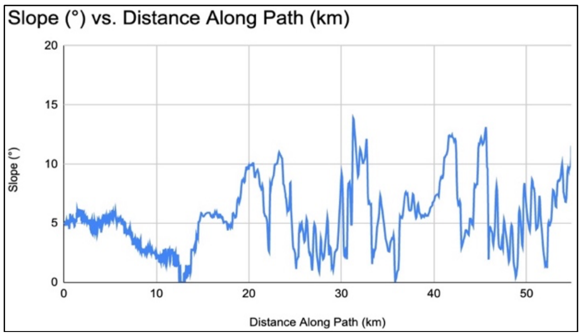

Figure 3b. "Pink Panther Pit" ("PPP") Traverse: Slope vs Distance Along Path. *From the Starting Point to "PPP", the traverse path length is 54.84 km. Along the traverse, slopes vary between 0° and 13.13°. Data from NASA MRO MOLA. Profile generated via Mars QuickMap.*

4.4 Traverse to "Dragon Pits"

The "Dragon Pits" are a cluster of depressions interpreted as thermokarst "megaslumps" (Lee & Shubham 2024, Lee & Shubham, *in prep*).

The traverse path from the Starting Point to the "Dragon Pits" first heads east toward DP1, via which DP2 on the floor of the "Little Dragon Pit" may be accessed **(Fig. 4)**.

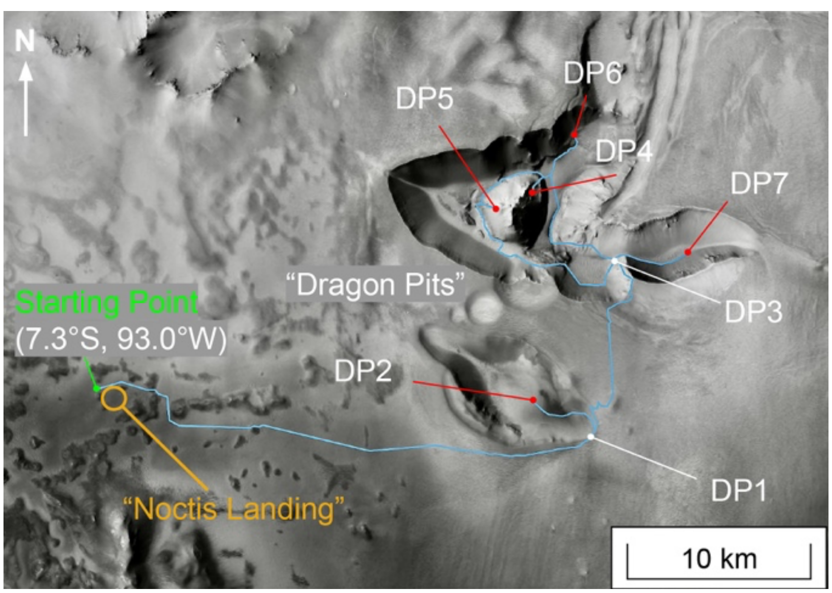

Figure 4. Traverse Path from "Noctis Landing" to the "Dragon Pits". *The traverse path from the Starting Point at "Noctis Landing" to the "Dragon Pits" first heads east toward DP1 via which DP2 on the floor of the "Little Dragon Pit" may be accessed. The path continues north to DP3 via which DP4, DP5 and DP6 in the "Dragon Head Pit", and DP7 in the "Dragon Tail Pit", may be reached.*

The path continues north to DP3 via which DP4, DP5, and DP6 in the “Dragon Head Pit”, and DP7 in the “Dragon Tail Pit”, may be reached **(Fig. 4)**. DP4 and DP5 are located on the slopes of the central positive relief feature located inside “Dragon Head Pit” designated “Eye of the Dragon Hill” (Shubham et al. 2019).

Between the Starting Point and DP1 (path length: 28.24 km), slopes vary between 0° and 10°. Between DP1 and DP2 (4.65 km), slopes vary between 1° and 10°. Between DP1 and DP3 (12.58 km), slopes vary between 0° and 5°. Between DP3 and DP4 (8.67 km), slopes vary between 0° and 10°. Between DP3 and DP5 (12 km), slopes vary between 2° and 15°. Between DP4 and DP5 (5.78 km), slopes vary between 0° and 17°. Between DP4 and DP6, slopes vary between 7° and 17°. Between DP3 and DP7 (4.37 km), slopes vary between 0° and 13°. Thus, along some sections, slopes exceed our pressurized rover’s *operational maximum slope*, S_{OMax}, of 13° (DP3 to DP5), and even reach its *operational never-exceed slope*, S_{ONE}, of 17° (DP4 to DP5, and DP4 to DP6), but remain below the *absolute never-exceed slope*, S_{ANE}, of 20°.

4.5 Traverse to “Noctis Caldera”

The central portion of the Noctis Volcano presents a flat, circular, terraced summit remnant caldera, which would have once been occupied by one or more lava lakes (Lee & Shubham 2024a). The “Noctis Caldera” represents an important scientific target, as analyzing samples from it would allow important episodes of the Noctis Volcano’s eruptive history to be documented and reconstructed.

