

Drone Imaging of Arctic Geology as an Analogue for Future Mars Rotorcraft Missions

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by

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Abstract

Between April 2021 and January 2024, the Ingenuity drone performed 72 flights in the Martian atmosphere. This technology demonstration paved the way for future exploration of Mars using Unmanned Aerial Vehicles (UAV). However, it is not yet clear which landforms and surface processes will benefit from this new technology.

This study therefore aims to further investigate the geomorphic features on Mars that will gain to be studied from a UAV perspective. To do so, a First Person View (FPV) drone is used to image Martian geomorphic features analogues at different ground sampling distance (GSD). Analysis of the images and comparison with current in-orbit capabilities on Mars are performed to determine the needed GSD and derive recommendations for future Mars rotorcraft missions. Analogues of ejecta blocks, gullies and patterned grounds were found and imaged within the Haughton impact crater on Devon island during the field campaign of the NASA Haughton-Mars Project (02/08/2024 to 14/08/2024).

The ejecta blocks and gullies appeared to be interesting targets for UAV studies on Mars. A GSD of 6 centimeters per pixels has been identified as an upper bound to properly observe the damage state of a boulder and distinguish its impact-related origin from other hypothesis (boulder slide remnant or glacier erratic). The gully characterization, and especially the identification of a wet origin can be performed with GSD lower than 2 centimeters per pixels.

However, UAV studies of patterned grounds revealed no particular benefits since the needed GSD to identify their formation mechanism was low enough to be performed using rovers. The UAV perspective only enable the identification of smaller patterns than the one observed with satellite imagery.

Acknowledgments

This master thesis gives proper closure to an important part of my life. It marks not only the end of an 8-month research work but also the end of my studies, both in France at the Ecole Centrale de Nantes and in the Netherlands at TU Delft. The amount of hours, emotion and sweat I put in this project reflects my passion for space exploration and science in general. All of this, of course, is not only my own accomplishment. Many people dedicated time and sweat to make this project possible.

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This work would have certainly not been possible without my thesis supervisor, Sebastiaan de Vet, that kindly accepted to work on a topic he did not choose only to be sure it would fit me perfectly and make me the happiest student possible. He made sure everything was set correctly both for the fieldwork and data analysis and always provided useful work directions and ideas, tremendous support and availability both to work on the thesis but also to collect the needed funds for the fieldwork. I am especially grateful for the Mars Institute, Foundation Ailes de France, National Space Society and the Koninklijke Nederlandse Vereniging voor Weer- en Sterrenkunde for their financial support that not only allowed me to participate in the expedition but also gave me the confidence I needed to be sure I was on the right path to become the scientist I have always wanted to be. Their trust and support warmed my heart and will never be forgotten.

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Contents

Abstract

Acknowledgments

Nomenclature

vii

1	Introduction	1
1.1	Geological history of the Martian surface	1
1.1.1	The Noachian	1
1.1.2	The Hesperian	3
1.1.3	The Amazonian	3
1.2	Mars science missions	4
1.2.1	Past and current missions	4
1.2.2	Future science missions on Mars	5
1.2.3	Martian rotorcrafts	6
1.3	Thesis objectives	6
1.4	Report outline	7
2	Methods	8
2.1	Drones on Earth for science	8
2.2	Planetary analogues	9
2.3	Devon Island and the Haughton Impact Crater	10
2.3.1	Geological History and Present day situation of the Haughton Crater	10
	Impact crater formation	12
	A Mars analogue field site	13
2.3.2	The NASA Haughton-Mars Project	13
2.4	Field campaign Haughton Crater 2024	14
2.4.1	Ground Sampling Distance: the key property for drone imaging	14
2.4.2	Drone selection	15
2.4.3	UAV Camera Calibration	16
2.4.4	Traverse Plan and Studied Geomorphic Features	17
2.4.5	Encountered difficulties	20
3	Results	21
3.1	Impact Ejecta Blocks	21
3.1.1	Occurrence, distribution, and significance on Mars	21
3.1.2	Boulder origin hypothesis and impact ejecta block diagnoses	24
3.1.3	Implication for future Mars rotorcraft missions	29
	Mission level recommendations	30
	Operation recommendations	31
3.2	Gullies	31
3.2.1	Occurrence, distribution, and significance on Mars	32
3.2.2	Gully resolution: wet or dry origin diagnoses	34
3.2.3	Implication for future Mars rotorcraft missions	39
	UAV study case: examples of gully operations	40
3.3	Patterned Ground	42
3.3.1	Occurrence, distribution, and significance on Mars	43
3.3.2	Origins of patterned ground on Mars and needed GSD	44
3.3.3	Implication for future Mars rotorcraft missions	48
3.4	Other geomorphic features	48

4	Discussion	50
4.1	Recommendation for future Mars Helicopter Missions	50
4.1.1	Imaging requirements	50
4.1.2	UAV attitude and camera stabilization	51
4.2	Future prospects for Martian rotorcrafts	51
4.2.1	Hale Crater	52
4.2.2	Mawrth Vallis	53
4.2.3	Noctis Labyrinthus	54
4.2.4	Drone Mission Operations Architecture	54
5	Conclusion	56
A	Gantt Chart	64

List of Figures

1.1	Figure from (Solomon et al., 2005). (A) Map of martian surface units grouped on the basis of age. Units transitional between Noachian and Hesperian and between Hesperian and Amazonian have been included in the younger of the two epochs. Areas in white are impact craters and their ejecta deposits. (B) Topographic map of Mars with major regions noted.	2
2.1	Map of the Canadian High Arctic showing the Haughton impact structure location on Devon Island (Fletcher et al., 2017)	10
2.2	Shatter cone (a) and breccia (b) found in the crater during NASA HMP 2024 fieldwork	11
2.3	Simplified geological map of the Haughton impact structure (Osinski et al., 2010)	11
2.4	15 meters tall ejecta block found inside the Haughton impact structure	12
2.5	Schematic diagram of the initial impact, and subsequent formation of the transient crater cavity during the excavation stage by Kenkmann et al. (2014).	13
2.6	Map of the HMP base camp in 2024	14
2.7	Calibration of Ingenuity's cameras. Data from Maki et al. (2024)	15
2.8	GSD as a function of the flight altitude	16
2.9	Landing pad seen from 30m with dimensions (a) and from 200m (b)	17
2.10	Location of imaged features and traverse roads	18
2.11	Rock circle 5m	18
2.12	Rock circle, 28m	18
2.13	Periglacial Polygons, 5m	18
2.14	Periglacial Polygons, 90m	18
2.15	Sodom and Gomorrah Ejecta Blocks, 30m	19
2.16	Sodom and Gomorrah Ejecta Blocks, 350m	19
2.17	Matt Ejecta Block, 30m	19
2.18	Matt Ejecta Block, 350m	19
2.19	Impact Breccia Gully, 15m	19
2.20	Impact Breccia Gully, 335m	19
2.21	Seepage, 15m	19
2.22	Seepage, 335m	19
3.1	Crater density maps according to the category assigned in Lagain et al. (2021), (A)Density of standard impact craters. (B) Density of buried or degraded craters.Secondary impact crater density and 108 primary craters that have produced 70crater population for D (diameter) >1 km. Figure from Lagain et al. (2021)	23
3.2	Ejecta blocks from Odyssey crater. (A) Pancam false color image of the block Tisdale acquired on sol 2690 using the 753-, 535-, and 432-nm filters, sequence p2387. Height of Tisdale is 30 cm. Square shows location of image in (B). (B) MI image acquired on sol 2696. Scale across the image is 2.5 cm. (C) Pancam false-color image of the ejecta block Kidd Creek acquired on sol 2694 using the 753-, 535-, and 432-nm filters, sequence p2593. Scale across Kidd Creek is 1 m. Figure by Squyres et al. (2012)	24
3.3	Pictures of Sodom ejecta taken at three different altitudes with a zoom on fractured and pitted area of the boulder. (a) 400m. (b) 200m. (c) 30m. (d), (e), (f) are the same zoomed pitted and fractured area of respectively (a), (b), (c). The red arrow point at two large fractures of the ejecta. The bleu arrow points at the patterned ground next to the ejecta block	25
3.4	Altitude vs GSD, drones and satellite capabilities with GSD zone allowing ejecta imaging	29
3.5	Altitude vs GSD, drones and satellite capabilities with GSD zone allowing ejecta imaging zoomed in the drone part	30

3.6	Failed nadir pointing image of Matt's rock	31
3.7	Four different types of gullies found on Mars. (a) 6000 meters long Alcove-Channel-Apron gullies as seen by HiRISE (<i>ESP_011806_1665</i>). (b) 5440 m wide landslide from the east of Valles Marineris taken by the HRSC instrument of Mars Express (<i>lat</i> : -14.04 <i>lon</i> : -55.42). (c) Hundreds of meters long dark streaks found on dust-covered slopes by the HiRISE instrument (<i>ESP_025155_1720</i>). (d) 1000 meters long and few meters wide linear gully, showing no alcove and an abrupt end without apron (HiRISE: <i>ESP_020770_1300</i>).	32
3.8	RSL appearance as seen by HiRISE. (b) shows the darkening of two RSL not present in (a). (a): <i>ESP_030530_2155</i> . (b): <i>ESP_035567_2155</i>	33
3.9	Location of known RSL on Mars, from Tebolt et al. (2020); McEwen et al. (2011); Millot et al. (2021)	34
3.10	Oblique view of an impact breccia gully found in the Medusa Valley inside the Haughton crater.	35
3.11	Nadir view off a seepage found in the Haughton crater next to Matt's rock. The dark arrow indicates the slope direction.	36
3.12	Altitude vs GSD, drones and satellite capabilities with GSD zone allowing gully characterization	39
3.13	Altitude vs GSD, drones and satellite capabilities with GSD zone allowing gully characterization zoomed in the drone part	40
3.14	Four different gullies found on Mars. The red rectangles delimits the size of a picture with a 0.02 meters per pixel GSD. (a) 6000 meters long Alcove-Channel-Apron gullies as seen by HiRISE (<i>ESP_011806_1665</i>). (b) 1500 m long dark streak on the northern wall of Hebes Chasma (<i>ESP_040791_1785</i>). (c) 500 meters long and few meters wide linear gully from the western part of Matara Crater Dune Field (HiRISE: <i>ESP_030528_1300</i>). (d) 1.200 meters long Alcove-Channel-Apron gullies as seen by HiRISE (<i>ESP_066220_1430</i>)	41
3.15	Two possibles trajectories to map the presented gully. (The trajectories are not fully representative of the actual path that need to be taken to ensure a full coverage of the orange zone but the red full squares are scaled for a GSD of 0.02 meters per pixel)	42
3.16	Large size polygons found next to the base camp. (a) Horizontal view of the polygon field. (b) Nadir view of the polygon field taken with the DJI MINI 3 drone at 100 meters from the ground.	43
3.17	Distribution of patterned ground on Mars from MOC images M01 to E06. The background shows a mosaic of MOC wide angle images with Tharsis hemisphere at right (Eastward longitudes). LPC polygons are close to south polar cap at longitude especially around 270° E. There is a strong limit at 55° of latitude. Crack class: A = Random orthogonal, B = Orthogonal, C = Hexagonal. Type LT = Large and influenced by Topography. LPC = Large around Polar Cap. S1 to S3 are Small. VF = Variable with fractal shape. VV = Variable without organization. VCX = Variable and complex Mangold (2005)	43
3.18	Different types of polygons found on Mars (all pictures come from HiRISE instrument). (a) Rectangular pattern (<i>ESP_075366_1155</i>). (b) Araneiforms off south polar layered deposit (<i>ESP_057195_1000</i>). (c) Rectangular pattern near the Inca City region (<i>ESP_048703_0985</i>). (d) Large polygons field next to a north polar crater (<i>ESP_079190_2500</i>). (e) Straight cracks field off south polar layered deposit (<i>ESP_056599_0935</i>). (f) Cracks networks off south polar layered deposit (<i>ESP_056599_0935</i>).	44
3.19	Materials sorted to form a rock circle, 400m west to the HMP base camp. Picture taken with the DJI Mini 3 flying 10 meters above ground.	45
3.20	Rock Layering on top of a steep mount in the valley of the planet of the apes, Devon island. (a) Steep Mount. (b) North-West side of the top of mount shown on (a) with visible layering. (c) South-East side of the top of mount shown on (a) with visible layering.	49
4.1	Diversity of geomorphic features in the Hale crater. (a) High number of gullies on the North-East side of the crater rim (<i>ESP_073613_1445</i>). (b) Boulder field in the center of the crater (<i>ESP_030425_1440</i>). (c) Rough terrain inside the crater (<i>ESP_026403_1445</i>). (d) Sand dunes inside the crater (<i>ESP_030425_1440</i>).	53

A.1 Gantt Chart	65
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List of Tables

1.1	Comparison of Mars satellites, their instruments, Ground Sampling Distance, and orbit altitudes	5
1.2	Comparison of Ingenuity, Sojourner, and Spirit	5
3.1	Characterization of Matt's Rock impact ejecta block	26
3.2	Characterization of Sodom impact ejecta block	27
3.3	Characterization of Gomorrah impact ejecta block	28
3.4	Characterization of an impact breccia gully	37
3.5	Characterization of a Seepage in the Haughton crater	38
3.6	Flight characteristics for studying gullies	41
3.7	Characterization of a rock circle	46
3.8	Characterization of a polygon field	47
4.1	Imaging requirements.	51
4.2	UAV attitude and camera stabilization requirements.	51

Nomenclature

Abbreviations

Abbreviation	Definition
ACA	Alcove-Channel-Apron
ATV	All Terrain Vehicle
CaSSIS	Colour and Stereo Surface Imaging System
CNSA	Chinese National Space Agency
CTX	Context Camera
DTM	Digital Terrain Model
DEM	Digital Elevation Model
ESA	European Space Agency
Ga	Giga annum
GSD	Ground Sampling Distance
HiRISE	High Resolution Imaging Science Experiment
HMP	Haughton Mars Project
HRSC	High Resolution Stereo Camera
ISRO	Indian Space Research Organization
JAXA	Japan Aerospace Exploration Agency
JPL	Jet Propulsion Laboratory
LRO	Lunar Reconnaissance Orbiter
MARCI	Mars Color Imager
MGS	Mars Global Surveyor
MOC	Mars Orbiter Camera
MRO	Mars Reconnaissance Orbiter
MSL	Mars Science Laboratory
NASA	National Aeronautics and Space Administration
ROI	Region of Interest
RSL	Recurring Slope Lineae
RTE	Return to Earth
SETI	Search for Extraterrestrial Intelligence
UAV	Unmanned Aerial Vehicle

1

Introduction

Mars is one of our neighbors. It is the fourth inner planet in the solar system and has similarities to Earth. It is a terrestrial planet with a thin atmosphere and a mean radius of 3389.5 kilometers. Its solar day (a sol) lasts for 24 hours and 24 minutes, and its rotational axis tilt is of 35 degrees, which results in seasonal changes comparable to the one experienced on Earth. The geological history of Mars is rather different and can be divided in four major periods ([Carr and Head, 2010](#)). The pre-Noachian (4.6 to 4.1 Ga), the Noachian (4.1 to 3.7 Ga), the Hesperian (3.7 to 3.0 Ga), and the Amazonian (3.0 Ga to present). Unless the pre-Noachian, each other periods can be studied thanks to the surface geology through different geomorphic features ([Andrews-Hanna and Bottke, 2017](#); [Carr and Head, 2010](#)). For instance, valley networks and impact craters are related to the Noachian period (4.1 to 3.7 Ga) whereas the outflow channels or canyons can infer properties of the Hesperian period (3.7 to 3.0 Ga), and the polar layered terrains are associated to the Amazonian period. These terrains related to different epochs are shown in [Figure 1.1](#), with the major regions noted in ([Solomon et al., 2005](#)).

1.1. Geological history of the Martian surface

1.1.1. The Noachian

The Noachian began after the Hellas forming impact and is characterized by high rates of cratering, erosion, valley formation, and surface conditions that allowed the production of weathering products. The high rates cratering are still observable on the actual surface of Mars where plains with superimposed impact crater covered 40% of the planet ([Figure 1.1 A and B](#)). This bombardment era is thought to be responsible for bringing a non-negligible part of the surface water that later shaped the Noachian terrains ([Anderson et al., 2022](#)). Observations of hydrous weathering and valley network dating from this period suggest a large timescale for warm conditions. Furthermore, the lack of general glaciation evidence in early Noachian terrains suggests an arid climate before a rise in fluvial erosion ([Ramirez and Craddock, 2018](#)). The semi-arid climate coupled with the evidence of stable liquid water on the surface also raised question about habitability. On Earth, life may have originated as early as 3.8 Ga ([McClendon, 1999](#)). A period that corresponds to the Noachian during which the conditions were favorable for life to appear ([Anderson et al., 2022](#)). Another characteristic of this epoch is the widespread presence of phyllosilicates that results from the aqueous alteration of basalts ([Zolotov and Mironenko, 2007](#)). However, this conditions changed before the Hesperian to a dry and cold climate under which hydrous weathering was not possible, as suggested by the unaltered olivine-rich rocks overlaying the phyllosilicates ([Carr and Head, 2010](#)).

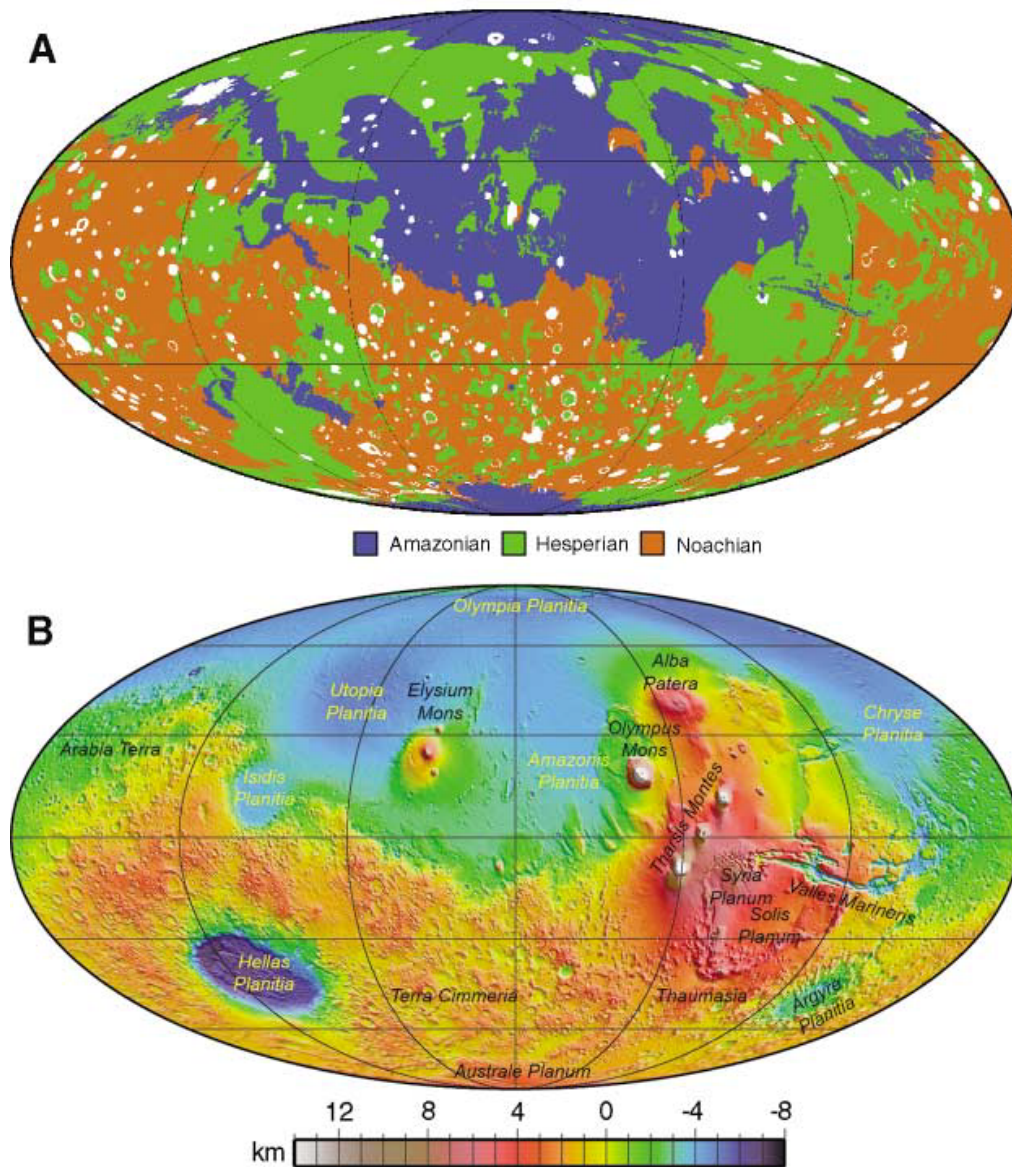


Figure 1.1: Figure from (Solomon et al., 2005). (A) Map of martian surface units grouped on the basis of age. Units transitional between Noachian and Hesperian and between Hesperian and Amazonian have been included in the younger of the two epochs. Areas in white are impact craters and their ejecta deposits. (B) Topographic map of Mars with major regions noted.

The Noachian is also associated to volcanism that essentially occurred in the Tharsis region (Andrews-Hanna and Bottke, 2017). The regional activity deeply marked the planet surface with the creation of vaults all around the Tharsis volcanoes. The formation of the Tharsis bulge started in the pre-Noachian and lasted until the early Hesperian. Its activity during the Noachian created volcanic outpourings resulted in the growth of the Tharsis volcanic rise. However, if faults at Tempe Terra, and Claritas confirms tectonic deformation in the Tharsis region started in the Noachian, the induced stresses peaked in the early Hesperian (Bouley et al., 2018). The Valles Marineris are the most visible evidence of the tectonic activity intensity that occurred at the boundary of the two periods. Andrews-Hanna (2012) proposed a sequence of events for this formation that corresponds to geological observations of the region that suggest a faulting in the late Noachian, but the presence of Hesperian material on the rim of the Valles Marineris suggests that most of the opening occurred after the early Hesperian.