The Noctis Volcano has experienced protracted thermal activity combined with extensive episodes of glaciation (Lee & Shubham 2024a,b). A wide variety of minerals have been identified within the perimeter of the structure, including hydrated sulfates, phyllosilicates, jarosite, olivine, opal, etc. (Shubham et al. 2019; Shubham & Lee 2024a,b and refs therein). These mineral associations suggest aqueous environments possibly favorable to life. Additionally, CRISM (Compact Reconnaissance Imaging Spectrometer for Mars) data indicates that the caldera itself contains high Ca pyroxene (*e.g.*, augite) (Lee & Shubham 2024a,b, Shubham & Lee 2024).

The traverse from Starting Point to “Noctis Caldera” meanders through vast, chaotic, and hummocky collapse zones in the central portion of the Noctis Volcano **(Fig. 5a)**.

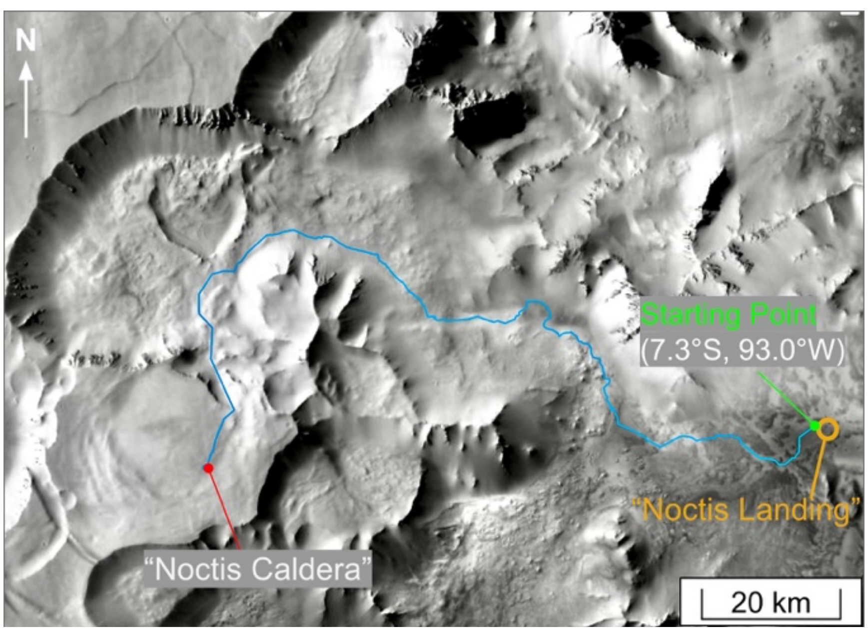

Figure 5a. Traverse Path from “Noctis Landing” to “Noctis Caldera”. *The traverse path from the Starting Point to the Noctis Volcano’s summit caldera meanders through vast, chaotic, and hummocky collapse zones while climbing from +353 m to +6364 m.*

The path rises progressively from an elevation of +353 m at the Starting Point to a final elevation of +6364 m at "Noctis Caldera". This end point at +6364 m is the lowest point in the Noctis Volcano's caldera, which is reached after attaining a maximum elevation of approximately +6,450 m. The traverse to "Noctis Caldera" comprises a total of ~350 vertices, or waypoints, and covers a total one-way driven distance of 145.74 km. Along this path, slopes at ~0.1 km spatial scales vary between 0° and 16.29° **(Fig. 5b)**, exceeding the pressurized rover's *operational maximum slope*, S_{OMAX}, of 13°, but still below its *operational never-exceed slope*, S_{ONE}, of 17°. The highest slope value of 16.29° is encountered ~10 km from the end of the path where the rover must go down a steep incline to reach the floor of the caldera.

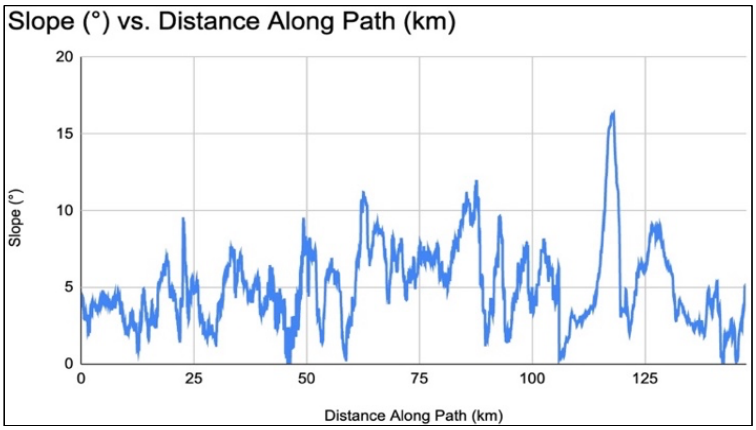

Figure 5b. "Noctis Caldera" Traverse: Slope vs Distance Along Path. *From the Starting Point to "Noctis Caldera" (145.74 km), slopes vary between 0° and 16.29°. Data from NASA MRO MOLA. Profile generated via Mars QuickMap.*

4.6 Traverse to Oudemans Crater.

Oudemans Crater, located ~150 km SSE of "Noctis Landing", is a 120-125 km-wide impact structure with a distinct central uplift. The crater was named after Dutch astronomer Jean Abraham Chrétien Oudemans (1827-1906). The Mars Orbital Camera (MOC) on NASA's Mars Global Surveyor (MGS) orbiter was the first to reveal layered formations in the central uplift. These layered formations, which were excavated by the Oudemans impact from depths similar to the depth of exposed layers in nearby Valles Marineris (~ 7 km), have been suspected to share the same mode of origin as the layers in Valles Marineris: massive volcanic deposits from the Tharsis volcanoes (Tornabene 2007). Ongoing research, however, suggests that the layered materials exposed in Oudemans' central uplift as well as in the far western portion of Valles Marineris likely include major contributions from the Noctis Volcano (Lee & Shubham, *in prep.*). Accessing the layered formations in the central uplift of Oudemans could yield important information on the eruptive history of the region—in particular of the Noctis Volcano—the effects of the large Oudemans impact, and the evolution of Valles Marineris. From a science operations standpoint, it should be noted that, because rock layers have been laid flat but still kept in sequence in Oudemans' central uplift, they are uniquely "walkable" or "drivable", *i.e.,* far more easily accessible than up along the towering cliffs of Valles Marineris (Lee et al. 2015).

The traverse path from Starting Point to Oudemans Crater is a relatively direct route **(Fig. 6)**. It initially shares the path to Pink Panther Pit up to "PPP Ramp", then continues south to Oudemans via SP1, "Dodo" Crater (8.85°S, 92.6°W), and "Sinai Junction" until arriving at the center of the crater. We informally named the ~5.5 km-wide "Dodo" impact crater after the Dodo bird (*Raphus cucullatus*), which went extinct ca 1662 and was extensively documented and studied by zoologist and cryptozoologist Anthonie Cornelis Oudemans (1858-1943), son of Jean Abraham Chrétien Oudemans. See section 4.7 on Traverses to Syria Planum for discussions of SP1 and "Sinai Junction". The traverse path to Oudemans Crater rises progressively from an elevation of +353 m at the Starting Point to a final elevation of +2217 m at the northwestern foothills of Oudemans Crater's central uplift.