1.1.2. The Hesperian

The Hesperian epoch is defined to begin at the end of the bombardment era and is marked by extensive volcanism responsible for large lava plains that buried some of the Noachian craters. It is also characterized by the formation of canyons, of the largest outflow channels ([Carr and Head, 2010](#)), and their terminal lakes and seas. The volcanism during the Hesperian also occurred around the Tharsis region but is additionally responsible for some of the eastern plains and the Hellas floor. The volcanic activity is also associated to the release of large amount of vaporized groundwater. Impactors are also responsible for the release of groundwater and may have initiated hydrothermal cycles when sufficient water was released ([Marzo et al., 2010](#)). Despite its dry conditions, the Hesperian experienced large catastrophic floodings resulting in large bodies of water on the surface. Furthermore, identified potential shorelines in the northern lands suggest the presence of oceans that carved the largest outflow channels [Carr and Head III \(2003\)](#). Crater lakes remnants have also been identified near Ares Vallis ([Warner et al., 2010](#)). These large amount of water could have covered one third of the planet surface but have now disappeared. A major part of this water could have been lost to space since the late Hesperian due to sublimation and changes in the atmospheric conditions and another part must be kept in the polar ice caps ([Carr and Head III, 2003](#)).

The interaction between the volcanic gases and in particular sulfur dioxide and the water created the formation of extensive amounts of layered sulfates areas, especially throughout the Arabia terra. Sulfate rich deposit has also been found within crater fill ([Gaillard et al., 2012](#)). Three impact basins that existed during this period have been chosen for the search of the earliest habitat of life on Mars (the Gusev, Gale, and Jezero craters) ([Anderson et al., 2022](#)). The Gale crater has been explored by Opportunity rover and analysis of samples reveals the presence of sulfates ([Gaillard et al., 2012](#)). The Hesperian is also characterized by its changing climate that went from warm and wet at the end of the Noachian to cold and dry at the beginning of the Amazonian. This resulted in the dropping of the water table below the surface conducting to the erosion of kilometer thick layered sedimentary deposit ([Andrews-Hanna, 2012](#)).

1.1.3. The Amazonian

The Amazonian began approximately 3 billion years ago and despite being the longest period in Martian history, resurfacing and geomorphological changes less impacted the planet. The major flooding already modified the Martian surface and volcanic activity was less intense than in the Hesperian. The average eruption rates dropped by a factor ten ([Carr and Head, 2010](#)) and volcanism happens periodically around the Tharsis and Elysium volcanoes. The dry and cold climate inherited from the Hesperian allowed ice to play a major role in the landscapes modifications. Glaciation occurred in nearly all regions of the planet, poles, mid-latitudes, and tropics as well. and the south pole may be a sink for some of this water, as previously mentioned ([Carr and Head, 2010](#); [Carr and Head III, 2003](#)). Fluvio-glacial cycles shaped the Amazonian terrains, especially at high latitudes, and geological evidence suggests the presence of a short-lived sea near the Isidis Basin ([Erkeling et al., 2014](#)).

The obliquity of the planet is also responsible for some geomorphic changes that occurred during the Amazonian. It induced thermal cycles of the ice present on the surface. Glacier lobate debris aprons (LDA) resulting from the melting of glacier ice ([Baker et al., 2010](#)) and polar layered terrains ([Kolb and Tanaka, 2001](#)) dating from this period have been imaged. LDAs are located on mid-latitudes and polar layered terrains in the North and South poles of the planet; they are both evidence for Late Amazonian glaciation. The seasonal flow of briny water could have also shaped some of the Amazon terrain by digging gullies and forming recurring slope lineae (RSL) ([Philippe et al., 2023](#)). Most of the surface modification in this last period is due to the accumulation and movement of ice ([Carr and Head, 2010](#)).

The extensive modification of the Martian landscapes since the Noachian resulted in the formation of key geomorphic features that have been gathered by multiple space countries that launched planetary missions towards Mars to study the geomorphology of Mars and retrieve the knowledge we currently

have on its history.

1.2. Mars science missions

1.2.1. Past and current missions

Mariner 4 is the first mission that sent to Earth images of Mars while performing a flyby in 1965, this event paved the way for the scientific exploration of Mars. Since then, the planet has always been a main scientific target for space agencies. NASA and ESA often published predecadal surveys and long-term planning of science missions to enhance the general knowledge we have of the universe. For nearly 60 years, Mars has been considered a major target in all of these long-term strategic plans which led to the development of numerous missions towards Mars. Over the past few decades, its extensive exploration has provided significant data about the planet's surface geology, atmosphere, interior and potential for past life but also raised new questions about its past history. The vision of a desolate planet we had from the first images of the surface sent to Earth by the Mariner missions has given way to the image of what was once similar to Earth. In the 1970s, the Viking missions 1 & 2 identified ancient river beds and determined a mostly carbon dioxide composition of the thin Martian atmosphere (Mars has only about 0.6% of the atmospheric pressure found on Earth at sea level ([Zurek \(1992\)](#))). These missions also provided images of Mars' polar ice caps, showing seasonal changes and confirming the presence of water ice ([Elachi et al., 1976](#)) on Noachian terrains. 30 years later, the rovers Spirit and Opportunity provided new evidence of ancient water activity through the identification of minerals such as hematite and sulfate, indicating past water-rich environments that could have harbored life ([Squyres et al., 2004](#)) during the Late Noachian-Early Hesperian period. Hints of past water activity have also been observed from orbit with the Mars Global Surveyor (MGS) through detailed imaging of Mars' surface in the late 90s. The search for traces of water and life has been a major topic for Mars exploration, space-borne imagery and rovers have both been complementary tools to do so. Their complementarity has been a real advantage to explore and understand many features such as Aeolis Mons inside the Gale crater. MRO provided context to its overall structure and allowed scientists to plan rover paths and targets for the Curiosity rover to safely go and analyze sediment layers and mineral compositions ([Vasavada et al., 2014](#)).

However, some outcrops and geological features lack a way to be investigated. For instance, Recurring Slope Lineae (RSL) have been identified with orbit imagery ([McEwen et al., 2011](#)), and especially images taken by the HiRISE instrument but cannot be observed from the ground due to steep and inaccessible slopes for rovers on Mars. Their understanding will be a valuable insight into finding liquid water on the Martian subsurface. RSL are narrow, low-reflectance features that appear and disappear every year on Martian warm and steep slopes. They are thought to be transient flow of liquid water even though no consensus has been reached regarding the amount of liquid involved in this processes that could also be dry ones. As pointed by [Ojha et al. \(2015\)](#), the freezing point depression of water due to dissolved salts identified in RSL with spectral imagery can increase the chances of forming liquid water on Mars and can explain the seasonal appearance of this features.

Indeed every exploration technology has its own limitations. Rovers are limited in their range of motion both in the speed and path planning. During its 14 years mission, Opportunity covered 45.161 kilometers on Mars which correspond to an average distance of 8.8 meters per sol. Perseverance is doing better with an average distance of 23 meters per sol ([Verma et al., 2023](#)). This can be explained by the difficulty of the terrain navigation. During its traverses, Curiosity encountered numerous dangerous hazards on the terrain and has been significantly damaged, especially between Sol 415 and Sol 505 ([Ono et al., 2015](#)). It encountered soft soil and sharp embedded rocks that were not clearly visible in the pre-mission satellite images, and the NAVCAM images did not allow proper determination of slippage or sinkage rates ([Arvidson et al., 2011](#)). Orbiting instruments are mostly used for global mapping, atmosphere studies or large scale observations but lack a fine resolution to observe small size geomorphic features. As shown on [Table 1.1](#) the best Ground Sampling Distance (GSD) achieved is 0.25 meters per pixels which does not allow for sub-meter object to be identified. Landers are by

definition fixed on the Martian ground and only have one place to do experiments.

Table 1.1: Comparison of Mars satellites, their instruments, Ground Sampling Distance, and orbit altitudes

Satellite	Instrument	GSD (m/pixel)	Orbit Altitude (km)
MRO	HiRISE	0.25-0.30	~ 300
Mars Global Surveyor	MOC (Narrow Angle)	1.4	~ 378
ExoMars TGO	CaSSIS	4.6	~ 400
MRO	CTX	6	~ 300
Mars Express	HRSC	10-12.5	~ 250
Mars Odyssey	THEMIS (Visible)	18	~ 400
Mars Odyssey	THEMIS (Infrared)	100	~ 400
Mars Global Surveyor	MOC (Wide Angle)	230	~ 378
MRO	MARCI	1,000-10,000	~ 300

To avoid some of these limitations, the use of Unmanned Aerial Vehicle (UAV) has been investigated for future Mars exploration missions. NASA sent in 2021 a technology demonstrator called Ingenuity aiming to perform five flights in the thin Martian atmosphere. As pointed by [Balaram et al. \(2021a\)](#), Ingenuity has outperformed these expectations and demonstrated the potential of using aerial vehicles for Martian exploration and its benefits for high-resolution imaging of areas inaccessible to rovers. [Table 1.2](#) provides a comparison between rover-based and drone-based exploration, highlighting the advantage of UAV in terms of distance coverage and displacement speed. The comparison between Ingenuity and Sojourner aims to shed light on the differences for UAV and rover technology demonstrators and the comparison between Sojourner and Spirit the performance of a proper mission designed after the technology demonstration. Such differences strongly advocate for the use of UAV as a solution for future missions.

Table 1.2: Comparison of Ingenuity, Sojourner, and Spirit

	Ingenuity (UAV)	Sejourner (rover)	Spirit (rover)
Distance Traveled	~ 17 km	~ 100 m	~ 7.7 km
Number of Trips	72 flights	N/A	~ 1,400 sols of driving
Total Time Moving	128.8 minutes	N/A	~ 1,000 hours
Mission Lifespan	3 years (2021-2024)	83 sols (1997)	6 years (2004-2010)
Cost	\$85 million	\$25 million	\$400 million
Weight	1.8 kg	10.6 kg	185 kg
Max Ground Speed	10 m/s	0.004 m/s	0.005 m/s
Mission Objective	Demonstrate powered flight in Mars' atmosphere	Technology demonstration for future rovers	Search for signs of past water and habitability
Landing site	Jezero Crater	Ares Vallis	Gusev Crater

1.2.2. Future science missions on Mars

Future missions aim to answer new research questions that arose from previous studies or have not yet been answered. For example, the potential shorelines identified by [Parker et al. \(1989\)](#) have led to a controversial theory for a Northern ocean since higher resolution images revealed parts of the shorelines being misinterpreted ([Carr and Head III, 2003](#)). [Erkeling et al. \(2014\)](#) also mention that strong arguments are both in favor or against this theory. Such a hypothesis still needs to be tested through sample analysis ([Carr and Head III, 2003](#)). Bringing back samples to Earth is a common goal for NASA, ESA and CNSA. NASA and ESA joint effort for the Mars Sample Return mission ([McCubbin et al., 2025](#)) which aims to collect samples gathered by the Perseverance rover in the Jezero crater and China is currently developing the Tianwen 3 Mars sample return mission ([He et al., 2024](#)). The Japan Aerospace Exploration Agency (JAXA) also aims to return some samples to Earth but from Phobos with the Martian Moon Explorer ([Kawakatsu et al., 2023](#)). Other missions are planned to continue exploring Mars both from orbit and the surface. The Indian Space Research Organisation (ISRO) is currently

developing the Mars Orbiter Mission MOM-2 ([Anand and Chauhan, 2020](#)). ESA is about to launch its Rosalind Franklin Rover in the coming years.

Other missions aim to overcome the challenges previously described and faced by current technologies such as the Mars CHOPPER initiative.

1.2.3. Martian rotorcrafts

The Mars CHOPPER initiative is a project proposed by the JPL aims to create an SUV-sized hexacopter able to fly on Mars up to 400 meters above the ground with a 5 kilogram payload. It should also be able to fly 3 kilometers per day on the Martian surface. A major difference with Ingenuity is that the technology demonstrator was dependent on Perseverance since the rover hosted the *Base Station Electronics* ([Balaram et al., 2021b](#)). In other words, Ingenuity needed to communicate with the rover to fly and send the data back to Earth. It also had no instruments onboard excepting the navigation camera (NAVCAM) and return to home (RTH) camera. We can define Ingenuity class drones as UAVs relying on a rover to fly and operate on-boarding imaging sensors only. If the technology demonstration has already been done, such a UAV can be used as a rover assistant for navigation and terrain recognition to determine optimal paths ([Tonasso et al., 2024](#)). It can also be useful to select targets before moving the rover across an unknown area.

Another class of UAV on Mars will be fully independent ones. This new technology will need some additional development and precise requirements, as the science done using standalone UAVs can be different from the rover-based or satellite-based experiments. For example, the ability to choose a flying altitude can affect the resolution of images taken to study a target. The design of imaging sensors will hence need a proper set of requirements to ensure a sufficient resolution is achieved with the UAV to study small scale geomorphic features. A UAV equipped with science instruments will also perform experiments in different conditions, whether it is hovering or after landing on the target.

1.3. Thesis objectives

In this perspective, this Master thesis aims to delve into the future use of drones on Mars and especially a characteristic that will be necessary in all types of mission architectures. By overcoming the limitations of orbiters to resolve these features and the hurdles faced by rovers to access non-flat terrain, rotorcrafts enable new sciences themes for next generation of Martian exploration such as sedimentology and stratigraphy in steep environment, surface mapping, or characterization of exposed layers ([Balaram et al., 2021b](#)). Such missions will inherently need high-resolution sensors and a proper definition of imaging requirements to study these particular, small-size, geomorphic features.

In order to optimize the use of science drones on Mars, important research questions regarding the experiments that can be performed still need to be answered. The cost of sending UAVs directly to Mars to perform design studies and optimize their missions force on the use of planetary analogues. Hence, this study focuses on the following research questions.

- Which geological features and processes on Mars can benefit from UAV imagery?
- How do data collected by drones in terrestrial environments compare with satellite imagery currently available for Mars?
- How can these comparisons between drone and orbital data provide insight into selecting key areas and geological features for future Mars helicopter missions?

To answer these questions, a 12 days fieldwork was conducted on Devon island in the Haughton impact crater during the summer campaign of the NASA Haughton-Mars Project. The Haughton crater is a recognized Mars surface analogue and presents interesting geological features for this study such as gullies, ejecta blocks, patterned ground, and canyons that resemble the one found on Mars.

1.4. Report outline

The report consists of 5 chapters. **Chapter 1** describes general information on Mars and introduce the use of UAV as a potential solution to overcome challenges faced by current used technologies. **Chapter 2** outlines the methods of investigation, with a center of attention being the Haughton impact structure and the fieldwork carried out. **Chapter 3** gather three main sections on the studied geomorphic features (ejecta blocks, gullies, and patterned ground). Each subsection is composed of general knowledge and a literature review on the feature to understand the science interest for these topics, results on the GSD needed for their characterization, and a description of implication for future Mars rotorcraft missions. Other exciting geomorphic features are also mentioned before **chapter 4** in which the previous results are discussed. Finally, **chapter 5** summarizes and concludes the findings.

2

Methods

2.1. Drones on Earth for science

On Earth, a wide variety of small features on its surface help us understand the geological and geomorphic processes that shaped its landscapes. These features include sand dunes, glacial striations, volcanic or impact craters, and erosional landforms such as gullies and mud cracks. They provide valuable clues about the forces of erosion, deposition, tectonic activity, volcanic processes, and weathering that have modified Earth's surface over time ([Summerfield, 1991](#); [Ritter et al., 2011](#)). Studying small geomorphic features and processes is commonly done with traditional fieldwork, which includes direct and precise measurement with manual data collection to provide detailed descriptions of a target. This makes fieldwork a very close-up observation that does not capture the entire complexity of some features and can be labor-intensive and time-consuming ([Eppes et al., 2015](#)).

To complete these observations, remote sensing done with satellite imagery is often used to gain a better understanding of the environment on a larger scale. However, spatial resolution is often limited, and satellites only provide a nadir point of view, meaning small geomorphic features may not be efficiently studied ([Lillesand et al., 2015](#)). The use of Unmanned Aerial Vehicles (UAVs) has emerged as a solution to bridge this gap between ground-based and satellite observations by surveying very large area in a short amount of time with an in-between resolution ([Iizuka et al., 2018](#); [Ruwaimana et al., 2018](#)). UAVs are lightweight transportable vehicles that can be flown from a significant distance and provide access to hazardous locations. They allow scientists to have an aerial point of view of their target for a fraction of the cost needed for manned aerial vehicles. UAVs platform can also be adapted to the intended work by choosing the right sensor to carry. For these reasons, they have been used in nearly all natural science domain. They have especially been proven useful in remote locations to monitor small geological features in isolated places with harsh environments such as in the North and South poles ([Śledź et al., 2021](#)) and other cold region ([Verfaillie et al., 2023](#)) where traditional methods may be logistically challenging or dangerous.

If the use of UAVs for geological studies on Earth still is in its early days, its relevance for planetary sciences has been anticipated, especially for Titan, the Jupiter moon that will be visited by the UAV Dragonfly in 2034. The use of UAVs to explore Mars has also been an interesting topic since Ingenuity proof of concept. [Sam et al. \(2020\)](#) studied lava tubes in Iceland and compared their results to what can be found on Mars offering clues about its past volcanic activity but also solutions for future Mars human and robotic exploration. A similar work is performed in this study. The Haughton crater on Devon Island is used as a planetary analogue to study geomorphic features on Earth that closely resemble the one found on Mars.

2.2. Planetary analogues

To train for planetary mission, prepare and test equipment or assist in the interpretation of observations, the use of analogues became a necessity for space studies. However, the word *analogue* is a very broad concept overarching different types of science studies. [Foucher et al. \(2021\)](#) proposed a classification of functional analogues to prepare for future planetary missions with a practical approach. This classification is based on the use that we make of the analogue and its relevance for a particular study. Five categories have been identified by [Foucher et al. \(2021\)](#).

The first category encompasses sites used for planetary analogy, that are sites used to explain or study extraterrestrial geomorphic features. The second category is related to a process analogy to illustrate extraterrestrial geological processes observed or expected. The third type of analogue is correlated with the petrology to study mineral formation. A fourth category is allocated to astrobiology to study the development of metabolism in similar conditions and search for detectable biosignatures. The last category is related to engineering for rover and instrument testing.

Each analogue setting offers different types of study to be performed and is therefore chosen differently. For example, engineering analogues can be created by scientists. Artificial facilities are built to support mission development, crew training, and equipment testing [Zemeny et al. \(2024\)](#). Regarding astrobiological analogue sites, they are found in the field where conditions favor, or once favored, the apparition of life ([Martins et al., 2017](#)). The three other categories are used to perform comparative planetology, said otherwise, to interpret geomorphologies or processes observed on another planet based on the studies of similar features on Earth.

In some cases, multiple classes of analogues can be found in one location. The Haughton crater on Devon island is one example. It can be considered an analogue site of biological interest [Léveillé \(2009\)](#), used for its planetary analogy to explain and illustrate geomorphic structures ([Lee and Osinski, 2005](#)) but also seen as an engineering analogue to develop mission instruments ([Glass et al., 2024](#)). In this study, we use the Haughton crater as a planetary analogue for geomorphology studies of some features that closely resemble Martian one and for which the study could benefit from the use of UAV. The aim being to elaborate protocols and requirements to study them on Mars using UAV. However, one thing to mention about the use of UAV missions on Mars, is that they exceed the comparative planetology we are doing on Earth because of the need to be fully autonomous on Mars. Previously cited fieldwork on sites of planetary analogy focused only on the imaging of expected extraterrestrial geomorphic structures and not on the engineering of the UAV, and especially autonomous flying capabilities. In this study, only the planetary analogy of the Haughton crater in terms of geomorphic structures is used. The UAV is not autonomous.

2.3. Devon Island and the Haughton Impact Crater

2.3.1. Geological History and Present day situation of the Haughton Crater



Figure 2.1: Map of the Canadian High Arctic showing the Haughton impact structure location on Devon Island (Fletcher et al., 2017)

The geological features imaged with the drone are located in the Haughton impact crater on Devon Island, Canadian High Arctic which is the largest uninhabited island in the world (Binsted et al., 2010). The impact origin of the structure has been confirmed when Robertson and Mason (1975) found shatter cones inside it Figure 2.2.a. It is a geological deformation forming when the pressure propagated by shock-waves reaches 2 to 30 GPa. This phenomena happens only with large impact due to large asteroid, meteorites or atomic bombs impact. The inside of the structure is also filled with impact melt breccias Figure 2.2.b.

The Haughton Crater has been formed 39 ± 2 million years ago (Sherlock et al., 2005) when a ~ 1 km comet or an asteroid hit the surface at ~ 14 km/s. No remnants of the impactor have been found yet and thus it leads us to think that a comet reached the ground and completely vaporized on impact. Before this event, Devon Island had the climate of shallow tropical waters. It was a flat-laying and sedimentary zone. The impact caused a final crater (diameter of the topographic rim that rises above the outermost slump block not concealed by ejecta) of 16 kilometers and excavated rocks in a zone of 12 km in diameter with a depth of 750 m. The platform was a thick layer of sedimentary rocks (1800m) covering a crystalline basement. The transient crater was 11 ± 1 km in diameter and $\sim 1500 - 2250$ m deep (Osinski et al., 2010).

The very dry climate of the Arctic since the Eocene preserved the impact structure despite the numerous ice ages it has undergone and makes it one of the best exposed mid-size impact crater on Earth. The apparent crater diameter currently is 23 km. Indeed minimal precipitation and lack of vegetation in and

around the crater have prevented the significant degradation of this landscape since ice exposure (Lee and Osinski, 2005). The surface of the crater is filled with impact melt breccias as shown on Figure 2.3. Carbonate rich pale grey breccias have been identified and used as analogues of the Moon and Mars to test drilling systems (Glass et al., 2024). This breccia layer is interpreted as a remnant of the ejecta blanket, blocks are also found on the surface (Figure 2.4).