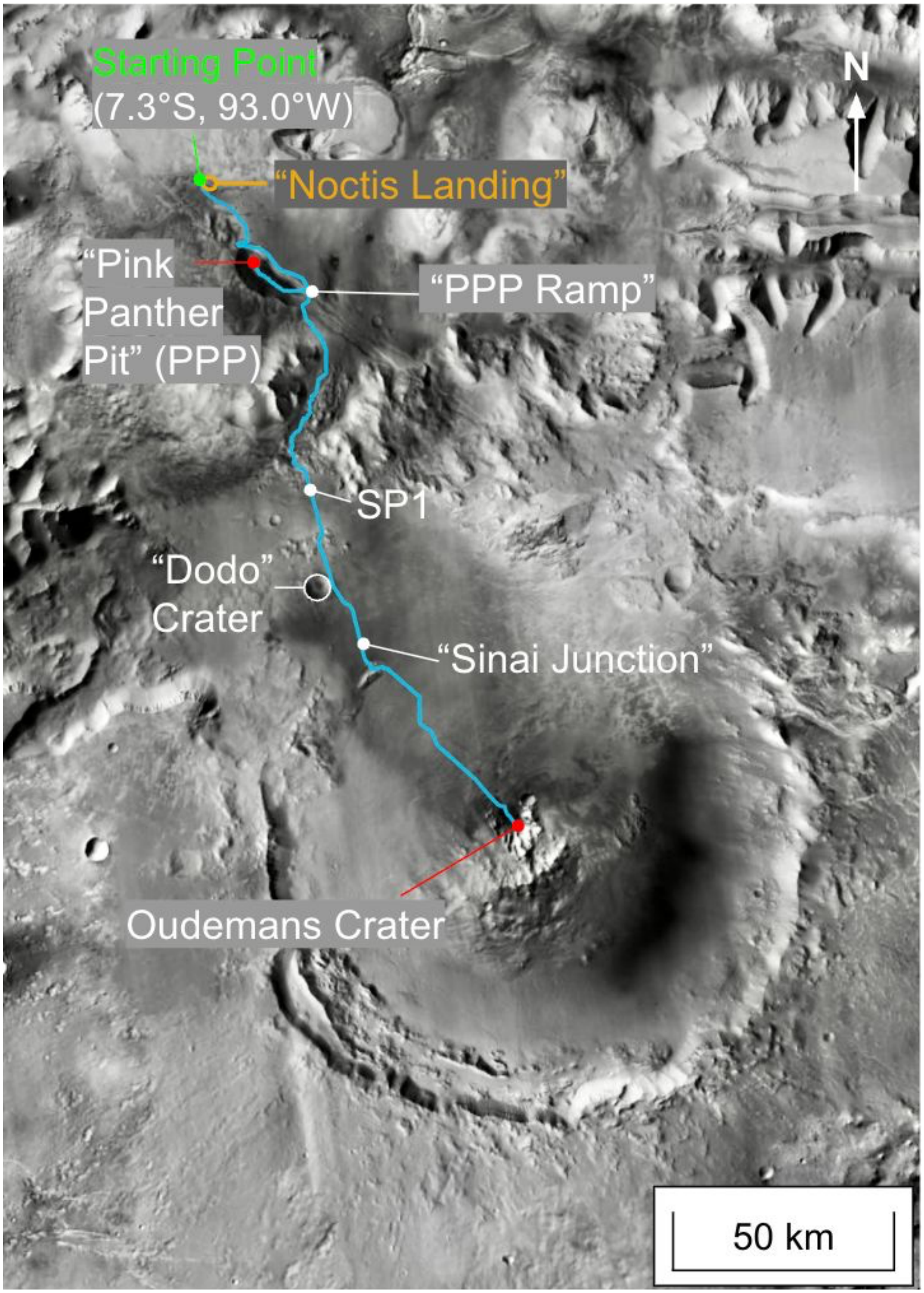

Figure 6. Traverse Path from "Noctis Landing" to Oudemans Crater. *The traverse path from the Starting Point to the central uplift in Oudemans Crater passes by SP1 and "Sinai Junction" where other paths (not shown) branch off towards Syria Planum and Sinai Planum. The Oudemans traverse also passes by the ~5.5 km-wide "Dodo" crater (8.85°S, 92.6°W).*

4.7 Traverses to Syria Planum

Syria Planum is a vast regional upland plateau, home to a large number of small volcanic domes. It is bordered in the West, North, and East by the extensive network of depressions forming Noctis Labyrinthus. Along the eastern edge of Syria Planum is a series of small Noctis Labyrinthus depressions, or *cavi*, in which a rich diversity of mineral deposits has been identified: Layl Cavus, Malam Cavus, and Noc Cavus (*e.g.,* Thollot et al. 2012).

Several traverse paths from the Starting Point to Syria Planum are identified **(Fig. 7a)**.

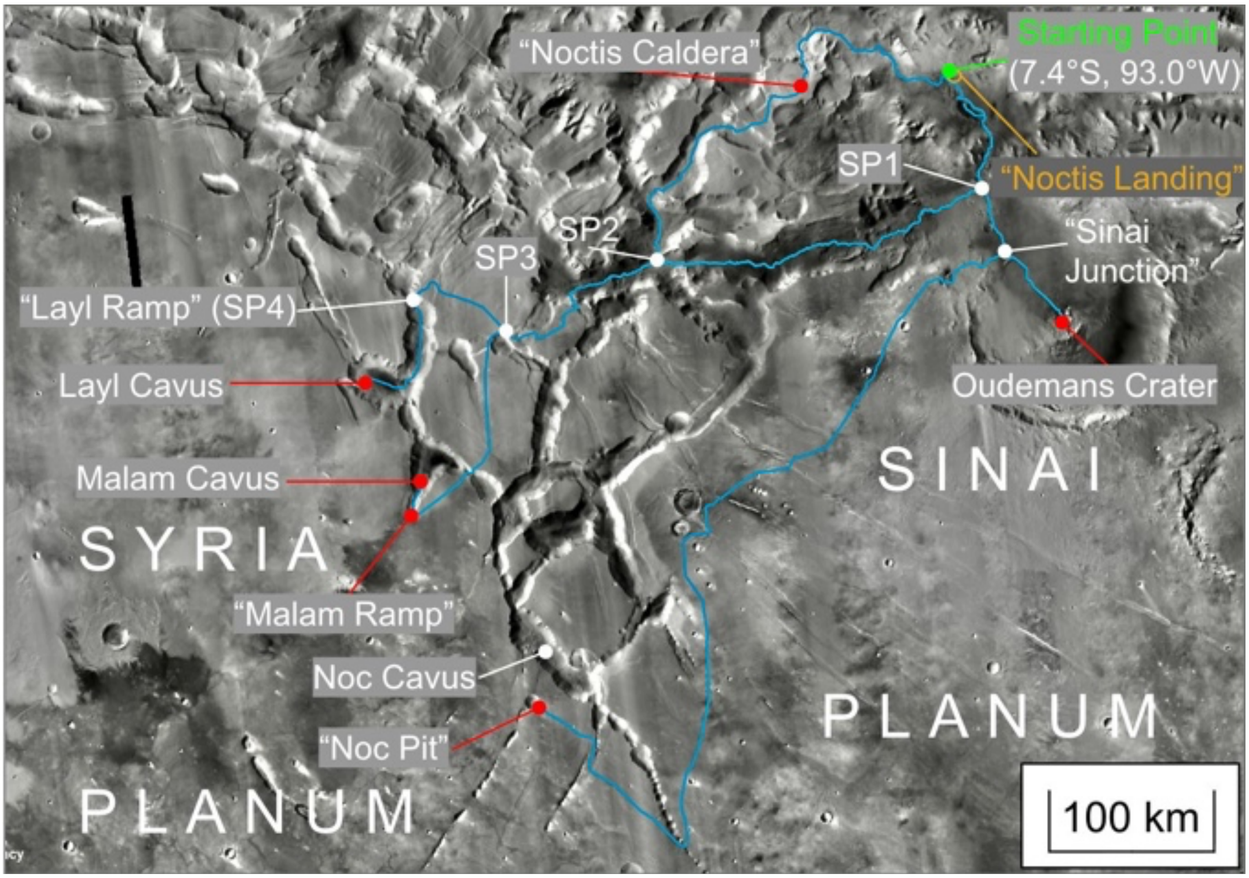

Figure 7a: Traverse Paths from "Noctis Landing" to Syria Planum. *Several traverse paths from the Starting Point at "Noctis Landing" to Syria Planum are identified. The western route reaches SP2 via "Noctis Caldera"; the southern route via SP1. From SP2, the two traverse paths merge into one continuing southwestward to SP3. From SP3, the floor of Layl Cavus may be accessed via "Layl Ramp" (SP4); the floor of Malam Cavus via "Malam Ramp". The Starting Point at "Noctis Landing" also connects to "Noc Pit" via "Sinai Junction" and a far southern route across Sinai Planum. (Background: NASA MRO CTX).*

The western route reaches SP2 via "Noctis Caldera", while the southern route reaches SP2 via SP1. From SP2, the two traverse paths merge into one, which continues southwestward to SP3. From SP3, the floor of Layl Cavus may be accessed via "Layl Ramp" (SP4), while the floor of Malam Cavus may be accessed via "Malam Ramp". The Starting Point also connects to "Noc Pit" via Sinai Junction and a southern route across Sinai Planum. The different traverse paths have different elevation profiles, but achieve a similar final elevation at their end points: Layl Cavus (+3693 m), Malam Cavus (+5162 m), and "Noc Pit" (+6616 m). The traverse distance from Starting Point to Layl Cavus is 602 km; from Starting Point to Malam Cavus, 616.6 km, and from Starting Point to "Noc Pit", 740.2 km.

The area between “Noc Pit” and “Malam Ramp”, on the highland plateau Syria Planum, is known to exhibit dust storm activity **(Fig 7b)**.