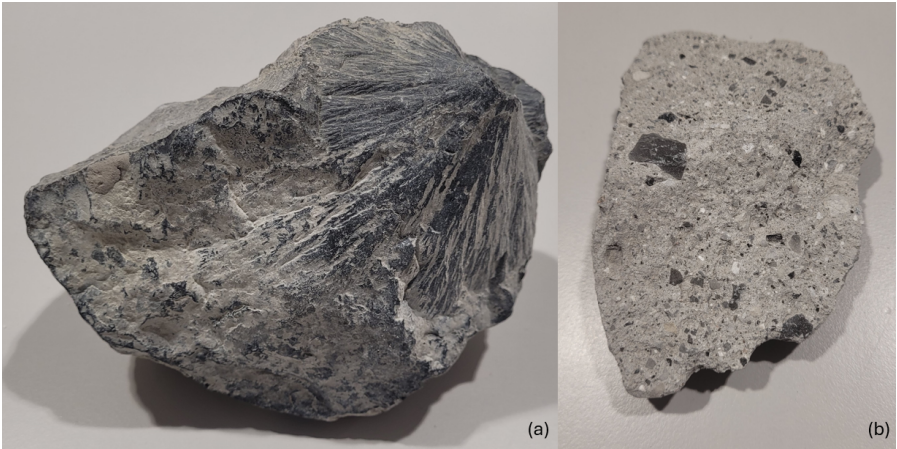


Figure 2.2: Shatter cone (a) and breccia (b) found in the crater during NASA HMP 2024 fieldwork

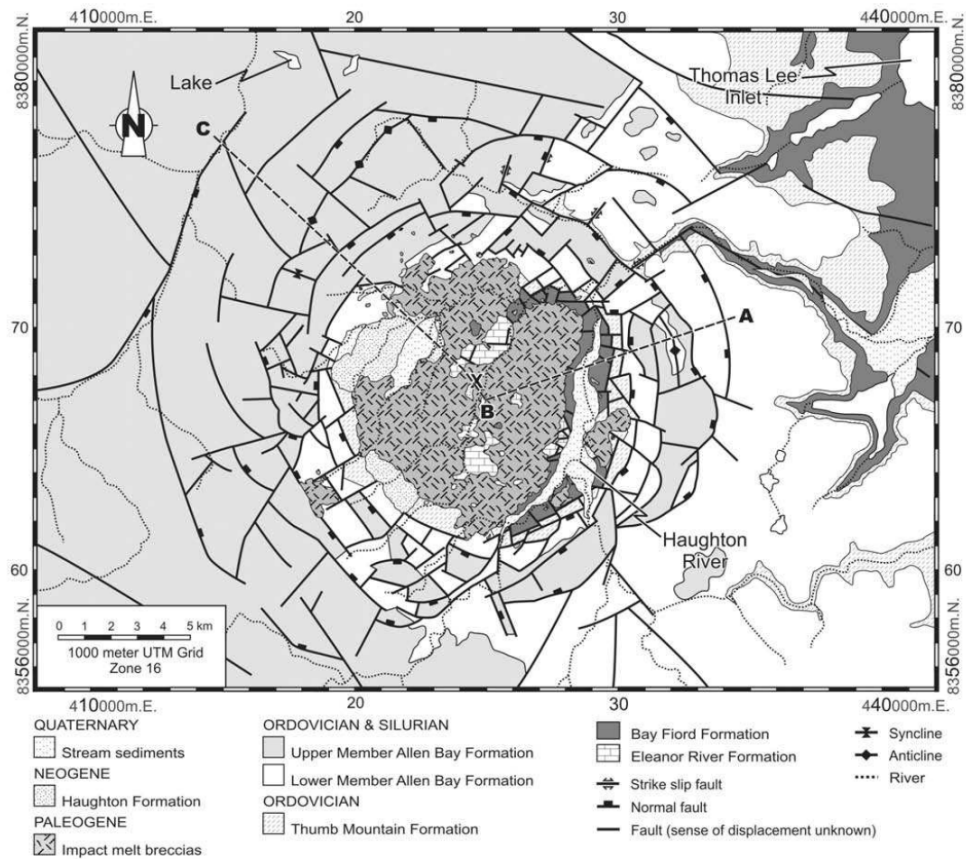


Figure 2.3: Simplified geological map of the Haughton impact structure (Osinski et al., 2010)



Figure 2.4: 15 meters tall ejecta block found inside the Haughton impact structure

Impact crater formation

The formation of an impact crater is the result of the shock between an impactor and the surface of planet. This event can be divided in three stages.

First, the contact and compression phase occurs. During this brief stage, a part of the kinetic energy of the impactor is partitioned into internal energies in both the ejector and the surface, resulting in spherical shock waves whose origin is the point of contact between the impactor and the target ([Kenkmann et al., 2014](#)). They are characterized by a nearly discontinuous change in pressure, temperature and density ([Yue et al., 2023](#)). They travel through the ground and induce shock metamorphism and heat.

The second phase is the excavation during which the dissipation of the shock wave and the opening of the crater occur. The passage of the shock wave sets the internal material in motion. The materials in the upper third of the transient crater are ejected outward to form an ejecta blanket, while the other two thirds of the material within the transient cavity are pushed downward ([Kenkmann et al., 2014](#)). [Figure 2.5](#) pictures these two first stages. If multiple layers of the surface are affected during the excavation, older layers cover younger ones and create an inverted stratigraphy [Senft and Stewart \(2007\)](#).

The third and last stage consists of the modification of the cavity and, especially, the collapse of the bowl-shaped transient cavity driven by gravity. The movement of material downward created a negatively buoyant cavity that hence try to come upwards again. If the transient crater is small, the strength of the ground counter this force and fix the cavity as a bowl-shaped simple crater. If the transient crater is too large for the ground strength to counteract the buoyancy effect, the cavity floor rises upward and inward ([Kenkmann et al., 2014](#)). This uplift can create a central peak, or a central peak ring that are a result of the rebounding of the central uplift [Morgan et al. \(2000\)](#).

The Haughton crater is a large impact structure with a central uplift. The final crater is filled with brecciated rocks that contain variable amounts of shocked fragments as shown on [Figure 2.2.b](#).

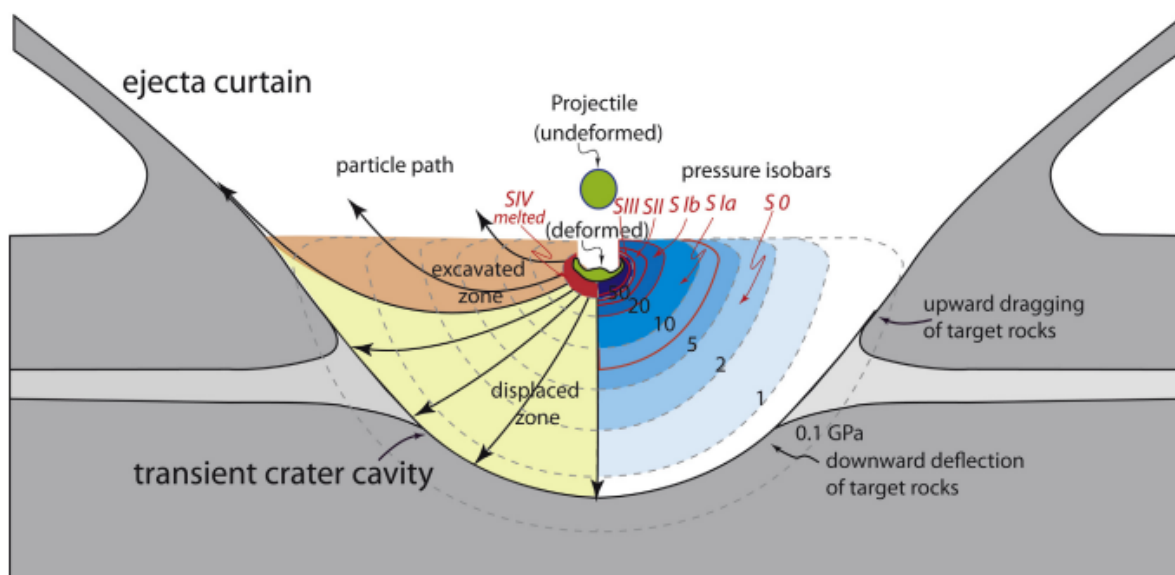


Figure 2.5: Schematic diagram of the initial impact, and subsequent formation of the transient crater cavity during the excavation stage by [Kenkmann et al. \(2014\)](#).

A Mars analogue field site

The island presents a lot of geological similarities with Mars such as fractured rocks, alluvial fans, gullies and the Haughton crater, that all closely resemble those found on Mars. These similarities help scientists understand Martian landscapes and the processes that shaped them, such as erosion by wind and the potential role of water in the past ([Ruso et al., 2024](#)). The crater lies in a polar desert on the west side of the island that is not covered by ice during summer making it practical to study. Polar deserts are defined as areas having less than 250mm of annual precipitation with maximum temperatures below 10° C ([Woo and Young, 2003](#)). The crater's geological structure is well conserved and the lack of vegetation and other forms of life on Devon, the absence of burial, tectonism or metamorphism preserved the landscapes as it is also preserved on Mars ([Lee and Osinski, 2005](#)). Studying geological features inside the crater mimics the science that can/will be done on Mars since it is possible to use its geomorphic features to study geological processes happening on Mars but also to mimic scientific process to derive operational recommendations.

The harsh climate conditions of the Arctic also make it an ideal analogue for astrobiologists [Léveillé \(2009\)](#). The region around the crater contains permafrost similar to what is believed to exist beneath the surface of Mars. Understanding how water and ice behave in this permafrost environment, as well as how microbial life can exist in such conditions, provides crucial information on the potential for water and the possibility of microbial life existing on Mars under similar conditions. ([Pellerin et al., 2009](#))

An additional benefit of the Haughton crater is that, as a remote location, it enhances the similarities with space missions and the challenges that astronauts encounter. Even during summer, access to the base camp is limited by the climate conditions. The logistical constraints needed for the field campaign in terms of supplies, waste management need to be optimized. Also, the impact of human presence on the island's microbiology must be minimized and is monitored every year. The isolation of the island makes it a practical place to study physiological, and technical aspects of living and working in isolation with limited resources ([Crucian et al., 2007](#)).

2.3.2. The NASA Haughton-Mars Project

Devon Island has therefore been a major location for analogue research. Since 1997, Dr. Pascal Lee and his colleagues have gone to the Haughton structure as part of the NASA Haughton-Mars Project

(HMP). The NASA HMP is conducted jointly by the Mars Institute and the SETI Institute. Its goal is to use the Mars and Moon-like terrain of the impact structure to develop and test new technologies for space exploration. Every year since 1997 a crew of scientists has gone to the HMP base camp located on the west of the crater to perform their research. [Figure 2.6](#) shows the HMP base camp configuration in 2024. The scientific campaign usually take place during the summer for a period of two to four weeks. The base camp, located on the north west side of the Haughton crater, can be reached using planes or vehicles. The vast majority of travels are made by plane. One year an expedition aimed to bring two humvees to the base camp. They have been brought during winter, using the North-West passage. The travel in plane begins at Resolute Bay, an Inuit village located on Cornwallis Island just next to Devon island, and is done only if the climatic conditions allow it; hence the fog is the main reason for flight delays back and forth the islands.

The organization of the camp life is done by Pascal Lee while John Schutt and Matthew Jones are in charge of the reparations at camp. The camp configuration for the 2024 summer campaign is described on [Figure 2.6](#). The other expedition members are scientists who come here to do their experiments. In 2024, drilling, astrobiology, and ground noise monitoring experiments were conducted within the crater. The activities depend on the climatic conditions, and the day-to-day planning always is impacted by snow, rain, and fog. When experiments need to be performed outside the camp vicinity, traverses are planned to move out of the camp. ATVs and a Humvee are used to move with the scientific equipments. In 2024, two traverses have been organized for the fieldwork related to this MSc thesis. They are described in [subsection 2.4.4](#).

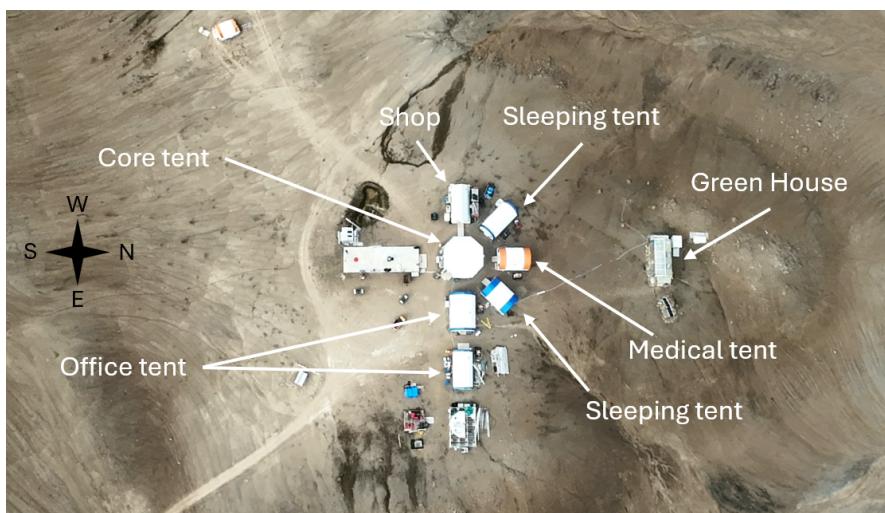


Figure 2.6: Map of the HMP base camp in 2024

2.4. Field campaign Haughton Crater 2024

The field campaign aims to use flying drones above geological features of the Arctic that are similar to the one found on Mars to determine which ones would be appropriate to study with an aerial point of view. This section focuses first on the Ground Sampling Distance (the key parameter of drone imaging applied to planetary science), then the drone selection for the fieldwork and image processing are detailed before camera calibration. The traverse plans and studied geomorphic features are presented in the following subsection, and finally, encountered difficulties are described.

2.4.1. Ground Sampling Distance: the key property for drone imaging

The Ground Sampling Distance (GSD) a key a parameter in geomorphology () for which detailed surface analysis is essential. It is defined as the length of a pixel on the ground. It is a measure of the sampling interval on the ground. The GSD is also commonly used to define the resolution of DTM and DEM because it influences the accuracy of an area ([Sarkar et al., 2023](#)). The GSD is influenced by

intrinsic factors of the camera, including the focal length and the physical size of the sensor's pixel, but also by extrinsic parameters such as the distance between the sensor and the target. The flight altitude of the UAV is linearly correlated with the GSD, as shown in [Figure 2.7](#).

However, the GSD needs to be distinguished from the spatial resolution of an image, which is a broader concept. The spatial resolution is related to the overall clarity and detail in an image. The spatial resolution of the imaged produced by the sensor is therefore influenced by the GSD, but also by lens quality, sensor noise, or atmospheric conditions.

The GSD appeared in this study as the key property for drone imaging, as it depends only on the imaging setup that can be adapted for a specific mission. It is also one of the main factors influencing the spatial resolution of an image which we want to be good enough to resolve geomorphic features on Mars. This interval will be reached by taking into account the flying capabilities of the drone and especially its altitude range, but also different camera setup. As seen on [Figure 2.7](#) the camera setups for the navigation camera (NAVCAM) and the Return to Home camera (RTE) were different. The NAVCAM is a low resolution grayscale camera and the RTE a high resolution color camera ([Maki et al., 2024](#)). Hence, flying between 5 meters and 30 meters would lead to very different GSD intervals. Hence, finding the needed GSD for multiple features is crucial to create GSD intervals and then design the future sensors and imaging setup onboard Martian rotorcrafts.

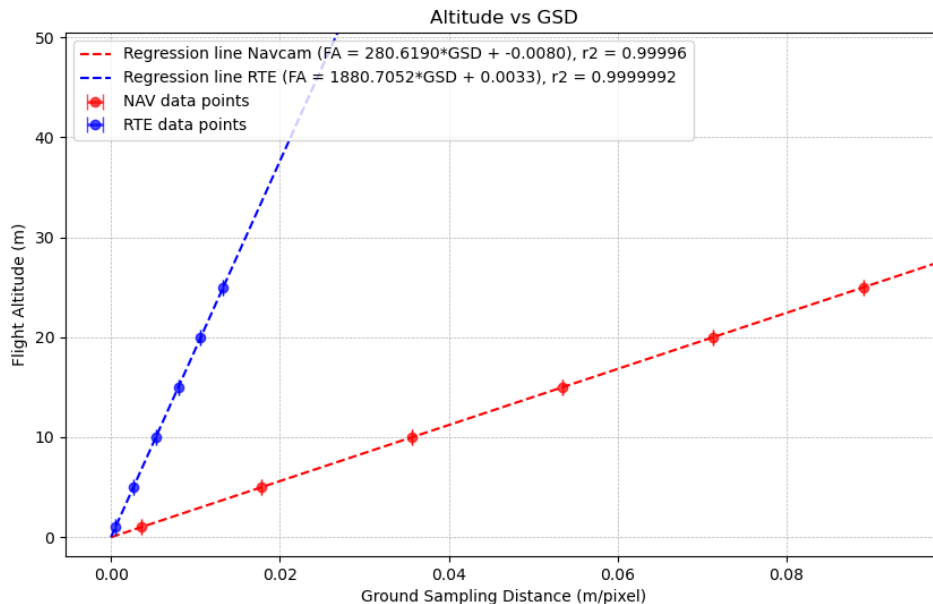


Figure 2.7: Calibration of Ingenuity's cameras. Data from [Maki et al. \(2024\)](#)

2.4.2. Drone selection

The aim of this study is to determine the needed GSD to study geomorphic features on Mars with UAV. Hence, the needed analogue to complete the fieldwork was a site of planetary analogy. A Martian rotorcraft analogue was not necessarily required. Furthermore, Ingenuity being a technology demonstrator and not a fully autonomous drone with a specifically assigned mission. The hardware onboard future Martian rotorcraft will certainly be much different, especially when it comes to science instruments and sensors. The drone selection was hence based on several criteria that are not related to Ingenuity cameras' specifications but rather related to the fieldwork location and experiments.

First, for logistical reasons, the drone had to be small and light to be brought to Devon island by planes

but also easily carried out on field during traverses. Second, the drone needed to withstand the climate conditions of the Arctic, especially the wind and cold. The previous year, winds were recorded up to 88 kilometers per hour with a mean speed of 30 kilometers per hour. The temperature fluctuated between 3°C and 8°C, and the vicinity of the north magnetic pole imposed a flying mode that should not depend on magnetic compass. Finally, national and local regulations were taken into account to select the UAV.

The chosen drone is the AVATA 2 from DJI. It is an FPV (first Person View) drone that features a manual mode which does not rely on magnetic compass to be flown. The small mass and accessibility of multiple power sources were critical benefits for the field campaign. Also, the distance coverage between the pilot and the drone is 13 kilometers with a battery lifespan of 23 minutes in temperatures that ranges from -10°C to 40°C, its speed can go up to 96 kilometers per hour in manual mode and can withstand winds up to 38 kilometers per hour (DJI, 2025), making the AVATA 2 suitable for Arctic conditions. The propellers guards were also a considerable advantage to ensure the drone safety in the field. As a backup, a DJI Mini 3 (brought by another team), was available with similar characteristics

2.4.3. UAV Camera Calibration

The drone camera calibration has been carried out under conditions similar to the stacks above the geological features. The protocol was the following:

- Measure the diameter of the landing pad and the size of the black H.
- Fly the drone above its landing pad with the camera pointing in the nadir direction.
- Take 10 pictures of the pad every 50 meters from ground to an altitude of 300 meters.
- Count the pixels needed on the picture to image the pad/H.
- Make a average for each altitude.
- Plot the Ground Sampling Distance (GSD) as a function of the flight altitude.

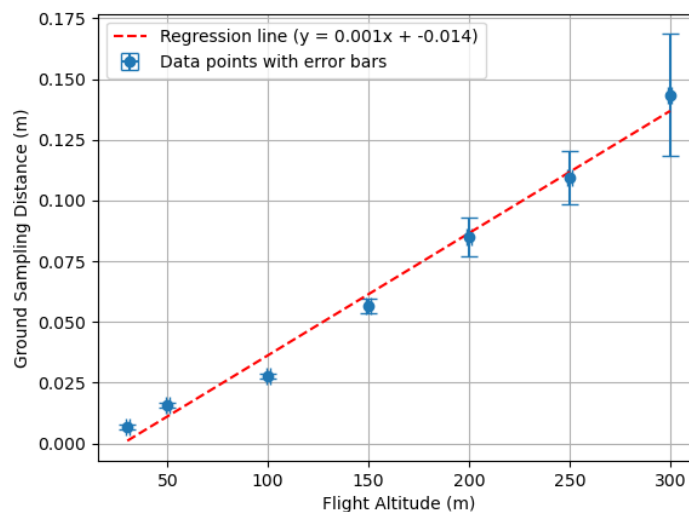


Figure 2.8: GSD as a function of the flight altitude

Figure 2.8 shows the linear function linking the GSD of the onboard camera and the flight altitude. The error bar on the GSD is determined by the length of one pixel, as shown on Figure 2.9 very faint pixels induce an error if we take it or not into account. For the flight altitude, the telemetry showed an oscillation of the drone of approximately one meter due to windy conditions.

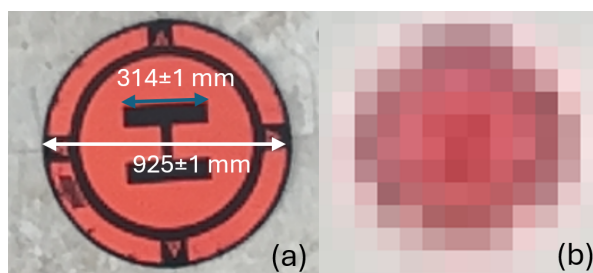


Figure 2.9: Landing pad seen from 30m with dimensions (a) and from 200m (b)

The data processing for the calibration has been done using a Python script to open the images. The pixels were then counted on multiple images at the same altitude to determine the average pixel size of the pad and retrieve the GSD with its error bars. The feature analysis has been performed using the same Python script. ArcGIS Pro and its Image Analyst Toolbox were first used, but did not provide results coherent with the reality observed on the field and raw images. In particular, the identification of the pits and clasts was not the same for different pictures of the blocks taken at the same altitude, leading to confusion for the description of the damage state of ejecta surfaces and the near ground. The description of feature images has hence been performed without the use of software.

2.4.4. Traverse Plan and Studied Geomorphic Features

The selection of the geomorphic features has been made by Dr. Pascal Lee that knows the crater and the location of Mars analogues. The ejecta blocks appeared to be targets of high interest because of their difficulty in being encountered in a similar preservation state on other impact craters. Gullies were also interesting targets, since their formation mechanism and conditions are similar to the one imaged on Amazonian terrains on Mars. Patterned grounds have also been selected as geomorphic features to study because of their relevance as Martian analogues and their link to the study of water cycles on Mars. Secondary targets have also been identified. Rock layering in canyons were present on site but can be studied in non-remote areas and were hence not prioritized. The central uplift of the Haughton crater was also a target for a drone survey.

The identification of these targets led to two traverses in the Haughton crater. Once on site, the ability to perform flights above the targets needed to meet several requirements before being approved. First, the UAV launch site needed to be flat and close enough to the area of interest to ensure that enough flight time was allocated to imaging operations considering the reduced batteries' lifespan due to the wind and cold. Second, the drone and the pilot had to be in direct line-of-sight during the whole flight above the area of interest without any hills or ejecta blocks in between to ensure a good radio signal.

The first traverse was done to join the Valley of the Planet of the Apes in the south part of the crater. The main objective of this first traverse was to shoot videos using the DJI Mini 2 brought for a project different from this one but. The possibility of imaging the rock layering in canyons was considered a secondary objective. The small amount of time remaining after drone shooting for the other project only allowed for simple flights around a mount featuring rock layering to be conducted but no stacks to assess the needed GSD were properly done. The second traverse has been done on August 11 with the main objective of imaging geological features such as ejecta blocks and gullies. The initial also intended to join the center of the crater and image its central uplift using the AVATA 2 drone but the wind and muddiness of the soil did not allow such a traverse to happen. The distance between the closest location for lift-off and landing was considered too far due to windy conditions that may have endangered drone return. Hence, only the ejecta blocks and gullies have been imaged on this traverse.

The strong wind, numerous features and small batteries' lifespan have been taken into account to come up with a short and effective protocol to image the features. For the first traverse (green line on [Figure 2.10](#), videos of a small mount have been taken all around it. For the second traverse (yellow

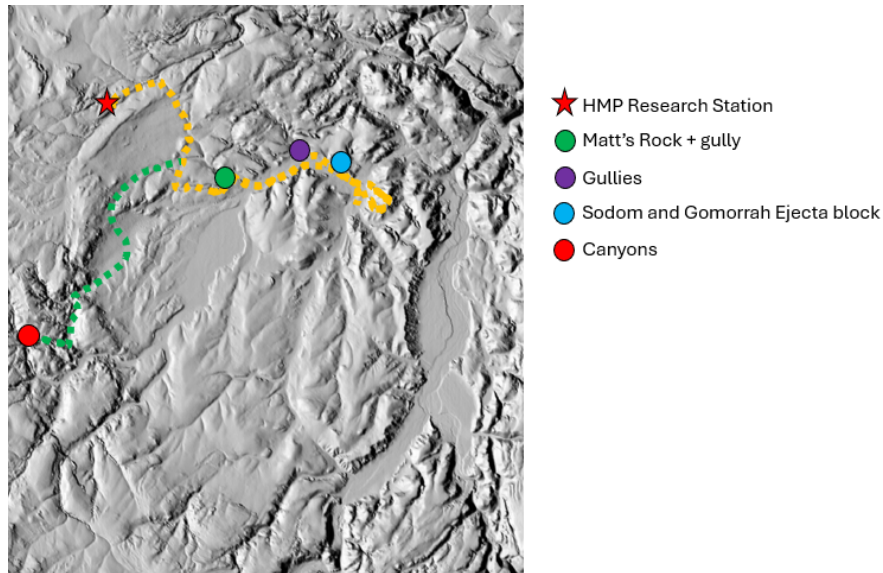


Figure 2.10: Location of imaged features and traverse roads

line on [Figure 2.10](#)), the approach to assess the needed GSD for Mars helicopter and compare it with satellite imagery changed the protocol. It merely consisted in doing a stack of pictures at different flight altitudes (i.e. at 30 meters and every 50 meters from 50 meters to 400 meters).

200 meters North West to the HMP Research Station, 2 patterned ground types have been imaged: periglacial polygons and rock circles. Stacks have been taken from 1 meter to 28 meters for the rock circles and from 1 meter to 100 meters for the periglacial polygons. The altitude limitation was due to a low cloud ceiling. The altitude observed in drone telemetry during flight was measured with respect to the helipad. Some pictures have an offset due to uneven terrain and different elevations. At each altitude, 5 to 10 images have been taken to counter blurring and inclination error induced by strong wind. The bottom of [Figure 2.21](#) shows the drone gimbal reached its maximum to counter the tilt of the drone facing the wind.



Figure 2.11: Rock circle 5m

Figure 2.12: Rock circle, 28m

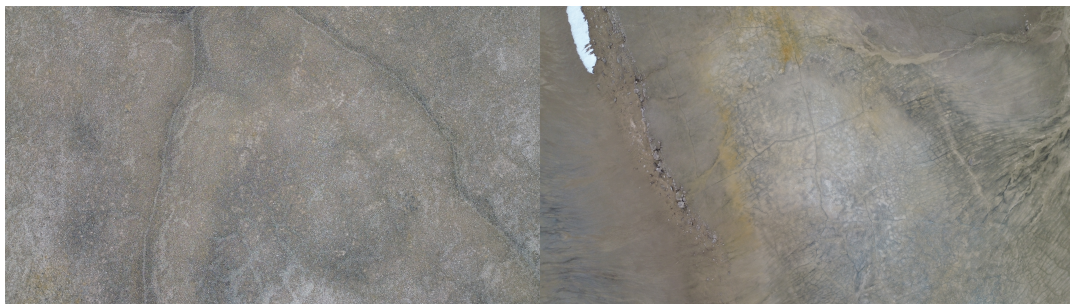


Figure 2.13: Periglacial Polygons, 5m

Figure 2.14: Periglacial Polygons, 90m



Figure 2.15: Sodom and Gomorrah Ejecta Blocks, 30m **Figure 2.16:** Sodom and Gomorrah Ejecta Blocks, 350m



Figure 2.17: Matt Ejecta Block, 30m

Figure 2.18: Matt Ejecta Block, 350m

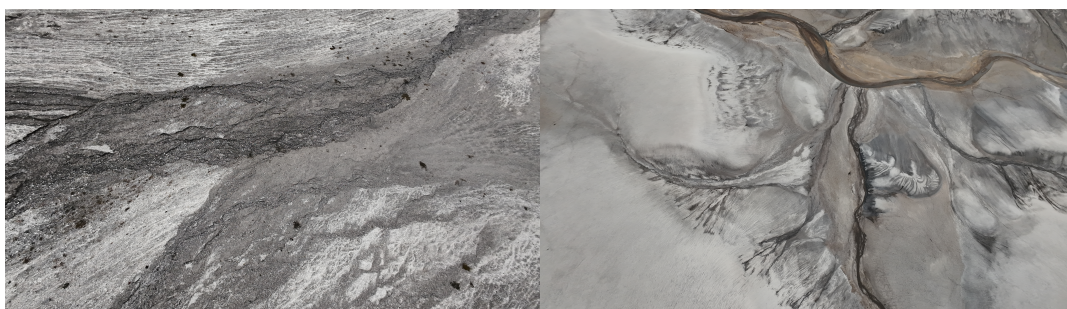


Figure 2.19: Impact Breccia Gully, 15m

Figure 2.20: Impact Breccia Gully, 335m



Figure 2.21: Seepage, 15m

Figure 2.22: Seepage, 335m

2.4.5. Encountered difficulties

The main difficulties for this fieldwork were the climate conditions. The main hurdle faced during the experiment was the attitude control of the drone. The drone uses a magnetic compass to fly and hover and near the North magnetic pole, the inclination of the magnetic field lines can create problems. Hence the drone needed to be flown in manual mode to bypass the compass potential problems making hovering more challenging, especially with very windy conditions. During the second traverse, when high altitudes needed to be reached, the wind became the main problem during the flights. Hovering was difficult, and countering the wind was not always possible. The strategy to do so consisted of positioning the drone so that it faces the wind and inclining it to make it move inside the air mass at the speed of the wind in order to be fixed in the ground reference frame. The problem with this is that the camera gimble was sometimes tilted and the nadir pointing images not always accurate. The blurriness of the pictures was also a concern under these conditions. Hence each picture has been taken at least five times. Verification of picture quality has also been conducted at the end of each flight to ensure adequate data quality. Additionally, difficulties to avoid drone batteries being discharged due to cold were recorded, especially during the second traverse for which many flights were planned. To limit this phenomenon, the batteries were transported inside the pilot's clothing and not in the travel case. Small discharges have still been observed.

Another difficulty encountered was the muddiness of the ground. ATVs have been stuck in the mud during all traverses and we lost time to get them out. This also speaks volumes on a completely autonomous UAV mission. The navigability of the terrain is not a problem for this type of mission but the strong wind is. When the terrain stopped the ATV and the question was raised of doing long-range flight with the drone to continue the imaging of geomorphic features we were trying to reach, the speed and direction of the wind were the only drawback.

The fog has also been a problem, images of patterned ground have been taken near camp but at small altitudes only because the clouds were low and did not allow to take pictures at altitudes higher than 28 meters for the rock circles and 90 meters for the periglacial polygons.

3

Results

This chapter focuses on the analyses of the images taken during the fieldwork for three main categories of geomorphic features. The impact ejecta block, gullies, and patterned ground are the three selected case studies and are successively described in three subsections that follow the same structure. Each subsection is divided into three parts. First, a general knowledge of the geomorphic features is required to complete the data analysis acquired by the drone. The results are then presented before a description of their implications for future Mars rotorcraft missions. They have been chosen because of their relevance as Mars analogues from which new studies could enhance the knowledge on research questions related to impact cratering and water cycles on Mars that shaped different types of terrain on Mars, ranging from the Noachian and Hesperian periods for the ejecta blocks, evidence of the bombardment era, and the Amazonian for the gullies and patterned ground.

3.1. Impact Ejecta Blocks

3.1.1. Occurrence, distribution, and significance on Mars

Ejecta blocks are boulders that have been moved and ejected in the air after an explosion. The ejection of material can occur during two different phases of the formation of the crater. First, during the spallation phase, in which the shock waves travel in the ground and fracture it, small fragments of the ground can be ejected outside the transient crater at high speed and create secondary craters. Those spalls fragments are small, lightly shocked during the process and comes from the near surface ground ([Bierhaus et al., 2018](#)). However, the materials ejected during the excavation phase are quite different. They are deeper materials prone to much higher shock waves pressure. They are usually bigger than spalls and ejected at smaller velocities. The boulders are always ejected outside the transient crater but the late phases of the final crater formation involve some redefinition of the rim with an enlargement and opening up of the initial cavity such as ejecta deposit falls into the final crater interior ([Osinski et al., 2012](#)). Boulders falling inside the craters cavity have been studied on Mars. The current resolution allows to see their falling tracks and is an opportunity to study the dynamics of boulder-substrate interaction ([Vijayan et al., 2022](#)).

Two different types of ejecta blocks can be distinguished. The first and main one is the ejecta blocks coming from impact crater, when a comet or an asteroid hit the surface of the planet. The second type is related to phreatomagmatic craters and explosive volcanism. [Sears et al. \(2022\)](#) studied this second type of ejecta blocks and calculated their mass and ejection velocities. They also provided a way to estimate subsurface water by studying ejecta blocks which can be relevant for Mars exploration and created a map to find potential sites for explosive volcanism such as the Tharsis Montes and probable pyroclastic regions with the Argyre and Hellas Basins. The problem with the red planet is that the current resolution on remote sensing orbiting Mars does not allow to resolve ejecta blocks resembling the

one studied on Earth around Kings Bowl crater by [Sears et al. \(2022\)](#). In this study of ejecta blocks the aim is to find the needed resolution to be able to resolve and characterize ejecta blocks and especially impact related ones since impact cratering is one of the most fundamental processes that shaped the surface of Mars. Operational and design recommendations will be made for future rotorcraft missions to effectively study ejecta blocks on Mars.

When it comes to impact ejecta blocks, their occurrences are numerous on Mars. They are present within nearly all of the impact crater ejecta blankets, but also within the crater itself, and are the main constituent of the ejecta deposit ([Krishna and Kumar, 2016](#)). Their distribution around craters has been studied for the Moon, using the Lunar Reconnaissance Orbiter (LRO) camera ([Zanetti et al., 2011](#); [Krishna and Kumar, 2016](#); [Singer et al., 2020](#)), for asteroids such as 243 Ida ([Lee et al., 1996](#)) and studies have been conducted for Europa and Ganymede ([Singer et al., 2013](#)) regarding the scaling of ejected blocks. On Mars, few studies have been conducted regarding impact ejecta blocks. This can be explained by two main reasons. First, because the science of impact cratering focused primarily on how craters formed, and especially how to classify the different types of crater based on the form of their ejecta blanket (single, double, or multilayered ejecta blanket) or the form and degradation state of the crater itself. An interested reader may want to dig into the work of [Barlow and Bradley \(1990\)](#) which presents several types of crater ejecta deposit. The list of crater types on Mars is the most diverse one compared to the Moon, Mercury, or Venus ([Osinski et al., 2011](#)), especially because of the volatile-rich nature of the martian crust and the presence of fluidized ejecta deposits (the so-called layered ones). Maps of Mars showing the concentration of the principal crater types on Mars, and thus the location of ejecta blocks can be derived from the work of [Lagain et al. \(2021\)](#). The crater locations are presented on [Figure 3.1](#). Buried and degraded craters will also present ejecta blocks, but only the larger boulder will remain due to weathering and other types of degradation.

The second reason behind the few studies of Martian ejecta blocks merely is the incapacity to do it due to poor resolution of this ejecta boulders. If blocks on the Moon have been studied, it is because the resolution of LRO and the boulder size around some craters allow certain types of studies to be done, but also because the certainty of these blocks being related to an impact ejecta is evident. The studies conducted on the Moon on the spatial distribution ([Krishna and Kumar, 2016](#)) shows that the boulders repartition is linked to the geometry of the event. An asymmetric repartition of the boulders around the crater can provide information on the angle of impactor. Also, the size of the blocks contains information on the impact process and target characteristics. The bigger boulders, ejected during the excavation phase, are close to the rim (and sometimes within the crater), whereas the spalls can be found farer from it. A similar study comparing the Lonar crater in India and a 1.82 km diameter unnamed impact crater within Arcadia Planitia on Mars ([Lakshmi and Kumar, 2020](#)) shows similar results. The large majority of boulders are also found within a 5-crater radii distance from the rim. On Mars, only few ejecta boulders have been properly imaged with a resolution high enough to characterize their surface. The images were taken in the Odyssey crater by the Opportunity rover ([Figure 3.2](#)). However, the GSD of the orbiting instrument does not allow the work done on the Moon to be conducted on Martian targets because other theories could explain the presence of blocks in or around impact craters.

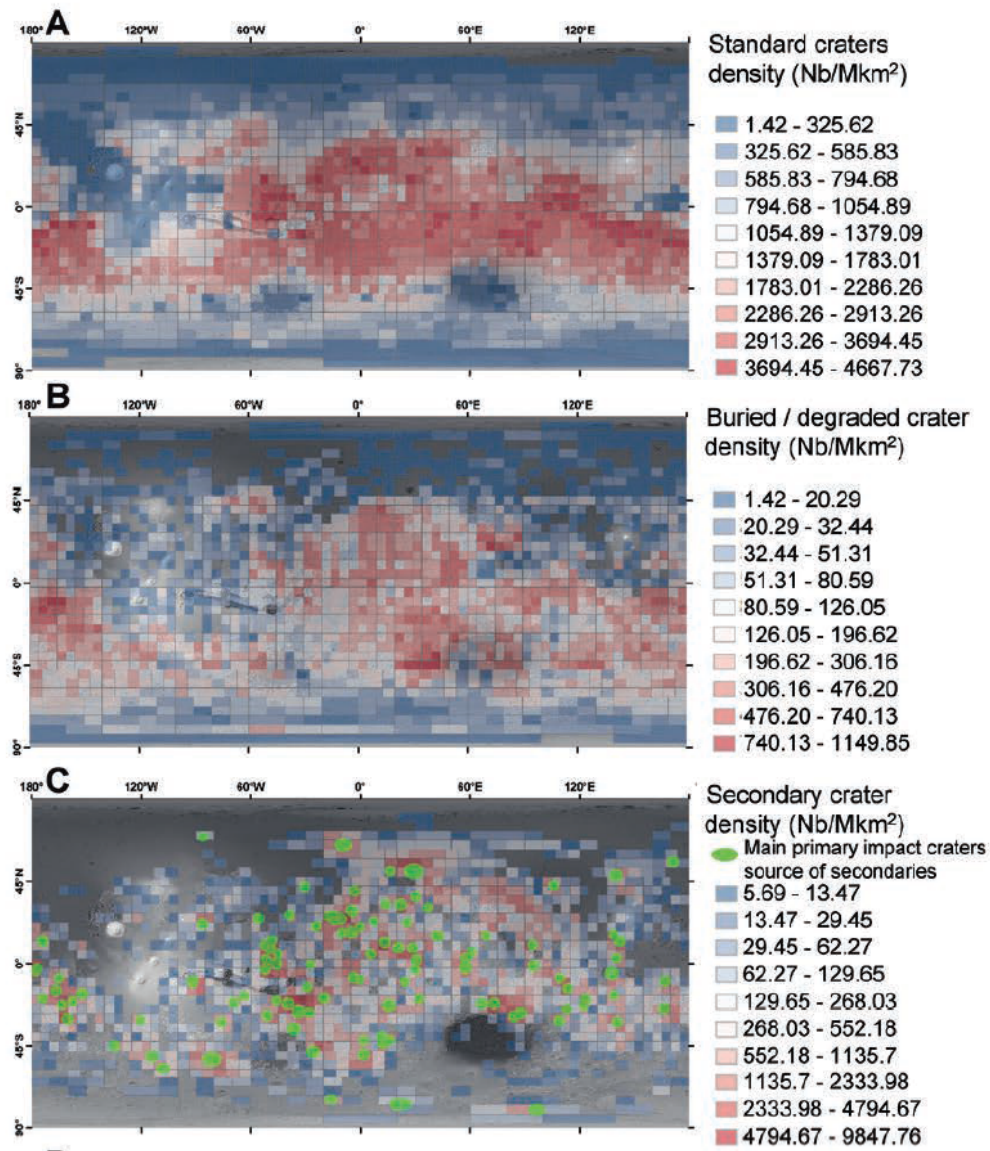


Figure 3.1: Crater density maps according to the category assigned in [Lagain et al. \(2021\)](#), (A) Density of standard impact craters. (B) Density of buried or degraded craters. Secondary impact crater density and 108 primary craters that have produced 70 crater population for D (diameter) > 1 km. Figure from [Lagain et al. \(2021\)](#)

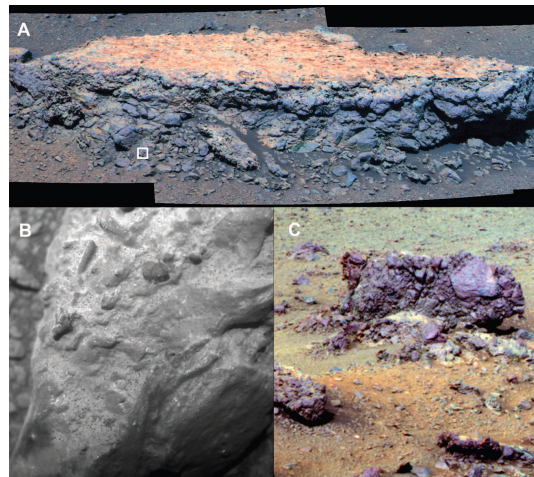


Figure 3.2: Ejecta blocks from Odyssey crater. (A) Pancam false color image of the block Tisdale acquired on sol 2690 using the 753-, 535-, and 432-nm filters, sequence p2387. Height of Tisdale is 30 cm. Square shows location of image in (B). (B) MI image acquired on sol 2696. Scale across the image is 2.5 cm. (C) Pancam false-color image of the ejecta block Kidd Creek acquired on sol 2694 using the 753-, 535-, and 432-nm filters, sequence p2593. Scale across Kidd Creek is 1 m. Figure by [Squyres et al. \(2012\)](#)

3.1.2. Boulder origin hypothesis and impact ejecta block diagnoses

An important work to do to be able to study these ejecta blocks on Mars is to know how to perform a diagnostic and ensure that the target rock is an actual impact ejecta block and not something else. To do that, we need to understand their surface properties and at which resolution we can properly identify these key properties to test and eliminate multiple hypothesis.

When it comes to boulders' origins, three hypotheses can explain their location.

The first one is the impact-related origin that created an ejecta block. The blocks ejected during the excavation phase may be the easiest to identify. As mentioned in [Figure 2.3.1](#), they are large boulders that have been prone to high pressures. Their surface possesses strong evidence of this with marks such as shatter cones, clastic, and brecciated rocks ([Figure 2.2.a](#), [Figure 3.2](#)). The damage state of the boulder is therefore the key property. Some mega-boulders on the Moon also present stratification making them easy to spot and to characterize. The study of these stratified boulders can also be a way to investigate the Lunar subsurface and see evidence of lava flows and possible pyroclastic activity. Regarding the spalls, they are smaller but, due to their high ejection velocity and secondary impact energy, they should have fractures, fissures, and similar surface properties as the other ejecta boulders.

The second hypothesis is the glacial erratic one. In this scenario, a boulder has been transported by ice movement. There is no violent action taking place and the boulder has no reason to be highly damaged. It usually is a big piece of material that has even surfaces with no or few small fissures or pits.

The third hypothesis is the House rock. It is merely a boulder slide remnant, a fallen boulder that has been disattached from a rocky surface. This hypothesis is easy to test. The matching geology between the boulder and the surrounding environment is usually enough to confirm it.

However, if the boulder's geology is different from what can be seen around, it means we are in either the first or second scenario. The distinction between the impact ejecta block and the glacial erratic is done by looking closely to the surface, the damage state being the key factor.

To understand at which resolution these hypotheses can be discussed, stacks of images of three mega-boulders within the Haughton impact crater have been taken. The resolution scale goes from 0.0011

to 0.1872 meters per pixels. Note that the description of the boulders' surface have been done from low to high resolution to avoid being influenced by the previous results.

A short description of the surface and near-ground characterization of the ejecta blocks imaged in the Haughton structure can be found, respectively, in [Table 3.1](#), [Table 3.2](#) and [Table 3.3](#). With these analogues, the House boulder hypothesis can be easily removed. The blocks are found in vast lands of impact breccia with no other rocks in the surroundings. Hence they either are impact ejecta blocks or glacial erratic and the focus of the analyses is put on the damage state of the rocks.