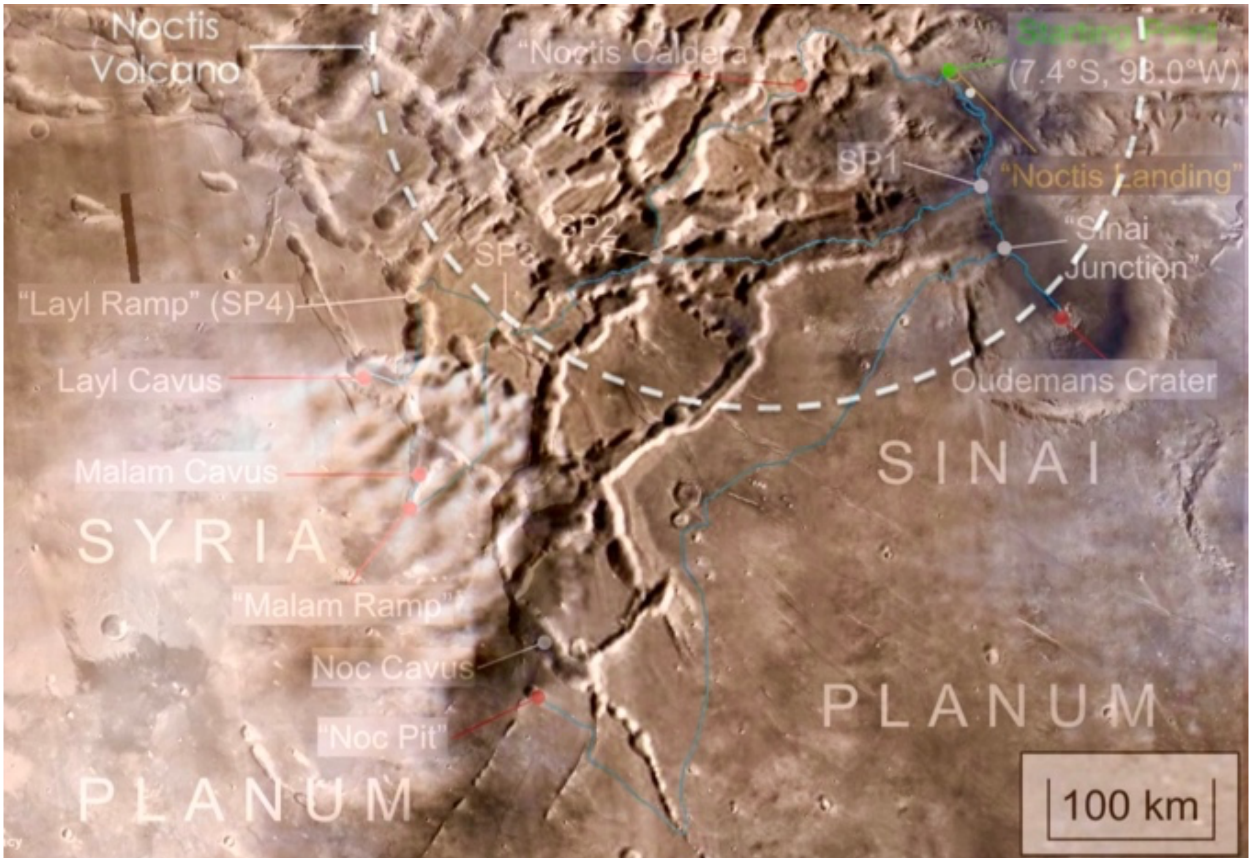

Figure 7b: Syria Planum Targets Relation to Dust Storms. *The previous map (Fig. 7a) is overlain by a Viking Orbiter image of an optically thick dust storm blowing across Syria Planum, affecting areas around Layl Cavus, Malam Cavus, and Noc Cavus. The traverses to these destinations allow* not *only the cavi to be explored, but also an area of dynamic dust storm activity to be accessed and monitored. (Background: NASA Viking Orbiter + NASA MRO CTX).*

5. Discussion

The results presented in Section 4 show that viable traverse paths exist from the Starting Point near “Noctis Landing” to several high-value science and exploration targets within the first five exploration zones, EZ1 through EZ5.

Table 2 shows the time required to complete each traverse one-way, for different values of the *speed made good* or SMG. *Speed made good* is defined as the actual, average speed of a vehicle between the starting and ending points of a traverse, calculated by dividing the total traveled distance by the total duration of the traverse (including the times during which the rover might be stopped along the way).

Speeds made good of 15, 20, 30, 50, and 100 km/day are considered, corresponding to daily average speeds of 0.625, 0.833, 1.25, 2.083, and 4.167 km/h, respectively. An SMG of 100 km/day is consistent with the SMG achieved during the NASA HMP’s Northwest Passage Drive Expedition in the Arctic (Lee 2010, 2015, Visaya et al. 2019). In the case of Mars, SMGs of order 100 km/day are expected to be plausibly achieved over time along known traverse routes established via prior slower-paced scouting and with adequate caching of supplies.

At an SMG of 100 km/day, round trips from the Starting Point to “Noctis Caldera”, Oudemans crater, Layl Cavus, Malam Cavus, and “Noc Pit” could be achieved in 3, 4, 12, 13, and 15 days, respectively **(Table 2)**.

Table 2. Traverses From “Noctis Landing” to Key Targets: Speed Made Good and Durations

Traverse From Starting Point To…	**One-Way Dist. (km)**	**Speed Made Good in km/day (km/h)**				
		15 (0.625)	20 (0.833)	30 (1.25)	50 (2.083)	100 (4.167)
		One-Way Traverse Duration				
“Relict Glacier”	22.11	1.5 days	1.1 days	17.7 h	10.6 h	5.3 h
“Lava Flow”	20.76	1.4 days	1.0 day	16.6 h	10.0 h	5.0 h
“Pink Panther Pit”	54.84	3.7 days	2.7 days	1.8 days	1.1 days	13.2 h
“Dragon Pits” (DP3)	40.82	2.7 days	2.0 days	1.4 days	19.6 h	9.8 h
“Noctis Caldera”	147.84	9.9 days	7.4 days	4.9 days	3.0 days	1.5 days
Oudemans Crater	189.26	12.6 days	9.5 days	6.3 days	3.8 days	1.9 days
Layl Cavus	601.99	40.1 days	30.1 days	20.1 days	12.0 days	6.0 days
Malam Cavus	616.59	41.1 days	30.8 days	20.6 days	12.3 days	6.2 days
“Noc Pit”	740.16	49.3 days	37 days	24.7 days	14.8 days	7.4 days

6. Conclusion

This study strengthens “Noctis Landing” as a candidate human landing site of exceptional value for Mars science and exploration, in particular for advancing the search for signs of life, past or present. The traverse paths identified create opportunities to reach high-value science targets, several with the potential of leading to the discovery of Martian indigenous biosignatures and possibly life, a milestone that would revolutionize our understanding of biology and of our place in the universe. This study has also helped validate the process for designing pressurized rover traverses, which may be applied to establishing other traverse paths across Mars in the future.

7. Future Work

The paths identified in this study remain preliminary, as a number of important factors in traverse planning, particularly for crewed rover traverses, were not taken into account, *e.g., terrain roughness* as determined from MOD THEMIS data which was considered only for the traverses to “Relict Glacier” and “Lava Flow”, *communications visibility* which can be mapped out only once optimal comms relay sites have been identified, optimal *supplies cache* locations, availability of *alternate paths* for contingencies, and prioritized *science stops and operations*. Future work will take these additional considerations into account, as well as expand the range of exploration reachable from “Noctis Landing”.

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9. References

Boeing 1972. *Lunar Roving Vehicle*, Boeing Press, 24pp.