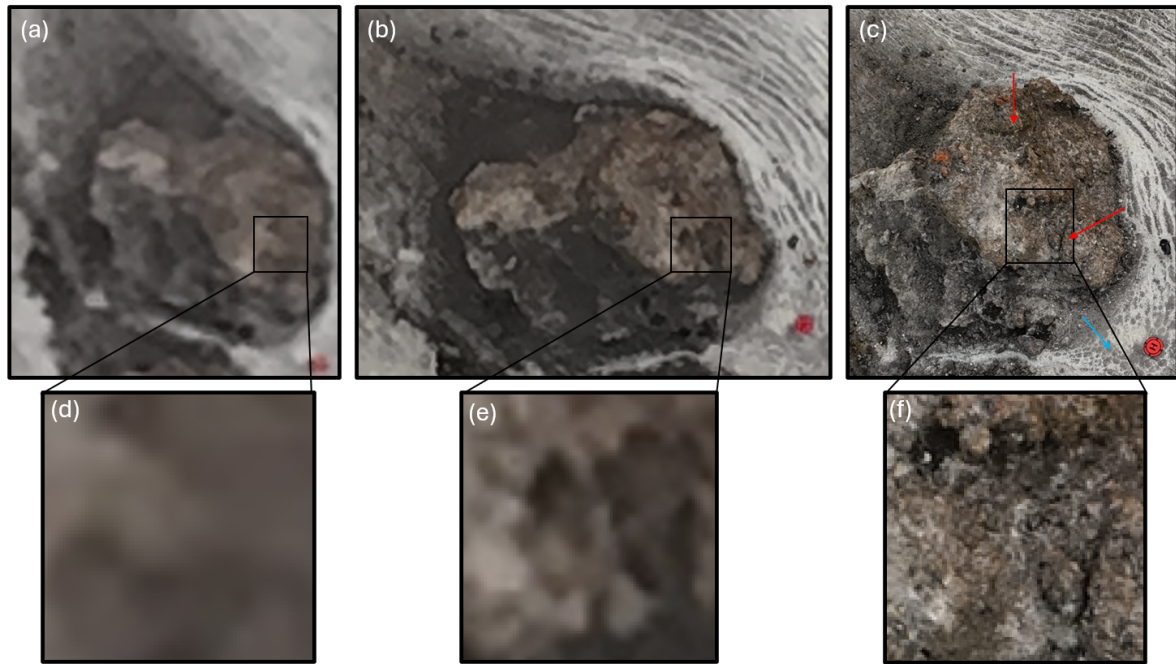


Figure 3.3: Pictures of Sodom ejecta taken at three different altitudes with a zoom on fractured and pitted area of the boulder. (a) 400m. (b) 200m. (c) 30m. (d), (e), (f) are the the same zoomed pitted and fractured area of respectively (a), (b), (c). The red arrow point at two large fractures of the ejecta. The bleu arrow points at the patterned ground next to the ejecta block

[Figure 3.3](#) shows the difference in GSD to characterize the surface and near ground of Sodom ejecta bloc. This [Figure 3.3](#) clearly shows the difference in surface characterization capabilities as described on [Table 3.3](#). The cracks and pits on [Figure 3.3\(f\)](#) are not visible at all on [Figure 3.3\(d\)](#) and [Figure 3.3\(e\)](#) is an between GSD in which only guesses can be made.

The three tables describing ejecta blocks ([Table 3.1](#), [Table 3.2](#) and [Table 3.3](#)) show that the characterization of the surface obviously depends on the block itself, but they all present similar features that allow for a certainty in their ejecta characterization for a GSD that is between 0.1 and 6 centimeters per pixels. The Near ground description is also important since it can emphasize on well-defined edges and topographic features that can help justify the ejected nature of the block. In particular, making a proper distinction between the ground and the block surface can be an asset to visualize the fracture and roughness of the rock, but also reveals itself confusing at some GSD. The Sodom block, for instance, has a black triangle at the top which can be interpreted as a shadow for GSD above 0.14 meter per pixel but appears to be some falling of degraded ejecta surface material at the 0.011 meter per pixel resolution with an idea of this nature at 0.11 meter per pixel.

Table 3.1: Characterization of Matt's Rock impact ejecta block

Altitude (m)	Pixel Size (m/pixel)	Surface Description	Near Ground Description
400	0.19	Two different colors with clear distinction, maybe a fracture	Same color as the circle but clear edges
350	0.16	Distinct parts, sharp edges or fissures	blurry, black surrounding may be a boulder shadow
300	0.14	fading colors, sharp edges, three stages	black spot may be a shadow and strip lines stopped before reaching the rock ,edge not identifiable on the right
250	0.11	three stages, fading colors with new dark spots	black spot may be a shadow, strip lines closer to the edge, edge not clearly identifiable on the right
200	0.087	one fissure, seems uneven and fractured	black spot may be a shadow, strip lines closer to the edge, edge not clearly identifiable on the right
150	0.061	big fracture in the middle, seems very rough uneven and fractured, colors are distinct (no fading)	flow lines avoiding the rock, clear edges and shadow?
100	0.036	big fracture in the middle, seems very rough uneven and fractured, colors are distinct (no fading)	flow lines avoiding the rock, clear edges and grey/white spot within the black one, it is not a shadow
50	0.011	big fracture in the middle, seems very rough uneven and fractured, colors are distinct (no fading)	flow lines bypass the rock and show topography, clear edges and grey/white spot within the black one, polygons visible
30	0.001	big fracture in the middle, very rough, uneven and fractured, colors are distinct and reveals pitted surface	flow lines bypass the rock, clear edges and grey/white spot within the black one, polygons visible, shading gives sense of 3D

Table 3.2: Characterization of Sodom impact ejecta block

Altitude (m)	Pixel Size (m/pixel)	Surface Description	Near Ground Description
400	0.19	Edges not sure at the top (black triangle), brown and black with smooth shading, seems regular	Grey lines around the rock, very distinct color from the boulder
350	0.16	Edges not sure at the top (black triangle), brown and black with smooth shading, seems regular on the top but pitted at the bottom	Blurry gray lines around the rock, very distinct color from the boulder
300	0.14	Seems uneven with cracks, still no clear edges,	looks like gray flow lines on white material avoiding the rock, top left black triangle seems to be a shadow
250	0.11	Seems uneven with cracks, still no clear edges,	looks like gray flow lines on white material avoiding the rock, top left black triangle seems to not be a shadow (clearer spots inside of it)
200	0.09	Seems uneven with cracks, still no clear edges,	Gray flow lines on white material avoiding the rock, top left black triangle seems to not be a shadow (clearer spots inside of it)
150	0.06	Seems uneven with cracks, still no clear edges,	Gray flow lines on white material avoiding the rock, top left black triangle seems to not be a shadow (clearer spots inside of it)
100	0.04	uneven with cracks and pits, still no clear edges, top left black triangle seems to be part of the rock	Gray flow lines on white material avoiding the rock,
50	0.011	Surface is heavily fragmented, pitted and irregular, clear edges and topography	Gray flow lines, the black triangle looks like material that fell from the rock and has been moved by the flow on a short distance
30	0.001	Surface is heavily fragmented, pitted and irregular, clear edges and topography very well resolved, no hesitation	Flow lines, Polygons, everything can be interpreted without hesitation

Table 3.3: Characterization of Gomorrah impact ejecta block

Altitude (m)	Pixel Size (m/pixel)	Surface Description	Near Ground Description
400	0.19	Seems like a long rock planted in the ground but dark spot can not be a shadow (not coherent with rock size), regular surface	Grey material, too blurry for any interpretation
350	0.16	Long rock planted in the ground with two pits at the top then seems regular and smooth	Gray material, too blurry for any interpretation
300	0.14	Long rock planted in the ground with two pits at the top and cracks on the right side	Gray material too blurry for any interpretation, dark spot is not a shadow because of gray shades, maybe some rocks
250	0.11	Pits on top and cracks on the right side, but seems smooth elsewhere	lines within the gray material seems to encompass the rock on the bottom part
200	0.087	Pits on top and cracks on the right side, but seems smooth elsewhere	Gray flow lines seems to encompass the rock on the bottom part, gray spot that looks like blurry polygons on the right side
150	0.061	Pits on top and cracks on the right side, but seems smooth elsewhere	Gray flow lines seems to encompass the rock on the bottom part, gray spot that looks like blurry polygons on the right side
100	0.036	Pits on top and cracks on the right side, but seems smooth elsewhere	Gray flow lines encompass the rock on the bottom part, polygons field on the right side
50	0.011	Pits on top and cracks on the right side, but smooth elsewhere	Gray flow lines around the rock on the bottom right part, polygons field on the right side, black surrounding is just dark material, no shadow
30	0.001	Pits, cracks and roughness very well resolved, no hesitation	Flow lines, Polygons, everything can be interpreted without hesitation

3.1.3. Implication for future Mars rotorcraft missions

Because the sensor specifications are not known, the recommendations are made using GSD and not flight altitude. The recommendations we can make for future Mars Helicopter missions with a focus on ejecta blocks are numerous and mission-specific. They can be divided into two major categories: operations and conception.

Three main GSD zone have been identify using [Table 3.1](#), [Table 3.2](#) and [Table 3.3](#) to determine which GSD allows a good certainty of surface characterization of the block (green zone), which gives a first hint but is uncertain (yellow zone) and which is not sufficient at all (red zone). They are presented in [Figure 3.4](#) with a zoom on the drones AVATA 2 and Ingenuity (NAVcam and Return To Earth camera) capabilities on [Figure 3.5](#).

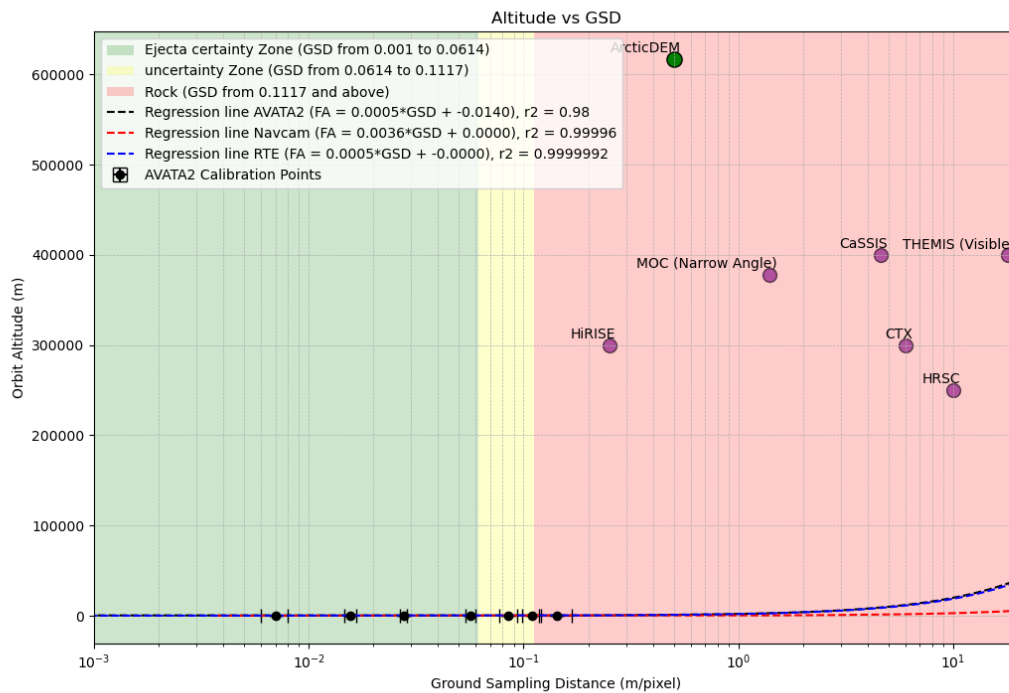


Figure 3.4: Altitude vs GSD, drones and satellite capabilities with GSD zone allowing ejecta imaging

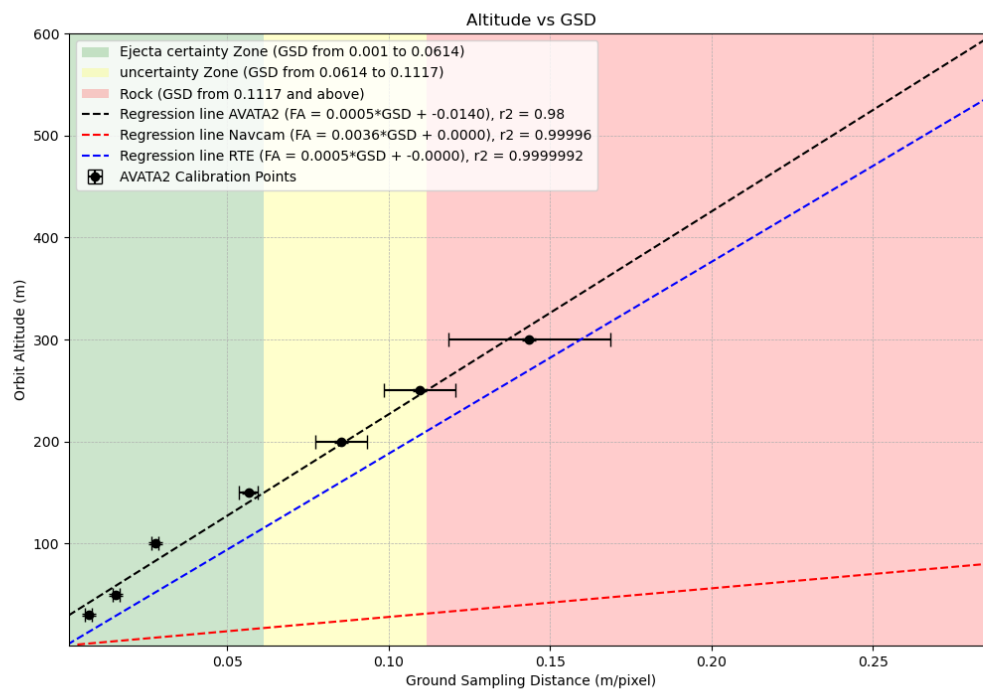


Figure 3.5: Altitude vs GSD, drones and satellite capabilities with GSD zone allowing ejecta imaging zoomed in the drone part

These results and especially the one presented on [Figure 3.4](#) highlight the lack of current capabilities to properly image ejecta mega-blocks with remote sensing as well as the superior resolution capacity of the AVATA 2 drone compared to the sensors equipped on Ingenuity. Indeed for the same altitude, the AVATA 2 has a smaller GSD. However this idea of a better resolution is to put in perspective with the notion of field of view.

Mission level recommendations

Two main constraints can be made on the design of the drone and its sensors to optimize the scientific return.

First, the drone has to be able to take nadir pointing and oblique images. It hence needs to have a camera equipped with a gimbal or two camera pointing in two different directions. From the field experience, the multi-axis gimble tool on the DJI MINI 3 appears to be the best solution. The AVATA 2 drone has a gimbal allowing only one rotation along the horizontal axis and the presence of high wind made some flight complicate to counter it and still take nadir pointing images. [Figure 3.6](#) shows a picture above the Matt's rock ejecta block with a gimbal that reached its maximum angle but still not face the ground in the nadir direction. To counter this, turning the orientation of the drone such as it faces the wind worked but for near future exploration of Mars, no pilot will be involved and multi-axis gimble will simplify the flight preparation by countering itself any windy situation that has not been foreseen and anticipated. The need for such a tool need to be anticipated and studied with respect to Martian conditions, especially wind force, to ensure the positing of the camera being in the desired direction.

Second, since the flight altitude has to be determined to ensure a resolution of images that is bellow 6 centimeters per pixels. The camera specifications have to be coherent with the UAV flying capabilities.



Figure 3.6: Failed nadir pointing image of Matt's rock

Operation recommendations

From the results of the previous subsection, the first operational recommendation can be derived. The drone altitude at which pictures will be taken has to allow a GSD that is inferior to 0.06 meter per pixels in order to have a good certainty of the ejecta nature of the block. Safety rules also have to be determined not to fly too close from the rock or too high to lose the UAV.

The second operational recommendation is to take wide angle images or to fly high enough to have the block and the surroundings in the picture. This will give critical context to the image and help identify a house rock or one related to explosive volcanism for instance. The presence of other boulders with different nature, fissures and cracks can help determine if it is part of a bigger formation or if the rock is the only one around.

A third operational recommendation will be not to take only nadir view of the block but also oblique views of all the visible areas of the boulder surface to have a comprehensive set of the topology of the rock and not miss any heavily damaged face of the boulder. On Gornorah ejecta blocks, some parts were considered smooth which can lead to a wrong hypothesis if the entire boulder is not taken into account.

A fourth recommendation can be to take multiple times the same picture to avoid blurry ones due to flight instability.

One last operational recommendation can be made for pre flight operations; to use HiRISE to explore the surroundings and find two flat landing areas not too far from the boulder at opposite sides.

3.2. Gullies

After discussing the resolution required to identify ejecta blocks on Mars, another significant geologic feature that could greatly benefit from the use of UAVs are gullies. Unlike ejecta blocks, which are often located on flat terrain and accessible to rovers, gullies typically form in steep environments. They are channel-like features due to down slope movement of material, usually found on the slopes of crater rims, chasmata, or canyon and ridges, making them inaccessible for ground-based imaging. This section explores how Ingenuity class drones and standalone UAV can revolutionize the study of gullies by providing high-resolution aerial imagery.

3.2.1. Occurrence, distribution, and significance on Mars

From space borne imaging, different types of gullies have been identified on Mars. **Figure 3.7** shows some of them. These range in size from large formations, such as the kilometer sized Chryse Chaos landslides studied by [Guimpier et al. \(2021\)](#), to smaller features like dark streaks and recurring slope lineae (RSL), which are only tens of meters long and a few meters wide. If some features like the Alcove-Channel-Apron gullies are sufficiently large to be studied with current technology orbiting Mars ([Dickson et al., 2015](#); [Sinha et al., 2022](#); [Morgan et al., 2010](#)), the smaller formations still raise questions about their formation processes and their possible link to ongoing water cycles on Mars.

Gullies are very common geomorphic features on Mars and can be seen nearly everywhere. The Valles Marineris, Inside walls of craters and chasmata are usual locations for the biggest gullies. Small scale ones can also be observed within craters, chasmata but also on sand dunes like in the Matara crater for instance.

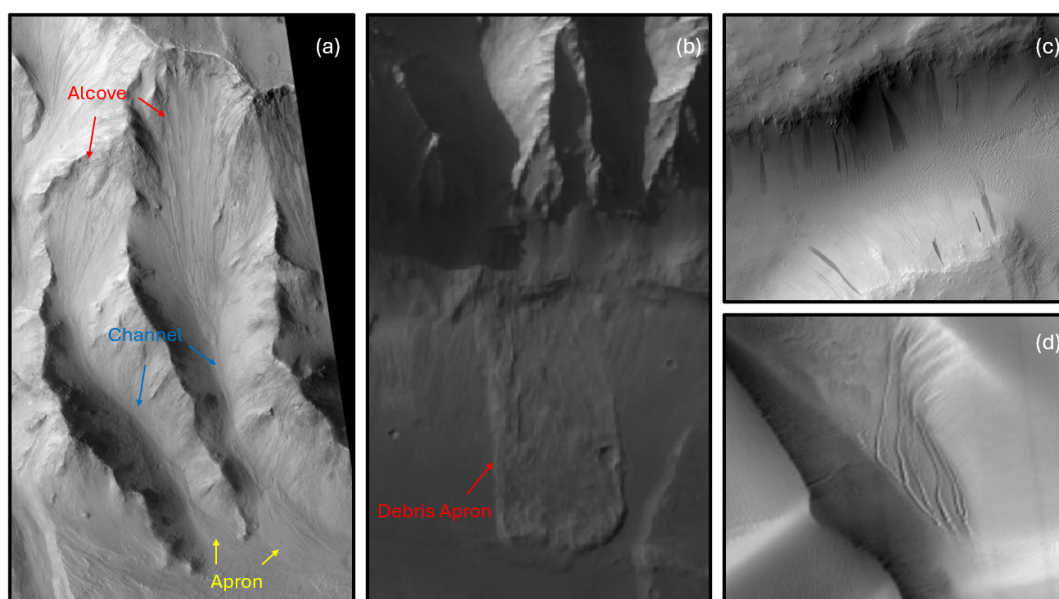


Figure 3.7: Four different types of gullies found on Mars. (a) 6000 meters long Alcove-Channel-Apron gullies as seen by HiRISE (*ESP_011806_1665*). (b) 5440 m wide landslide from the east of Valles Marineris taken by the HRSC instrument of Mars Express (*lat : -14.04 lon : -55.42*). (c) Hundreds of meters long dark streaks found on dust-covered slopes by the HiRISE instrument (*ESP_025155_1720*). (d) 1000 meters long and few meters wide linear gully, showing no alcove and an abrupt end without apron (HiRISE: *ESP_020770_1300*).

For instance, Recurring Slope Lineae (RSL) have been intensely studied since their discovery by [McEwen et al. \(2011\)](#). These thin, dark albedo features appear seasonally when the surface temperature of steep slopes increases but their origin and composition are still not fully understood. Three main characteristics have been established to identify RSL: they lengthen, fade away, and reoccur. **Figure 3.8** shows the occurring of two RSL within an unnamed crater in Mars lowland plains.

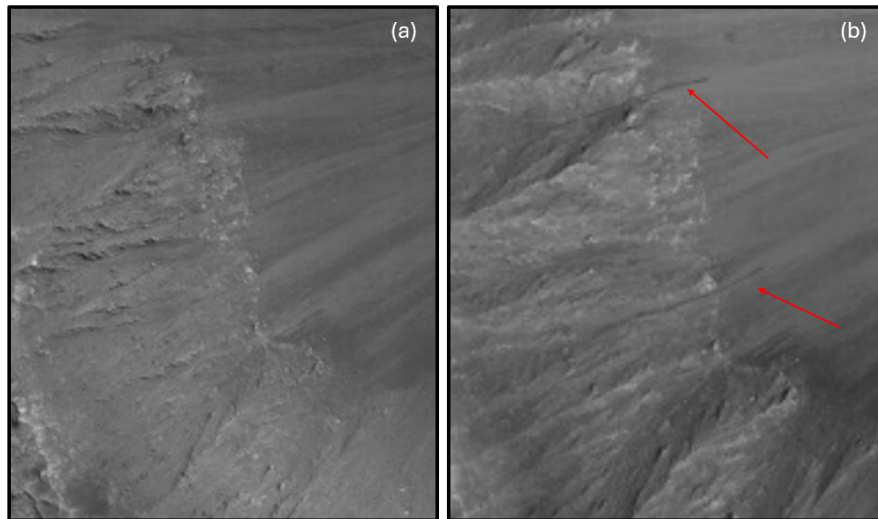


Figure 3.8: RSL appearance as seen by HiRISE. (b) shows the darkening of two RSL not present in (a). (a): *ESP_030530_2155*. (b): *ESP_035567_2155*

These characteristics make RSL one of the most interesting geological features to study on Mars since their appearance during warm seasons and fading when slope temperatures decrease suggest a surface process potentially linked to briny water or sublimation, possibly revealing water in the near-surface ground of Mars ([Chevrier and Rivera-Valentin, 2012](#)). If this theory was really exciting in the early days of RSL, many studies rather explain the formation of RSL through dry granular flows or a combination of both. Wet scenarios put the melting of ice, sublimation of salts or presence of aquifer at the origin of these RSL whereas dry ones emphasizes on forcing mechanism such as thermal pumping or aeolian processes that can both disrupts surface stability and trigger the mechanism associated to RSL production. A third scenario has also been studied and takes into account the influence of wet mechanism that would trigger a flow of dry material. The boiling or evaporation of salty water could disrupt the ground cohesion and lead to dry granular flows ([Mason and Scuderi, 2024](#)).

The current knowledge of RSL is based on their length, slopes morphology, elevation, thermal inertia trends and sinuosity. [Tebolt et al. \(2020\)](#) mapped over 10,000 RSL and found that their thermal inertia are consistent with sand and gravel, that they are oriented towards the west and the equator but that the beginning and ending points angle of repose of RSL are not consistent with dry material behavior. [Mason and Scuderi \(2024\)](#) focused on the interweaving of RSL at Raga crater and highlighted their channel count and sinuosity. Only 4% of the studied channel were classified as sinuous and none of them have been found to be meandering. The average slope is estimated at 34.39% and they are also oriented towards the west and equator. [Figure 3.9](#) shows the locations of known and studied RSL. They are all located in mid latitudes (i.e. between -60° and 60° latitudes) .

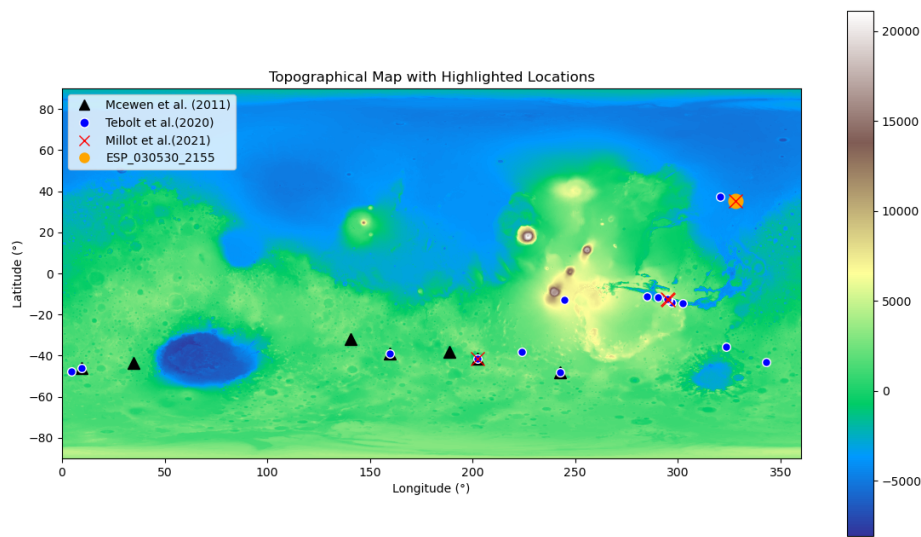


Figure 3.9: Location of known RSL on Mars, from [Tebolt et al. \(2020\)](#); [McEwen et al. \(2011\)](#); [Millot et al. \(2021\)](#)

The problem with RSL is that the current technology only allows us to observe their lengthening, darkening and fading, but not the material composition, shape within the channel or deposit structure. Hence, no consensus has been reached on whether RSL are linked to wet or dry granular flows, or whether they are related to subsurface water.

To push further the understanding of RSL and Martian gullies, many studies of analogue on Earth have been conducted. The aim is to understand their characteristics on Earth to perform similar studies on Mars. The analogue sites are nearly all located at the poles. The McMurdo Dry valleys and Transantarctic Mountains of the Northern Victoria land in Antarctica or Svalbard in the Arctic are common destination to study debris flows in arid environments similar to the one found on Mars. [Hauber et al. \(2017\)](#) studied gullies formed in the De Goes Cliff to help extent the observation and understanding of hydrological processes in polar deserts and establish hypothesis about the formation of similar features on the red planet. The morphology study emphasis on the shape of the channels and water tracks, highlighting indicators of wet and dry flows. Similar studies have been done on submarine landforms, gullies in meteor crater, and dune processes in Egypt ([Conway et al., 2018](#)). The characterization of the gullies on earth is more detailed and take into account many properties such as the slope degree, the origin and the structure of the alcove, the shape and cross section of the channel and the structure of the apron. All this work is possible thanks to UAV imaging and in-situ measurements.

A similar work has been conducted during the NASA HMP 2024 summer campaign. During the field-work two different gullies within the Haughton impact structure have been imaged. This work is not meant to address the wet/dry origin of the RSL or the characterization of gullies but rather to help create UAV based recommendations to study RSLs on Mars and to provide a resolution interval that will allow to display keys morphological evidences to finally understand their formation process and origin.

3.2.2. Gully resolution: wet or dry origin diagnoses

The aim is to identify at which resolution, the main properties of wet or dry gullies can be seen so we can hypothesize on the wet/dry nature of RSL, based on high resolution images taken with a UAV. Hence

we are looking for the resolution interval in which we see:

For Wet processes

- Smooth and well-defined alcoves, channels and fans edges.
- Sinuosity (especially for the channel).
- Sorted sediment in the fan or layered deposit.
- Reduced albedo due darkening of the surface.
- V-shaped channels.

For Dry processes

- Sharp and irregular edges.
- Poorly sorted material in the deposit.
- U-shaped or linear surface of the channel.

The study of topography such as slope gradients, orientation, location and seasonality may also help determine the wet or dry origin. Dry processes are induced by gravity and sometimes wind and hence require steep slopes to be triggered. Wet processes can be found on more moderate slopes.

During the fieldwork, an impact breccia gully shown on [Figure 3.10](#) has been imaged using the DJI AVATA 2 drone.

This gully is a seepage. It is thought to be formed by active layer drainage. The thaw of the uppermost part of the ground ice flows within the ground, on top of the permafrost, due to gravity until it reaches the surface in a sloppy area. [Figure 3.10](#) pictures this phenomena. Three sources of melt water can be seen even though no water was still running. The multiple head of the gully feeds a larger but shallower channel and the sediments transported finally reach the triangular shaped apron. The erosion of the middle head of the gully created a v-shaped channel that his meandering. Both characteristics implies a flowing liquid. This impact breccia gully hence is a formed by wet process.

The aim of the drone data analysis presented on [Table 3.4](#) is to understand at which GSD this conclusion can be reached to be reproduced on Mars.



Figure 3.10: Oblique view of an impact breccia gully found in the Medusa Valley inside the Haughton crater.

A second gully has been found near Matt's rock and imaged with the DJI AVATA 2 drone. It is a seepage with a small rock gathering on top of it. It is shown on [Figure 3.11](#). The drone data analysis is presented on [Table 3.5](#). The rock gathering has the shape of a small landslide tongue which make it interesting for the GSD analysis. This tongue is characteristic and easy to spot at coarse GSD but only a high resolution will show the rock size and that the bigger material is not at the bottom of the slope. Hence it is easy to mistakenly infer that the seepage is just below a landslide for coarse GSD but actually is not.



Figure 3.11: Nadir view off a seepage found in the Haughton crater next to Matt's rock. The dark arrow indicates the slope direction.

The presence of meandering and multiple sub-channel within the straight and main one is an example of a detail that could be missed in RSLs studies or more generally wider gullies. The seepage could also be interpreted as a small landslide tongue using a coarse instrument. Both facts highlight again the relevance of aerial imaging benefits for gully studies, in particular small scales ones like RSL. RSL are one of the most cited candidates for liquid water on Mars and without a high resolution range it will not be possible to understand them better.

Both tables [Table 3.4](#) and [Table 3.5](#) shows that depending on the gully size and type, the required resolution range to properly determine their nature and characteristics is higher than current in-orbit capabilities. The needed GSD to observe gully details also depends on the gully part. Indeed [Table 3.4](#) shows that all characteristics of the gully fan were observed for a GSD of 0.14 meters per pixels whereas a proper characterization of the channel with sense of v-shaped erosion state only appears for a GSD of 0.061 meters per pixel.

Table 3.4: Characterization of an impact breccia gully

Altitude (m)	Pixel Size (m/pixel)	Gully Description
350	0.16	Multiple alcove joining the same channel and long dark fan, smooth edges, no levées, no idea of erosion state, triangular apron with darker inside lines
300	0.13	Multiple alcove joining the same channel and long fan with dark inside lines, smooth edges, no levées, no idea of erosion state, meandrous lines within the fan, channel darkening is not uniform, triangular apron with darker, sinuous inside lines
250	0.11	Multiple alcove joining the same channel and long fan with dark inside lines, smooth edges shading the west side of the gully network, no levées, no idea of erosion state, meandrous lines within the fan, channel darkening is not uniform, triangular apron with darker, sinuous inside lines
200	0.087	Multiple alcove joining the same channel and long fan with dark inside lines, smooth and dark edges maybe with levées, no idea of erosion state, meandrous lines within the fan and channel, channel is divided in two main paths, triangular apron with darker, sinuous inside lines
150	0.061	Multiple alcove joining the same channel and long fan with dark inside lines, smooth and very dark edges, regular margin, darker side of lines gives sense of erosion, meandrous lines within the fan and channel, channel is divided in two main paths, triangular apron with darker, sinuous inside lines
100	0.036	Long fan with dark meandrous inside lines and no rocky deposit, regular margins, ground has been eroded and dug by flow, meandrous lines within the channel, channel is divided in many small paths, triangular apron with darker, sinuous inside lines
50	0.011	Alcove path are eroded and its ground is granular, margin are smooth and well resolved. Long triangular fan with dark meandrous inside lines and no rocky deposit, regular margins, ground has been eroded and dug by flow, meandrous lines within the channel, channel is divided in many small paths, triangular apron with no debris and darker, sinuous inside lines
30	0.001	Alcove path are eroded and its ground is granular, margin are smooth and well resolved. Long triangular fan with dark meandrous inside lines and no rocky deposit, regular margins, ground has been eroded and dug by flow, meandrous lines within the channel, channel is divided in many small paths, triangular apron with no debris

Table 3.5: Characterization of a Seepage in the Houghton crater

Altitude (m)	Pixel Size (m/pixel)	Gully Description
400	0.19	Looks like a small landslide ending on a dark line that acts as a source of three main erratic channels.
350	0.16	Looks like a small landslide ending on a dark line that acts as a source of three main erratic channels.
300	0.14	Looks like a small landslide ending on a dark line that acts as a source of three main erratic channels. One seems cut on some pictures and not on others.
250	0.11	Small landslide ending on a dark line that acts as a source of three main erratic channels. One seems cut. Bigger materials seems to be at the top of the landslide tongue .
200	0.09	Small landslide ending on a dark line that acts as a source of three main erratic channels. One seems cut and another one is meandering. Bigger materials seems to be at the top of the landslide tongue and within the dark channels.
150	0.06	Small landslide ending on a dark line that acts as a source of three main erratic channels. The channel cut seems to be a new channel originating from a continuity of the landslide tongue line on the side. one channel seems to be meandering. Bigger materials is at the top of a landslide tongue shaped area and within the dark channels .
100	0.04	Small landslide ending on a dark line that acts as a source of three main erratic dark streaks. The streaks cut actually is a new channel originating from a continuity of the landslide tongue line on the side. No channel is meandering. Bigger materials above the tongue shaped area and on top of the dark streaks.
50	0.01	High resolution of small landslide ending on a slope break that acts as a source of four main erratic dark streaks. No channel is meandering. the tongue line continuity is just the slope break and was there before the small landslide. Bigger materials above the tongue shaped area and on top of the dark streaks.
30	0.001	Same as above but lack of context and the seepage does not fit entirely on the picture.

3.2.3. Implication for future Mars rotorcraft missions

As for [section 3.1](#), three main GSD zone have been identify using the drone data analysis from [Table 3.4](#) and [Table 3.5](#). They are presented on [Figure 3.12](#) and [Figure 3.13](#). The GSD in the green zone allow a good certainty in the structure of the gully with detailed imaging of the alcove, channels and apron and consequently allows to determine the origin of its formation (wet or dry process).

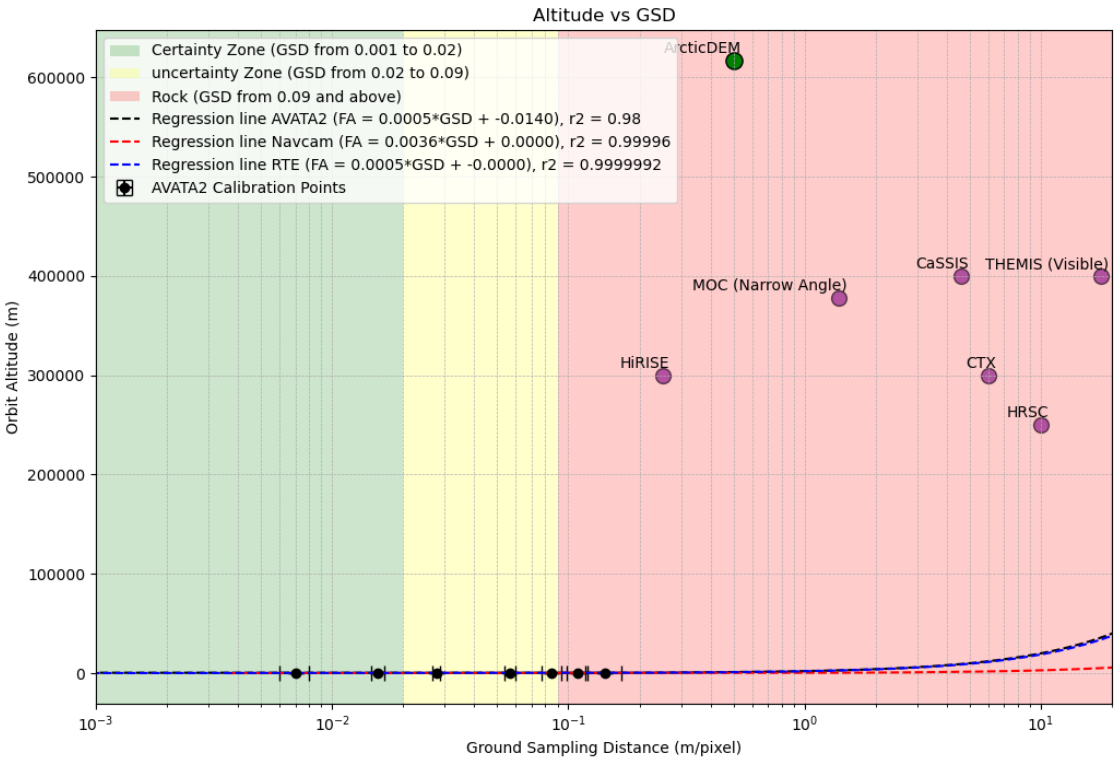


Figure 3.12: Altitude vs GSD, drones and satellite capabilities with GSD zone allowing gully characterization

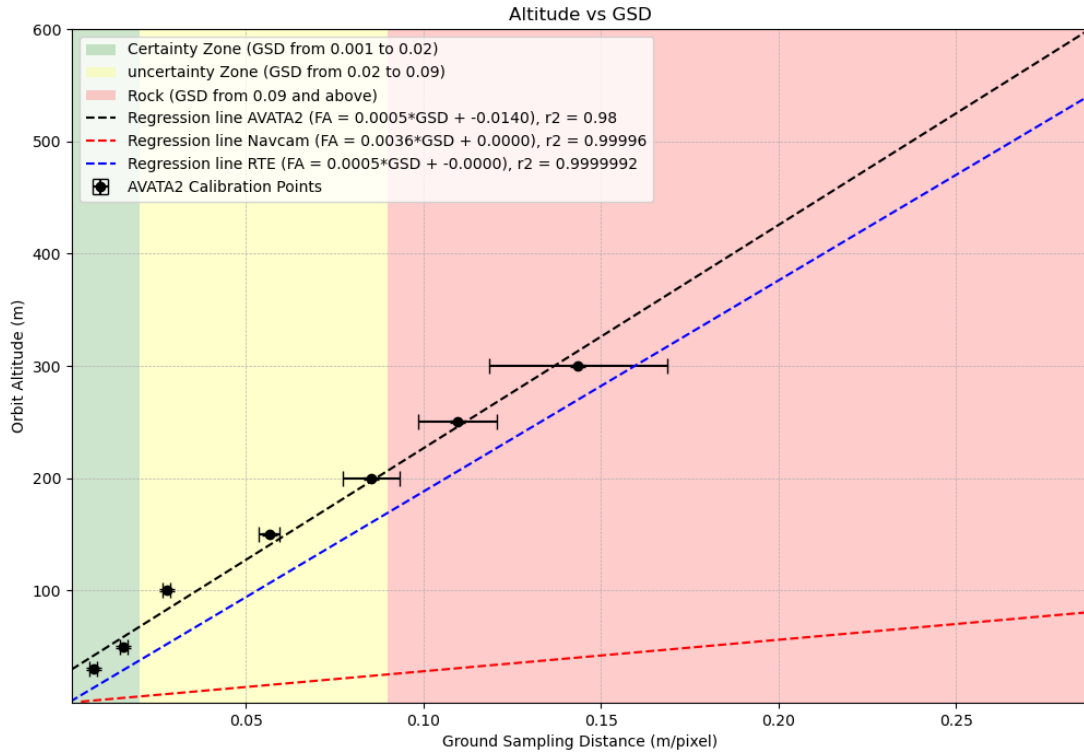


Figure 3.13: Altitude vs GSD, drones and satellite capabilities with GSD zone allowing gully characterization zoomed in the drone part

The recommendations we can make from this study are similar to those of [section 3.1](#). Only the first operation recommendation changes: the drone altitude at which pictures will be taken has to allow a GSD that is inferior to 0.02 meters per pixels in order to fully characterize the gully. All other recommendations can also be applied to this feature.

However, the design recommendations need to be completed. Gullies are less accessible and always found on slopes. They are often larger or at least longer than ejecta blocks and need specific attention in the flight route implementations. Indeed to maintain a constant GSD of 0.02 meters per pixels, the drone will need to change its hovering position and altitude in between pictures to fully and properly imaged the target by following its topography. The target hence needs to be chosen to ensure it can be studied entirely or, at least, effectively. [Figure 3.2.3](#) shows missions examples for gullies that differ in size and shape. The unevenness also need to be taken into account not to have a part of the picture (i.e. the bottom part of the gully) imaged with a resolution superior to the predefined interval. The flying path and time will also be dependent on the battery capabilities and atmospheric conditions.

UAV study case: examples of gully operations

Let assume we are using a camera similar to the DJI AVATA 2 one (i.e. 4000×3000 pixels) and that the target of the UAV study is the ACA gully described on [Figure 3.7\(a\)](#). It is a 7 kilometers long, 2 kilometers large gully, said otherwise, we need to image a $14\,000\,m^2$ area. The coarser, required picture resolution is 0.02 meters per pixel. On each image, assuming the unevenness is negligible because we mounted the camera on a gimbal, a surface area of $4800\,m^2$ is visible. Hence at least 2916 images need to be taken. and the drone will need to fly 239 kilometers. Assuming the recommendations described in [section 3.1](#) are followed, 5 times the same images will be taken to ensure at least one will

have a good quality and not be blurry.

If the operation aim is to derive DTM or DEM of the gully, images need to overlap by 70% to 90%. That is to say, 5547 images in the worst case scenario. This leads to a total of 27735 pictures to avoid blurriness.

Regarding Ingenuity, its longer flight has been 704 meters long and a maximum of 110 images taken while flying. Its maximum ground speed is 10 m/s. Using an Ingenuity class drone to image the gully shown on [Figure 3.7\(a\)](#) will lead to a 6.6 hours long flight, without counting the back and forth time flight to go and come back from the scientific target and the hovering time to take the pictures.

[Table 3.6](#) shows results of similar calculations for different gullies with different sizes using a GSD of 0.02 cm/pixels. These gullies are presented on [Figure 3.14](#).

Table 3.6: Flight characteristics for studying gullies

Gully ID	Length	Width	Number of images	Flight Distance	Flight Time without hovering
(a)	7 km	2 km	2916	239 km	6.6 hours
(b)	1.5 km	50 m	190	3 km	5 min
(c)	500 m	10 m	30	500 m	50 sec
(d)	1.2 km	300 m	600	9.6 km	16 min

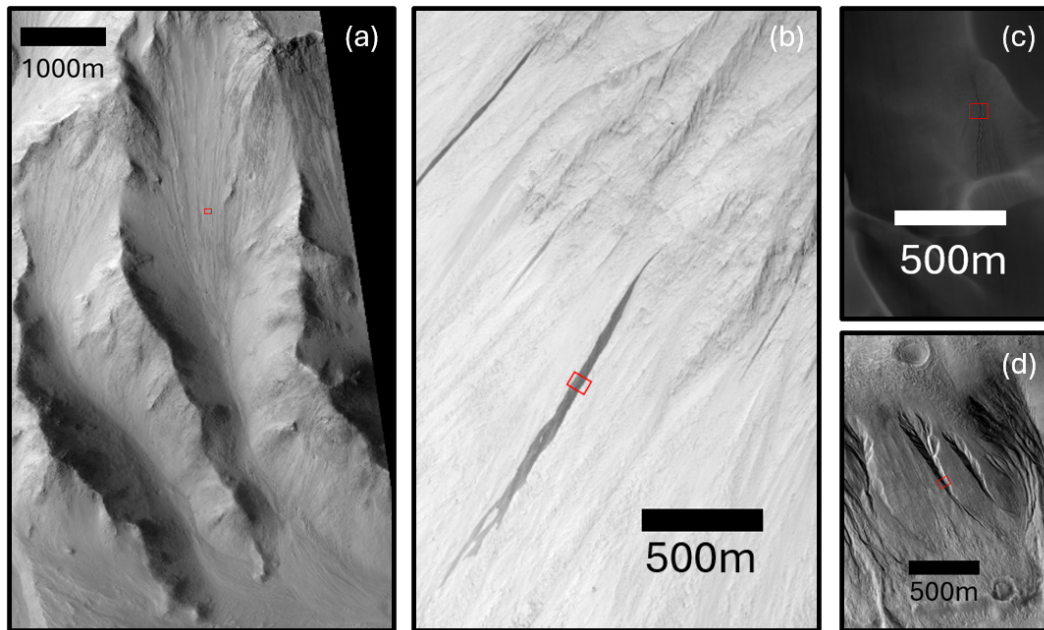


Figure 3.14: Four different gullies found on Mars. The red rectangles delimits the size of a picture with a 0.02 meters per pixel GSD. (a) 6000 meters long Alcove-Channel-Apron gullies as seen by HiRISE (*ESP_011806_1665*). (b) 1500 m long dark streak on the northern wall of Hebes Chasma (*ESP_040791_1785*). (c) 500 meters long and few meters wide linear gully from the western part of Matara Crater Dune Field (HiRISE: *ESP_030528_1300*). (d) 1.200 meters long Alcove-Channel-Apron gullies as seen by HiRISE (*ESP_066220_1430*)

From [Table 3.6](#) we see that some of the gullies won't be imaged entirely because of there size but the use of UAV will not necessarily be to image gullies of such sizes but rather to sample them. That is to say, the UAV has to be design to image small scales gullies entirely but also to fly long enough and high enough to perform image sampling on larger scale gullies. The Mars CHOPPER initiative, aiming to fly a UAV size drone with a five kilograms payload is the kind of mission that will enable all of this. Flying up to three kilometers a day and up to 400 meters high will help doing coarse first images of a target before refining the GSD during the sampling of interesting zones only.