Bussey, B. and S. J. Hoffman 2016. Human Mars landing site and impacts on Mars surface operations. *IEEE*.
https://ntrs.nasa.gov/api/citations/20160001040/downloads/20160001040.pdf

El Yazidi, M. *et al.* 2023. Evidence for Early Extension and Pressure Drop Related to Magma Plumbing in Noctis Labyrinthus (Mars). *Nasa.gov*, Mar. 13, 2023.
https://ntrs.nasa.gov/citations/20220019120

Harrison, D. et al. 2007. Next generation rover for lunar exploration, *Lunar Surf. Ops IEEEAC*, #1196.
https://www.lpi.usra.edu/lunar/strategies/lunarRover.pdf

Heineman, K. and P. Lee 2024. New location for the 'Noctis Landing' candidate human landing site on Mars. *NSS ISDC-2024*, Mars, #3002
https://isdc.nss.org/wp-content/uploads/2024/07/ISDC-2024-Mars-3002-HeinemannLee-Noctis-FINAL.pdf

Iqbal, W., J. W. Head III, C. H. van der Bogert, T. Frueh, M. Henriksen, V. Bivkel, D. Kring, H. Hiesinger, D. R. Scott, and T. Heyer 2024. Slopes along Apollo EVAs: Astronaut experience as input for future mission planning. *Acta Astronautica 223*, 184-196.
https://www.sciencedirect.com/science/article/pii/S0094576524003746

JAXA 2025. Pressurized rover mission concepts & expected capabilities.
https://humans-in-space.jaxa.jp/en/biz-lab/news/item/004354/Appendix.pdf

Lee, P. 2010. Northwest Passage Drive: Preparing for Mars. *Above & Beyond – Canada's Arctic Journal*, Sept–Oct 2010, 35–39.

Lee, P., S. Acedillo, S. Braham, A. Brown, R. Elphic, T. Fong, B. Glass, C. Hoftun, B. W. Johansen, K. Lorber, D. Mittlefehldt, Y. Tagaki, P. Thomas, M. West, S. West, and M. Zolensky 2015. Noctis Landing: A Proposed landing site/exploration zone for human missions to the surface of Mars. *First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars*, Houston, TX, 27-30 Oct 2015, #1050
https://ntrs.nasa.gov/api/citations/20150021128/downloads/20150021128.pdf

Lee, P., S. Acedillo, S. Braham, A. Brown, R. Elphic, T. Fong, B. Glass, C. Hoftun, B. W. Johansen, K. Lorber, D. Mittlefehldt, Y. Tagaki, P. Thomas, M. West, S. West, and M. Zolensky 2015a. Noctis Landing: A Proposed Landing Site/Exploration Zone for Human Missions to the Surface of Mars. *First Landing Site/Exploration Zone Workshop for Human Missions to the Surface of Mars*, Houston, TX, 27-30 Oct 2015, #1050.
https://www.lpi.usra.edu/lpi/contribution_docs/LPI-001879.pdf
https://ntrs.nasa.gov/api/citations/20150021128/downloads/20150021128.pdf

Lee, P., S. Acedillo, S. Braham, A. Brown, R. Elphic, T. Fong, B. Glass, C. Hoftun, B. W. Johansen, K. Lorber, D. Mittlefehldt, Y. Tagaki, P. Thomas, M. West, S. West, and M. Zolensky 2015b. Noctis Landing: A Proposed Landing Site/Exploration Zone for Human Missions to the Surface of Mars. *First LS/EZ Workshop for Human Missions to the Surface of Mars*. Video of presentation:
https://www.youtube.com/watch?v=0nMwIQhfy9g&t=4s [49:30 to 1:06:10 (16 min 40 sec)]

Lee, P. 2015. Polar Trek to Mars. The Northwest Passage Drive Expedition & Lessons for Future Road Trips on Mars. *SETI Talk*.
https://www.youtube.com/watch?v=NVyUs_rWbjw

Lee, P. 2022. *NSS Space Settlement Summit*

Lee, P. 2024. Artemis Base Camp: Lessons learned from field science operations in the Arctic and Antarctica for Lunar and "Moon to Mars" Exploration and Science. *NASA Lunar Surface Science Workshop LSSW-22*, #5012.
https://www.hou.usra.edu/meetings/lunarsurface22/pdf/5012.pdf

Lee, P. and S. Shubham 2024a. Large eroded volcano complex and buried glacier ice in Eastern Noctis Labyrinthus: Evidence for recent volcanism and glaciation near Mars' equator. *55th Lunar & Planet. Sci. Conf.*, #2745.
https://www.hou.usra.edu/meetings/lpsc2024/pdf/2745.pdf

Lee, P. and S. Shubham 2024b. Eroded giant volcano and buried glacier ice in Eastern Noctis Labyrinthus: Implications for Mars volcanism, glaciations, astrobiology, and exploration. *10th Int'l. Conf. on Mars*, #3553.
https://www.hou.usra.edu/meetings/tenthmars2024/pdf/3553.pdf

Lee, P. and S. Shubham. A giant volcano and buried glacier ice in Noctis Labyrinthus, Mars. *In prep.*