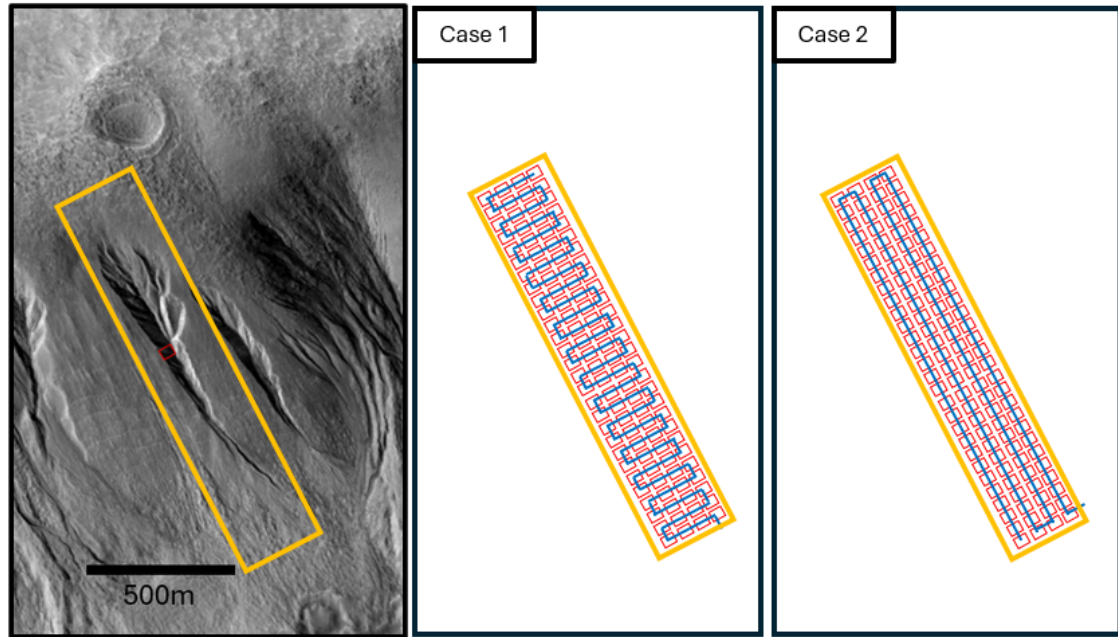


Figure 3.15: Two possible trajectories to map the presented gully. (The trajectories are not fully representative of the actual path that need to be taken to ensure a full coverage of the orange zone but the red full squares are scaled for a GSD of 0.02 meters per pixel)

Table 3.6 also reveals the necessity of predefined imaging strategies, whether it is going from a coarser resolution to then sample interesting areas with high GSD or to map entirely a gully. The drone trajectory need to be optimized with energy-aware battery management for long mapping path planning. Such conclusions are not relatable for 3D-mapping since DTM and DEM realized using parallax effect to see the topography based on multi angle images and do not need a constant GSD. **Figure 3.15** shows how the constant GSD trajectories can differ and the distance traveled in the two cases is very different. The trajectory for case 1 is 5.1 kilometers and 3.4 kilometers for case 2. For each case, the entire gully is mapped with a constant GSD of 0.02 meters per pixels. The first case is the most intuitive one, the drone is flown at a constant altitude from left to right and changes its altitude when it reaches the edge of the gully (left and right scanning). In the same spirit, the second case presents a similar trajectory but this time following the longer direction of the gully, hence going up and down until it reaches the top of the alcove or the bottom of the fan (up and down scanning). To choose between both trajectories calculations should be more effective and take into account the topography of the gully to compute energy-aware trajectories. Indeed the second case is shorter in terms of distance traveled but the required energy to go up and down would be more important than for the left and right scanning path presented on case 1. Furthermore, the positions of the take off and landing areas need to part of the initial conditions for the optimization. Especially, it appears to be more secure to start the gully mapping from the furthest location and progressively come closer in case of an emergency scenario that would require a fast landing. In this perspective, the left and right scanning trajectory seems more adequate with a scanning start at the top of the alcove and a take off/landing zone on the bottom of the fan. This consideration on drone mapping trajectory optimization is much in line with current research made for the application of UAVs in agriculture (Novak, 2024) but will need further studies to add the topography of gullies that is different from planar and regular fields as well as the emergency scenario.

3.3. Patterned Ground

The third set geomorphic features we have been able to observe on Devon Island are patterned ground. They can be encountered in many places inside and outside the crater. Some small scale patterned ground have already been mentioned in **Table 3.2** and visible on **Figure 3.3**. Bigger sets of patterned

grounds are also present in Arctic next to the HMP base camp (Figure 3.16).

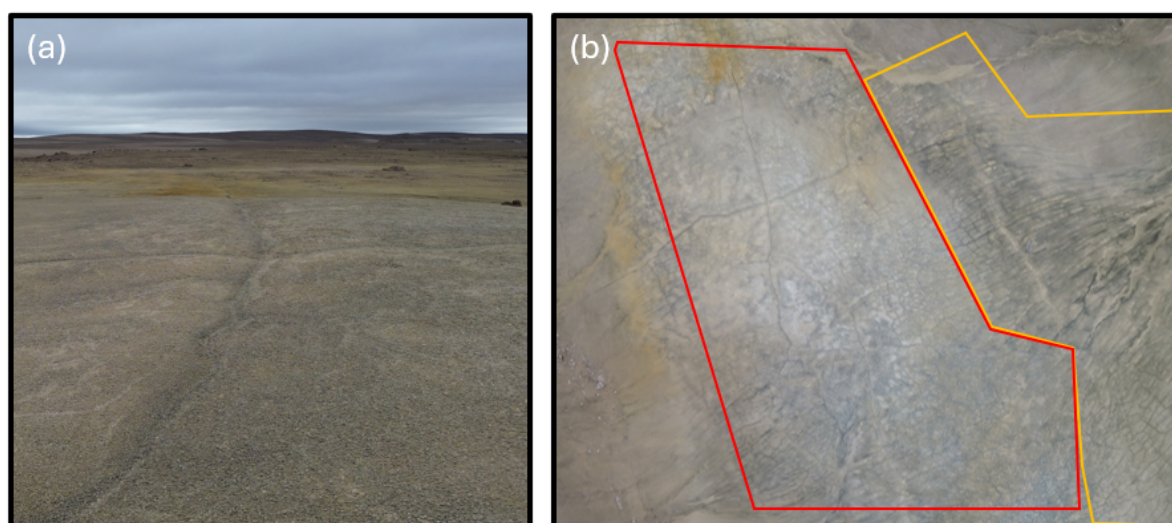


Figure 3.16: Large size polygons found next to the base camp. (a) Horizontal view of the polygon field. (b) Nadir view of the polygon field taken with the DJI MINI 3 drone at 100 meters from the ground.

3.3.1. Occurrence, distribution, and significance on Mars

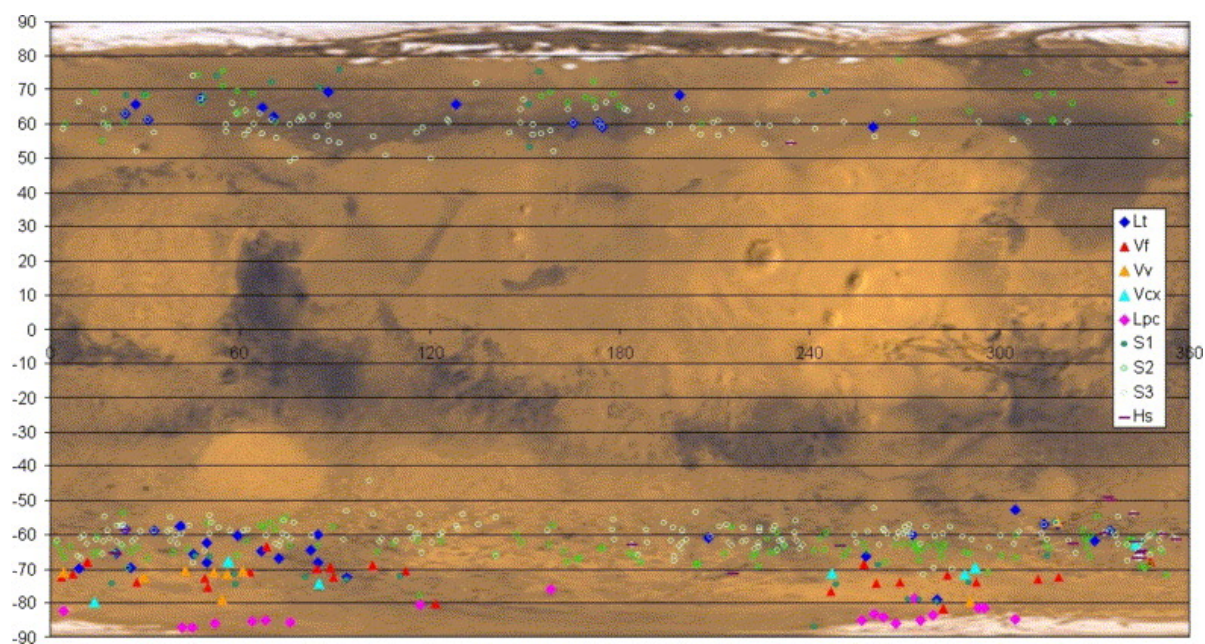


Figure 3.17: Distribution of patterned ground on Mars from MOC images M01 to E06. The background shows a mosaic of MOC wide angle images with Tharsis hemisphere at right (Eastward longitudes). LPC polygons are close to south polar cap at longitude especially around 270° E. There is a strong limit at 55° of latitude. Crack class: A = Random orthogonal, B = Orthogonal, C = Hexagonal. Type LT = Large and influenced by Topography. LPC = Large around Polar Cap. S1 to S3 are Small. VF = Variable with fractal shape. VV = Variable without organization. VCX = Variable and complex Mangold (2005)

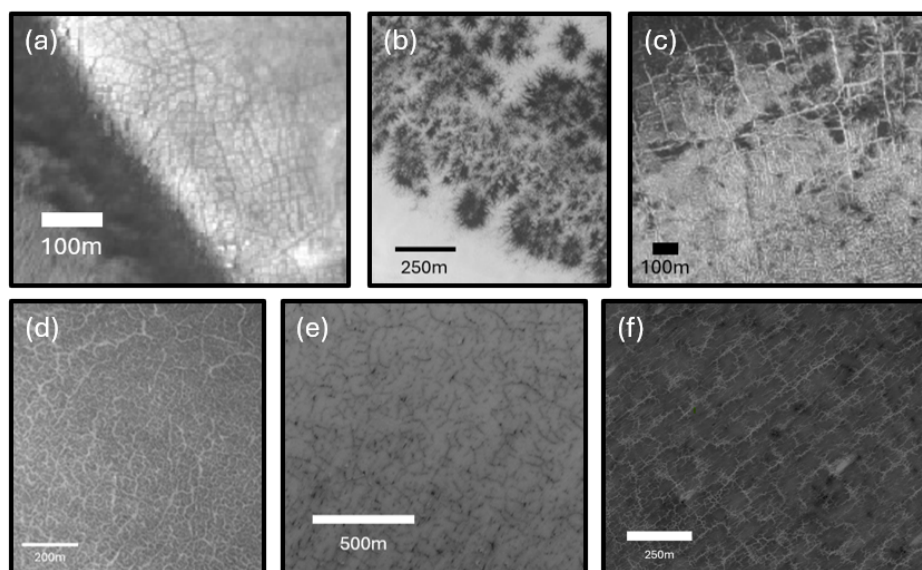


Figure 3.18: Different types of polygons found on Mars (all pictures come from HiRISE instrument). (a) Rectangular pattern (*ESP_075366_1155*). (b) Araneiforms off south polar layered deposit (*ESP_057195_1000*). (c) Rectangular pattern near the Inca City region (*ESP_048703_0985*). (d) Large polygons field next to a north polar crater (*ESP_079190_2500*). (e) Straight cracks field off south polar layered deposit (*ESP_056599_0935*). (f) Cracks networks off south polar layered deposit (*ESP_056599_0935*).

On Mars, patterned ground also are very easy to find. They are mainly located on the poles as shown in [Figure 3.17](#). The first were imaged by Viking more than three decades ago, and their size was much larger than what can be found here on Earth (between 2 and 10 kilometers wide ([Mangold, 2005](#))). Their size is not comparable to that of periglacial polygons on Earth and could be related to tectonic stresses instead. The HiRISE instrument now offers a much better GSD (0.25 meters per pixel) and helped identify different types of patterned ground on the surface of Mars that resemble more terrestrial periglacial polygons. [Figure 3.18](#) displays some of them.

The polygon field in [Figure 3.16](#) is a good analogue of these patterned ground. [Figure 3.18](#) (a), (c) and (d) patterns can be assimilated to the one seen on [Figure 3.16](#). The orange zone indicated in [Figure 3.16](#) shows rectangular polygons similar to [Figure 3.18](#) (a) and (c). The red zone displays a poorly organized polygon field similar to [Figure 3.18](#) (d). If the scale between these images on Mars and Earth is quite different, the processes behind the creation of patterned ground are roughly the same. They usually come from freeze-thaw cycles, thermal contraction of ground ice, desiccation of wet sediments, or tectonic stresses ([Mangold, 2005](#)).

3.3.2. Origins of patterned ground on Mars and needed GSD

Freeze-thaw cycles is a process during which a liquid repeatedly freezes and thaws. During the freezing phase, the volume occupied keep getting bigger and bigger pushing away the solid material. Its sorting happens in the next melting phase. When the liquid melts, the materials is sorted in size and density. This process creates patterns on the ground such as stripes, circles and polygons ([Mangold, 2005](#)). The three of them can be observed on the arctic geology. [Figure 3.3](#) displays some stripes of sorted materials around Sodom ejecta block, [Figure 3.16](#) shows polygons next to the HMP base camp and [Figure 3.19](#) shows a rock circle pattern found next to the previous polygon field. The visible features induced by these freeze-thaw cycles can infer some properties of the ground and the temporality of the cycles. The more cycles, the more the materials will be sorted and the more features will be visible. Polygons fields begin to form by random cracks that, along multiple cycles, expand until they join themselves to form polygons ([Beerten et al., 2021](#)).

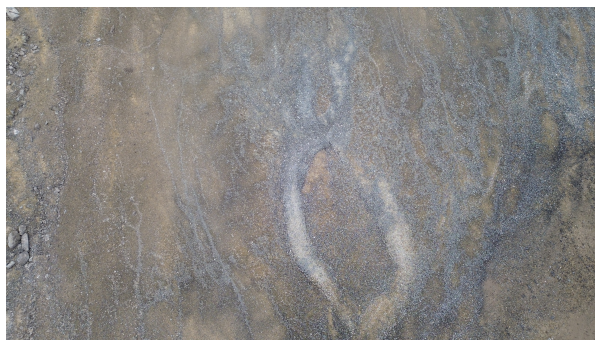


Figure 3.19: Materials sorted to form a rock circle, 400m west to the HMP base camp. Picture taken with the DJI Mini 3 flying 10 meters above ground.

The thermal contraction process works in some similar ways. As temperatures decrease, the ground ice tends to contract and causes tensile stresses. The tensile stresses applied on the ground create random cracks that, again, expand to polygons after numerous cycles (Soare et al., 2014; Beerten et al., 2021). The created polygons are very similar to the one created by freeze-thaw cycles, except that they tend to be more regular and symmetrical (Mangold, 2005).

The desiccation of wet sediments is a very different mechanism and is related to drying and re-wetting of lands. The evaporation and drainage of the wet sediments make them shrink and create cracks. These cracks are much more random than the one created by the two previous processes. The repetition of the wet-dry cycles make the cracks evolve into complex patterned ground (Mangold, 2005; El Maarry et al., 2012).

Finally, the tectonic stress hypothesis relies on the tectonic activity of the crust. The movement of the crust creates stress that can lead into cracks and, hence, patterned ground. It usually forms stripes or polygons (Mangold, 2005). This process leads to very large patterns as the tectonic stress affects large areas.

Of course, the ground properties such as material density, composition and humidity influence the shape and size of the patterns created by each aforementioned process. To differentiate the origin of the patterned ground, the environmental condition and regional context helps testing the multiple theories (Mangold, 2005). Freeze-thaw cycles won't happen in a hot and arid location whereas desiccation of wet sediments won't be responsible for patterned ground in glacial areas. The sorting of material can help identify a freeze-thaw origin of the pattern and very long, deep fractures expanding to the bedrock in a tectonic active area may lead to a tectonic stress origin.

Another origin, for Martian patterned ground, can be the crack of ice due to an accumulation of gaseous CO_2 beneath it that is expelled and deposits the eroded material in the form of a plume (Mc Keown et al., 2023). This process, not visible on Earth, is the one thought to be responsible for the Martian araneiforms depicted on Figure 3.18(b).

Other aspects of the polygons can infer on their formation origin. The color of the borders can reveal the presence of CO_2 trapped in the trough between the polygons. Bounding troughs will also suggest thermal stress origin as opposed to not bounded ones. Additionally, the filling of polygons is a key aspect during their formation. In areas prone to wind and sand transport, polygons' cracks can be filled with sand over the year and because the sand or ice within the cracks is usually weaker than the frozen ground, no new cracks will be formed. The cracks won't change over the thermal cycles and the pattern on the ground is fixed (Mangold, 2005). And the initial size of the polygons is thought to depend on the temperature gradient that resulted in its formation. The higher gradients lead to more cracks and thus smaller polygons (Beerten et al., 2021).

Table 3.7: Characterization of a rock circle

Altitude (m)	Pixel Size (m/pixel)	Ground Description
28	0.019	Polygon field and sorted material down slope with a bright white circle. Its material composition is blurry. Polygons cracks a bit blurry but no sorting of the material, very shallow cracks and no ridges.
20	0.014	Same as above
15	0.011	Same as above
10	0.007	Polygons not in the frame anymore, the white circle and other lines of sorted materials visible. We can not see the materials sizes and shapes
9	0.006	Same as above
6	0.005	Focus on the white circle. Particles sizes composing it are visible
3	0.003	Same as above
1	0.002	Very detail image of a very small part of the white circle with clear imaging of the small material composing it.

Table 3.8: Characterization of a polygon field

Altitude (m)	Pixel Size (m/pixel)	Ground Description
100	0.06	Large polygon field with different shapes. random shape in the center and rectangular one in the darker areas. Some strips also give a sens of topography and rectangular patterns seem to be on the slopes. Larger fractures at the middle and next to the bedrocks. some polygons within the bigger ones on the bright area. Larger fractures do not appear very deep and the smaller one neither. All patterns can be visible even small scales one. Material seem to be a bit sorted on the edge of the cracks but no visible ridges around those cracks.
90	0.06	Same as above
71	0.05	Same as above
60	0.04	Same as above
50	0.03	Same as above
35	0.02	Large polygon field with different shapes. random shape in the center and rectangular one in the darker areas. Some polygons within the bigger ones in the bright area. Larger fractures do not appear very deep and the smaller one neither. All patterns can be visible even small scales one. Material seem to be a bit sorted on the edge of the cracks but no ridges around those cracks.
30	0.02	Same as above
20	0.014	Large polygon field with different shapes. random shape in the center and rectangular one in the darker areas. Some polygons within the bigger ones in the bright area. Larger fractures do not appear very deep and the smaller one neither. All patterns can be visible even small scales one. Material seem to be a bit sorted on the edge of the cracks but no ridges around those cracks. The resolution allows to identify the edges of fine materials but not the tinniest ones.
15	0.011	Same as above
11	0.008	Same as above
5	0.004	Cracks are visible but not entire polygons. Material seem to be a bit sorted on the edge of the cracks but no ridges around those cracks. The resolution allows to identify the size of all tinny materials.
1	0.002	Same as above

Table 3.7 and **Table 3.8** shows a description of, respectively, the polygon field and white sorting circle. Going from the lowest GSD to the highest one has not changed very much the understanding of the field. The polygons resolution is enough at the lowest GSD. The highest GSD only provides a picture in which the material size can be derived even though this properties will not help directly understand more the formation process origin responsible for those patterned ground. Furthermore, such an image could be taken by a rover since the polygons fields are located on flat or very slightly inclined terrains. The use of an UAV to understand polygons field on Mars will be efficient but not necessarily more than using rovers or satellite imagery as they are sufficient to see patterned ground characteristics such as ridges, shape regularity and deepness.

3.3.3. Implication for future Mars rotorcraft missions

The previous section highlights the poor benefits UAVs offers in the imagery of Martian patterned grounds. Already existing technologies on board rovers and satellites are enough to provide new understanding of polygons fields, an aerial point of view is not needed for these geomorphic features. However, even if UAVs are not needed, they can be used to imaged polygons field as secondary targets in a mission. No particular recommendations regarding the GSD distance will be made as the results are straight forwards: only a very high GSD allowing to see the cracks properties (filling material, width, deepness) would have a strong benefit compared to satellite imagery. Some high altitude or wide angle images can help have an overview of the field and characterize properties such as their size, homogeneity or relation with local topography but satellite images can already provide that. Furthermore, the drone trajectory over the field will need to be optimized if a high GSD is chosen to study a polygon field.

3.4. Other geomorphic features

As previously mentioned, UAVs are useful especially in steep slopes, muddy or sandy environments and can be used to visualize places not accessible with rovers. Another major topic for the use of UAV can be the lateral examination of rock layering in canyons. The aerial point of view will allow us to come closer to the wall and to sample with high-resolution interesting areas of a target. **Figure 3.20** depicts this possibility. A very steep mount, around 30 meters high, possesses rock layering on top of it. The structure is too steep for a rover to climb and ground images won't be enough to properly identify the layers composition. With an UAV, the mission is completed in a few seconds.

The main hurdle when it comes to such geological features is the wind. The fieldwork on Devon was done under very windy conditions and the mount creates large zones of turbulences. When it comes to doing similar missions on Mars, the route planning must ensure the safety of the drone and anticipate for these turbulent areas. Software engineering will ensure hovering capabilities but a safety distance need to be taken to avoid crushing the UAV on the wall.