Lee, P. and P. C. Thomas 1993. Longitudinal dunes on Mars: Relation to current wind regimes. *J. Geophys. Res. – Planets*, 100, 5381-5395.
https://agupubs.onlinelibrary.wiley.com/doi/10.1029/95JE00225

Lee, P., S. Acedillo, S. Braham, A. Brown, R. Elphic, T. Fong, B. Glass, C. Hoftun, B. W. Johansen, K. Lorber, D. Mittlefehldt, Y. Tagaki, P. Thomas, M. West, S. West, and M. Zolensky 2015a. Noctis Landing: A Proposed Landing Site/Exploration Zone for Human Missions to the Surface of Mars. *1st LS/EZ Workshop for Human Missions to the Surface of Mars*, #1050.
https://www.lpi.usra.edu/lpi/contribution_docs/LPI-001879.pdf
https://ntrs.nasa.gov/api/citations/20150021128/downloads/20150021128.pdf

Lee, P., S. Acedillo, S. Braham, A. Brown, R. Elphic, T. Fong, B. Glass, C. Hoftun, B. W. Johansen, K. Lorber, D. Mittlefehldt, Y. Tagaki, P. Thomas, M. West, S. West, and M. Zolensky 2015a. Noctis Landing: A Proposed Landing Site/Exploration Zone for Human Missions to the Surface of Mars. *1st LS/EZ Workshop for Human Missions to the Surface of Mars*. Video of presentation:
https://www.youtube.com/watch?v=0nMwIQhfy9g&t=4s [49:30 to 1:06:10 (16 min 40 sec)]

Lee, P., S. Shubham, and J. W. Schutt 2023. A Relict Glacier near Mars' Equator: Evidence for recent glaciation and volcanism in Eastern Noctis Labyrinthus. *54th Lunar & Planet. Sci. Conf.*, #2998.
https://www.hou.usra.edu/meetings/lpsc2023/pdf/2998.pdf

Lorenz, R. D., L. K. Fenton, and N. Lancaster 2015. The Tallest Dunes in the Solar System? Dune Heights on Earth, Mars. 4th Int'l Planetary Dunes Workshop, Boise ID.

NASA 1972. *Apollo 16 Mission Report*. Manned Spacecraft Ctr, Houston, TX.

NASA 2002. *A Brief History of the Lunar Roving Vehicle.* NASA NP-2002-04-82-MSFC, Pub 8-40034, 27pp.
http://www.ninfinger.org/karld/LRV%20Documents/MSFC-LRV.pdf

NASA 2021. *Lunar Terrain Vehicle RFI NNH20ZCQ001L*.
https://sam.gov/opp/be6b922337ec457dab73dbe5f3821efc/view

Parteli, E. & H. Herrmann 2007. Dune formation on the present Mars. *Phys. Rev. E*, 76, 041307.
https://doi.org/10.1103/physreve.76.041307

Pedersen, L., M. Allan, V. To, H. Utz, W. Wojcikiewicz, and C, Chautems. 2011. High speed lunar navigation for crewed and remotely piloted vehicles.
https://ntrs.nasa.gov/api/citations/20110003563/downloads/20110003563.pdf

Shubham, S. and P. Lee 2021. Noctis Landing, Mars: Regions of interest with diversity of hydrated minerals. *52nd Lunar & Planet. Sci. Conf.*, #2591.
https://www.hou.usra.edu/meetings/lpsc2021/pdf/2591.pdf

Shubham, S. and P. Lee 2024. Noctis Volcano: Mineralogic evidence for protracted volcanism and volcano-H2O interaction. *10th Int'l Conf. on Mars*, #3551.
https://www.hou.usra.edu/meetings/tenthmars2024/pdf/3551.pdf

Shubham, S., P. Lee, and S. Gupta 2019. Noctis Landing, Mars: MRO CRISM mineralogy and water signatures at a proposed human landing site and exploration zone in West Valles Marineris. *9th Int'l Conf. on Mars*, #6305.
https://www.hou.usra.edu/meetings/ninthmars2019/pdf/6305.pdf

Thollot, P., N. Mangold, V. Ansan, S. Le Mouélic, R. E. Milliken, J. L. Bishop. C. M. Weitz, L. H. Roach, J. F. Mustard and S. L. Murchie 2012. Most Mars minerals in a nutshell: Various alteration phases formed in a single environment in Noctis Labyrinthus. *J. Geophys. Res. Planets*, 117.
https://doi.org/10.1029/2011JE004028

Tornabene, L. and HiRISE Team 2007. Oudemans crater central uplift: A sample of well-preserved layering.
https://hirise.lpl.arizona.edu/PSP_001602_1700

USGS 2023. Thermal Emission Imaging System (THEMIS) USGS Controlled Mosaics. *Astrogeology Analysis Ready Data*, Feb. 28, 2023.
https://stac.astrogeology.usgs.gov/docs/data/mars/themis_controlled_mosaics/

Visaya, V., B. Day and P. Lee 2019. Noctis Landing, Mars: Concept Vehicular Traverse Paths From a Proposed Human Landing Site and Exploration Zone in West Valles Marineris.
https://www.hou.usra.edu/meetings/lpsc2019/pdf/3272.pdf