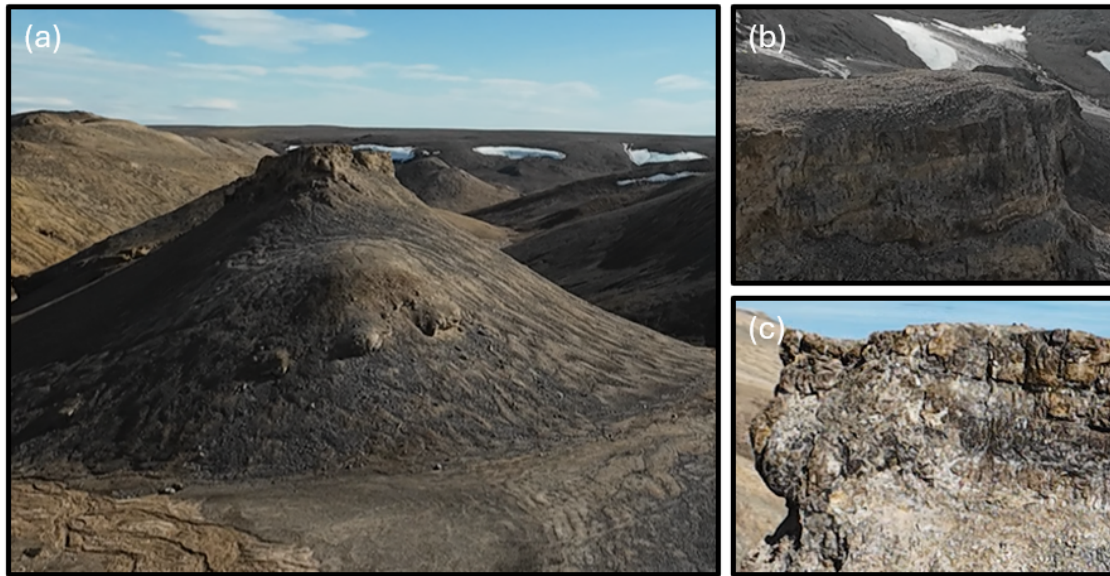


Figure 3.20: Rock Layering on top of a steep mount in the valley of the planet of the apes, Devon island. (a) Steep Mount. (b) North-West side of the top of mount shown on (a) with visible layering. (c) South-East side of the top of mount shown on (a) with visible layering.

Other exciting possibilities not imaged on Devon but that could strongly benefit from the use of UAVs on Mars are non flat features such as lava tubes, pits, small size craters, steep walls and sand dunes but also unpracticable flat areas because of sand, ice or too abrasive surface that could damage rovers wheels.

4

Discussion

The results presented on the previous section show how the use of UAVs can be beneficial for certain types of missions but also that they are not necessarily needed to study geomorphic features such as polygons fields. The data analyses on the patterned ground revealed that a higher resolution than the current satellites capabilities only allows to see smaller polygons but not to characterize them necessarily better. However, the results sections focusing on ejecta boulders and gullies emphasize on two main types of recommendations from which imaging, UAV attitude and camera stabilization requirements can be derived and used to plan future missions.

4.1. Recommendation for future Mars Helicopter Missions

4.1.1. Imaging requirements

To comply with all types of camera, the requirements are based on the GSD enabled by the sensors and not the rotorcraft altitude. Both are linearly linked as seen on [Figure 2.8](#) and hence strongly dependent on one another. The data analysis made on the Haughton analogues revealed different results depending on the studied geomorphic feature.

Regarding ejecta blocks, the GSD needed is the lowest one possible to provide detail images of the rock surface and a clear overview of its damaged state. This damaged state can be characterize for GSD up to 0.0614 meter per pixel. Bigger GSD will also be beneficial for the characterization of the surrounding. A wide angle camera can also help providing context of the block area. One thing not to forget when it comes to blocks is not only to sample it but properly imaged all of the block not to avoid any major cracks or pits that would be visible only on one of its faces.

When it comes to gullies, similar results have been found. Detailed images are needed to fully understand some important properties such as the regularity of the edges, the presence of levées and shape of the channel. The GSD needs to be inferior to 0.02 meter per pixel to do so. Such a small GSD necessarily implies that the area covered by the images will be small and a full mapping of some of the bigger gullies will not be possible. Hence pictures with coarser GSD need to be taken before in order to choose which zone to sample. Based, on the results presented in [section 3.1](#) and [section 3.2](#), a GSD of 0.1 meters per pixels is chosen to define the context images resolution.

Consequently, the main imaging requirements for future Mars rotorcrafts missions are presented in [Table 4.1](#).

Table 4.1: Imaging requirements.

Requirement ID	Requirement Description
IR-MR-01	The drone camera specifications and flying capabilities shall be determined to ensure GSD inferior to 0.02 meters per pixel for high resolution images.
IR-MR-01	The drone camera specifications and flying capabilities shall be determined to ensure GSD up to 0.1 meters per pixel for context images.

4.1.2. UAV attitude and camera stabilization

Taking good quality images strongly relies on the sensor but also on the attitude of the rotorcraft. Images are usually taken during a hovering phase which is prone to destabilization due to the wind. The fieldwork has been a useful experience to shed light on stabilization issues. The aim is to take nadir pointing images that are not blurry and to make the drone flying and hovering phases stable, even in windy conditions. On Mars, surface wind speed can go up to 30 meters per second with brutal changing from calm conditions (0 meters per second) to 15 meters per second wind in a few minutes (Viúdez-Moreiras et al., 2022; Jackson et al., 2024). Ingenuity was designed to be operated with winds up to 5 meters per seconds in very favorable conditions at 11 am while air density was near its maximum (Balaram et al., 2021b). For a completely independent mission aiming to image geomorphic features close to topographic features that can unexpectedly modify winds directions such as cliffs, gullies interior or large rocks, the UAV shall withstand higher wind speed than Ingenuity requirements. Furthermore, the Martian atmosphere being thinner than the one on Earth, the force induced by the wind on the rotorcraft is different and its effect will need to be studied based on the rotorcraft aerodynamism. In any case, the design of the drone has to ensure rapid changes in wind speed won't affect the rotorcraft safety. This can be done by creating a strong enough rotorcraft that would withstand the maximum wind speed will flying and to create an emergency landing scenario to land the rotorcraft if rapid changes in wind velocities are detected.

Furthermore, two recommendations have been made to ensure nadir pointing images in [section 3.1](#). The first one is to add a multi-axis gimbal on the camera. With this equipment, pointing the camera in the nadir direction will be easy in every windy situation. If the drone needs to be inclined a certain way and angle to counter the wind and hover, the gimbal will compensate and ensure nadir pointing images. A gimbal can also be useful to change the camera angle and take horizontal images to characterize ejecta boulder sides and canyon walls layering for instance. The aerodynamism study of the rotorcraft will need to be taken into account in the trade-off between having a gimbal equipped or a fixed camera. If the drone will not be affected by wind, whether because it is aerodynamically engineered to withstand it or because operations will never be conducted in windy conditions, not having a gimbal enable more mass for different equipment and fewer moving parts on the drone but remove the possibility of varying the camera angles to follow the topography.

Hence, the main UAV attitude and camera stabilization requirements for future Mars rotorcrafts missions are presented in [Table 4.2](#).

Table 4.2: UAV attitude and camera stabilization requirements.

Requirement ID	Requirement Description
STAB-MR-01	The drone shall withstand wind speeds of up to 15 meters per second.
STAB-MR-02	The drone software shall have an emergency landing procedure accounting for wind conditions.
STAB-MR-03	The drone camera shall be equipped on a multi-axis gimbal.

4.2. Future prospects for Martian rotorcrafts

As previously mentioned, this study aims to quantify the scientific benefits of UAVs on the different types of terrains on Mars. We have seen that ejecta boulders and gullies are very interesting for this new type of missions but that others exciting possibilities need to be investigated. However, some geomorphic features such as the patterned ground are not ideal targets as rovers and satellites imagery

are sufficient. With the announce of JPL in December 2024 regarding plans for a Mars CHOPPER mission, the future prospects seems promising. Rotorcraft on Mars are not just a simple tool that will bridge the gap between rovers and satellite imagery but a clear revolution in Martian exploration. They enable a complete new way to explore the red planet and will offer a very broad set of operational possibilities. This subsection opens new thoughts about this future missions by providing a very succinct list of location on Mars that would be interesting to investigate using an aerial vehicle.

The research made through this study often conducted to three main location that either harbor the topic analyzed or were previous regions of interest disqualified in the final round of landing site selection because of reasons that can be overcome using UAVs. These regions are the Noctis Labyrinthus, the Hale crater and the Mawrth Vallis. These three different targets show how drones can revolutionize the exploration of the Martian surface. It is first able to survey very different geologic features and areas compared to rovers (i.e. the Hale crater example), navigate through very difficult terrain and overcome challenges for known areas of interest (Mawrth Vallis) for which rovers capabilities where a strong drawback, but also scope new locations and prepare human exploration (Noctis Labyrinthus).

4.2.1. Hale Crater

The Hale crater is a mid latitude massive impact crater (150 km in diameter) that gather different geomorphic features mentioned earlier that would strongly benefit from aerial vehicle. The Hale crater has a very rough surface (Figure 4.1.c) and some parts are filled with sand dunes Figure 4.1.d) making it a very tough area for rovers. Although, dunes can also gives UAVs a hard time. Ingenuity ended its mission after miscalculating its flying altitude above dunes and hence did a too quick descent before landing. The landing was strong enough to brake a rotor blade. Recurring slope lineae have been observed on its central peak (Munaretto et al., 2020) and other types of gullies are found on its rim as well(Figure 4.1.a). The gullies pictured here are typical Martian gullies, carved years ago, that have very clear v-shaped channels running downhill. Gullies within the Hale crater are particularly interesting since gullies found at similar location have been proven to still be active. The basement of the crater contains numerous alluvial fans supposed to indicate an ice-rich floor of the target before the crater formation. Its ground should still be an interesting area to sample and find evidences of past or present microbiological life. The boulders (Figure 4.1.b) present in its crater and on the surroundings plateau also are key scientific targets to image with a rotorcraft.

The deepness of the crater (250 meters) allows a drone like the CHOPPER hexacopter to fly in and out of the crater to explore the Argyre region as a secondary objective if the missions planning allow it. The Argyre region especially contains large amounts of permafrost molards. They are conical mounds of debris resulting from the degradation of ice-rich material mobilized by landslides. These molards are an evidence to support the hypothesis of a cryosphere penetration of the impactor (Morino et al., 2023) and would be a meaningful target.

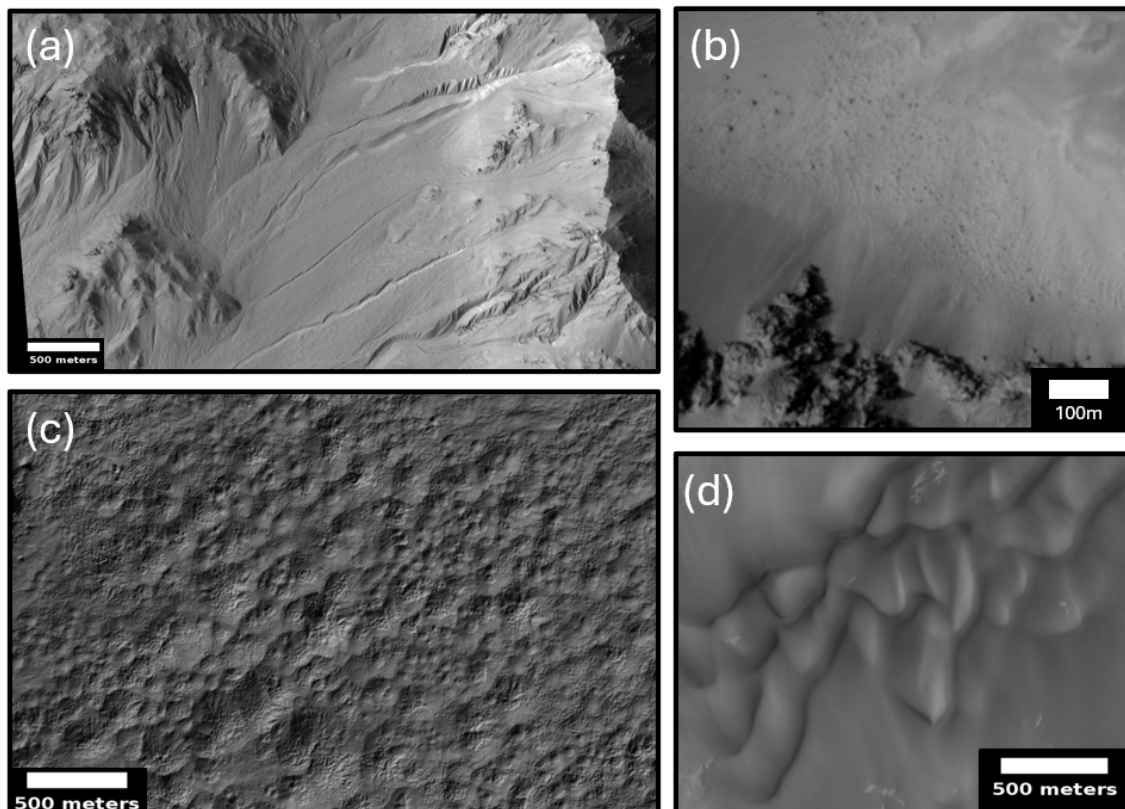


Figure 4.1: Diversity of geomorphic features in the Hale crater. (a) High number of gullies on the North-East side of the crater rim (ESP_073613_1445). (b) Boulder field in the center of the crater (ESP_030425_1440). (c) Rough terrain inside the crater (ESP_026403_1445). (d) Sand dunes inside the crater (ESP_030425_1440).

4.2.2. Mawrth Vallis

Another location of significant scientific interest for Mars exploration is Mawrth Vallis, an ancient valley system that has been considered as a final landing site candidate for multiple missions (i.e. Mars Science Laboratory (MSL), Mars 2020 and ExoMars 2020). The Mawrth Vallis is considered a Region of Interest (ROI) due to its unique and diverse geological features which provide insights into Mars' aqueous history and its past potential for habitability. Mawrth Vallis is thought to have hosted ancient subsurface habitable environments, possibly linked to past groundwater circulation. Geological evidences also suggest that these environments could have been present over an extended period of time. Mawrth Vallis also harbors large exposure of ancient rock formations that could contain evidence of past biosignatures. The region exhibits complex mineralogical diversity, including extensive deposits of phyllosilicates (clay minerals), which form in the presence of water suggesting again that liquid water was present for an extended period. The stratigraphy of the valley, with layers of altered basalt and a complex valley network, provides a geological archive of Mars' environmental evolution. The diversity of exposed rocks across the proposed landing ellipses made Mawrth Vallis a strong contender during the Mars 2020 site selection process. Furthermore, ongoing wind-driven erosion suggests that some outcrops are relatively young and recently exposed, which means that any preserved biosignatures would have had less exposure to Mars' harsh radiation environment, improving their chances of detection.

Even though Mawrth Vallis was considered an ROI, some factors ultimately led to the selection of other landing sites. The committee of Mars 2020 selected Jezero Crater and the one for ExoMars 2020 decided to aim for Oxia Planum instead. The primary concern was the difficulty of the terrain, which posed potential challenges for rover navigation and operations and the uncertainty surrounding the origin of the phyllosilicates in this region also contributed to the decision. While these minerals are often associated with water-rich environments, their exact formation history at Mawrth Vallis is defined

as uncertain by [Grant et al. \(2018\)](#). This uncertainty between the phyllosilicates and its relevance for potential astrobiological significance was a major drawback for the Mars 2020 mission but is not mentioned by in the ExoMars 2020 landing site selection report. Only the terrain navigability and path planning seemed to be an issue in the selection of Mawrth Vallis as the final landing site because it harbors much more large obstacles than the chosen Oxia Planum ([Loizeau et al., 2019](#)).

A rotorcraft-based mission could overcome this limitation and offer a new approach to the exploration of Mawrth Vallis. Additionally, new discoveries within the Mawrth Vallis region may be an additional argument to investigate this area with a rotorcraft. [Bhardwaj et al. \(2019\)](#) discovered candidates re-occurring slope lineae on the slopes of a crater located few kilometers up North from the ExoMars 2020 landing ellipses.

4.2.3. Noctis Labyrinthus

Slopes streaks, gullies and boulders mentioned in this studies are also common features in the Noctis Labyrinthus region especially because of the proximity of the Oudemans crater and the Valles Marineris.

The Noctis Labyrinthus is located in between two areas of interest (the Valles Marineris and the Tharsis Region) and is thought to have been formed by the collapse of large lava tubes formed after volcanic eruptions in the Tharsis region. The Noctis Labyrinthus area features a lot of interesting target for a future mission on Mars and has even been proposed as a potential landing site for human exploration by [Lee et al. \(2015\)](#). A rotorcraft mission in this region could explore the landing zone and look for in-situ resources available that would be needed for human exploration. It would also help answer main science questions related to Mars history since it gather interesting geomorphic features such as remnants of glacier with possible ice in the shallow ground of an eroded volcano caldera. [Lee et al. \(2024\)](#) proposed a Mars Chopper mission named Nighthawk to the Noctis landing area to address key scientific and exploration objectives on Mars. The main target would be the relict glacier before aiming for the stratigraphy observable on the canyon walls offering a chronological record of the geological processes. Other targets such as fresh lava flows, rootless cone fields and thermokarst pits would be hard to investigate with a rover mission making UAVs like Nighthawk particularly interesting for this location.

4.2.4. Drone Mission Operations Architecture

The Mawrth Vallis example however reveals some discrepancies between drones and rovers. The primary science objectives of both Mars 2020 and ExoMars 2020—studying past habitability and searching for signs of life—could hardly be addressed through an aerial mission such as the NASA Mars CHOPPER initiative, even with the appropriate instruments. Indeed it aims for a 5 kilograms payload being carried by the rotorcraft, that is to say nearly ten times less than the rovers capacity (respectively 59 and 45 kilograms for Mars 2020 and ExoMars 2020). To overcome this payload mass differences, different types of missions and operations architectures can be studied.

The first architecture can be inspired by the current use of drones on Earth. Delivery companies use them to carry packages from a depot to a defined area. In this frame, a planetary science mission could be composed of a drone able to collect then carry samples up to five kilograms and a fixed base station, merely a lander, equipped with the appropriate instruments. In this way, the drone shall only be equipped with imaging sensors to navigate or select a target and instruments able to collect samples of the aforementioned target. The analysis of these samples will then be conducted at the base station. This is similar to the architecture proposed by [Pergola and Cipolla \(2016\)](#) and [Zhu et al. \(2024\)](#)

Another architecture could be to have a collection of instruments on a base station that can be equipped and interchanged on the drone. This concept is similar to the previous one, but offers a different range of possibilities. For instance, in the previous scenario, drilling experiments would be possible at only one place, i.e. the landing zone, whereas a movable drill can be set to different locations selected with another instrument. This concept will, however, be more difficult to engineer, especially or payload management, since the drone will need to fly autonomously with different payload mass unless they

are standardized. The connection between the drone and the payload also needs to be addressed. If the payload is only carried and can operate alone on the Martian surface, the need for energy storage will be a hurdle and a redundancy. To avoid such mass-wasting, instruments could be operated thanks to a connection with the drone enabling energy transfers and data transfers. The data could also be transferred to a base station but this would still require standardization of the payloads and enhance the dependency of the mission on a fixed hardware, limiting the surveyed area. The best solution for this kind of architecture seems to be in the trade-off between having standardized instruments relying on the drone energy storage and fewer, less standardized but energetically autonomous instruments.

A third scenario for drone missions can be to have a swarm. Many drones, each having a payload of five kilograms to carry, with not necessarily the same instruments. This allows for fully autonomous instruments that can be carried independently on the surface. It can be seen as independent, smaller-scale missions behaving coherently. The redundancy of drones however seem to be mass wasting, but this can surely be optimized, it also helps for hardware redundancy, a drone crash will not necessarily mean the end of the mission. The optimization can be on the rotor capacity being adapted to each payload mass and not standardized. Communication systems can also be optimized with only one drone (or two for redundancy) behaving as an intermediary between the Earth and all other drones. Having a swarm is also a cost-effective solution to cover large areas in a short period of time by reducing the risks of failure due to redundancy ([Kour et al., 2022](#)).

5

Conclusion

This thesis demonstrates that UAV exploration of Mars is not only a way to bridge the gap between rover-based and satellite-based imagery but a complete new way to study the planet.

The high resolution images provided with the drones reveals that ejecta blocks ([section 3.1](#)) and gullies ([section 3.2](#)) will strongly benefits from UAV imagery compared to the satellite currently orbiting Mars. The Ground Sampling Distance limit for ejecta characterization (i.e. the certainty of the block origin between three main hypotheses that are the impact ejecta block, the house rock or the glacier erratic) has been established to be 6 centimeters per pixel. Such a GSD provides high resolution images on which the damaged state of the boulder can be clearly determined. The characterization of the gully required a higher resolution of 2 centimeters per pixel allowing to spot clear evidences of wet or dry properties in and around the gullies. Satellites orbiting Mars are not capable of such high resolutions and constraints on the size and weight of future in-orbit missions will certainly be a huge restriction before reaching the needed GSD. UAVs consequently appear to be a good solution for both cases.

Different results have been obtained for the patterned ground ([section 3.3](#)). The use of UAVs for this geomorphic process has no particular benefits compared to traditional means of exploration. Satellites offer a good enough GSD and rovers can easily access and move on the patterned ground. The pictures taken with the UAV were beneficial only for very high resolution obtained at several meters from the ground. Same results would easily be obtained with a camera equipped on a rover and the terrain navigability do not always justify the use of UAVs. The data provided by satellites can still be good enough when it comes to study patterned ground but can also be of interest for other small geomorphic features. [Chapter 4](#) sheds lights on how remote sensing can help identify key areas that may benefit from UAV missions, especially in the planning of such missions.

The results from the UAV-based studies realized on Devon Island provided insights that can directly influence the design and operational strategies for future Mars rotorcraft missions. These implications span multiple aspects, from the aforementioned hardware specifications to study geomorphic features such as gullies and ejecta blocks to mission-level planning, ensuring that future rotorcraft can efficiently gather scientific data in diverse Martian terrains. However, some key aspect of UAV utilization still needs to be investigated. The study especially recommends that future research should focus on mapping strategies for three-dimensional geomorphic features such as gullies to ensure a constant GSD. The fieldwork also raised concerns on flight safety around elongated geomorphic features such as mounds, especially for an autonomous vehicle that will not be operated by a pilot making autonomous flight safety around these particular features a topic to further investigate. Additionally, new studies similar to this one need to be performed to expand the catalog of geomorphic features that would benefit from UAV studies on Mars but also to mimic science operations with fully autonomous drones. Some of them can be conducted in the Haughton crater again, since it features interesting targets that have not been integrated in this work, such as mounds and layered canyon walls.

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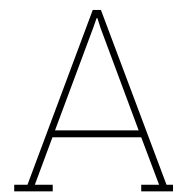
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Gantt Chart

