A FRAMEWORK FOR PLANETARY RESOURCE CLASSIFICATIONS TO FURTHER SUSTAINABILITY IN SPACE EXPLORATION MISSIONS

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A FRAMEWORK FOR PLANETARY RESOURCE CLASSIFICATIONS TO FURTHER SUSTAINABILITY IN SPACE EXPLORATION MISSIONS

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Dedication

For Dadi – my beloved grandmother. May you look upon this moment and this accomplishment with joy from heaven above.

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ABSTRACT

A FRAMEWORK FOR PLANETARY RESOURCE CLASSIFICATIONS TO FURTHER SUSTAINABILITY IN SPACE EXPLORATION MISSIONS

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The long-term impacts and overall sustainability of space exploration missions in the space environment were often unknown in past space missions. Historically, the space exploration vision of various space-faring agents refers to "planetary sustainability" as a synonym for mission assurance, rather than as an evaluation of long-term viability or as a means to ensure the sanctity of the space environment. Moreover, past missions have treated the space environment as an infinite frontier and not as a finite resource. NASA's Artemis program aims to return to the moon and achieve sustainable presence in lunarspace by 2028. Many planned future endeavors require resource extraction or in-situ resource utilization efforts. Resource prospecting is considered the first step in accessing resources in the lunarscape. Prospecting is a term utilized most in the mining and extractive industries and, by definition, is a means of experimental drilling and excavation. Prospecting, however, is not the same as classifying. Resource prospecting is more invasive than resource classification, although resource prospecting can advance resource classification efforts. When terrestrial (Earth-based) resources are evaluated on various measures – including availability, recoverability, accessibility – quantifying resource reserve estimates are a part of the evaluation; however, there is no framework established to characterize planetary resources on the basis of mission resource metrics. This investigation develops a framework to classify resources on the lunar surface, in response to the current, heightened interest in resource recovery and utilization in planetary resource-focused missions. Resource and risk classification methods established by the Society of Petroleum Engineers and General Electric will guide framework development. In the process, the investigation considers existing research proposals to establish resource limits and discusses how resource restrictions and risk thresholds are implemented in the final proposed framework. A novel resource classification framework is the final deliverable and is applied to geologic data from lunar fly-by and surface missions, thereby increasing the yield of existing mission data. Additionally, the framework integrates availability, recoverability, and accessibility metrics, while also addressing a composite sustainability metric. These four metrics are established as essential resource classification benchmarks to ensure that sustainable mission design is implemented early in the space systems engineering lifecycle by space systems engineers and mission designers in multidisciplinary teams.

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CHAPTER I:

INTRODUCTION AND BACKGROUND

Introduction

NASA has developed a cohesive plan for exploration beyond Low Earth Orbit (LEO) under the new Artemis program, with the goal of landing the next humans on the moon by 2024. Beyond 2024, NASA will "establish sustainable exploration by 2028" through collaborations with commercial and international partners [1]. NASA's current vision defines in-situ resource utilization (ISRU) as an enabling technology for sustainable lunar exploration [1]. This thesis will explore the intersection of space systems engineering and sustainable exploration, with a focus on developing a framework for planetary resource classifications for use early in any mission lifecycle. The scope of research is captured in Figure 1, where the broader context is space exploration policy and mission design, the intermediate context is the planetary sustainabilty pursuit, and the research focus is the classification of planetary resources.

Figure 1. Scope of Research

The investigation will explore existing terrestrial examples of resource classifications and resource risk evaluations – especially industrial practices and proposed planetary sustainability solutions. Multi-disciplinary approaches for evaluating terrestrial resources will inform the framework for planetary resource evaluations. This investigation is concerned with incorporating planetary resource evaluations into the design of space exploration missions. To this end, a planetary resource classification framework is developed to guide early space systems engineering approaches to space resource missions. The framework connects technical ambitions with long-term feasibility by examining relevant natural and industrial processes through a systems thinking perspective.

Background and Motivation

The long-term impacts of space exploration missions on the space environment were often unknown during space mission design and exploration vision discussions [2]. The accounting of finite planetary resources and implementing a long-term vision for space exploration that accounts for finite conditions in space is encompassed in the idea of *planetary sustainability* (also called space sustainability). Planetary sustainability is frequently mischaracterized in the plans for space exploration [2]–[4]. Current approaches to mission design and proposed visions for space exploration vaguely refer to "sustainable presence in space"; however, such statements reflect a focus on continuity of operations rather than a careful expansion into pristine space territories. In his discussion of a sustainable model for lunar exploration, Williamson states that "the space profession needs a new model or 'ethic' of environmental-awareness," further noting that "mainstream scientists and engineers involved in space exploration and development seem largely unaware of the legal, ethical, and value-based issues of long-term lunar development"[2]. The latest discussions by the International Science Council's Committee on Space Research (COSPAR) and the United Nations (UN) on planetary sustainability highlighted a need for an improved approach to space exploration endeavors that accounts for the finite nature of space resources [2]. The current international framework was ratified by the United States, United Kingdom, and the Soviet Union in 1967 and is spelled out in the Outer Space Treaty of 1967:

> “...parties to the Treaty shall pursue studies of outer space including the Moon and other celestial bodies, and conduct exploration of them so as to avoid their harmful contamination and also adverse changes in the environment of the Earth resulting from the introduction of extraterrestrial matter and, where necessary, shall adopt appropriate measures for this purpose...” [5]

While the legal and ethical issues of lunar development are not the focus of this investigation, it is worth noting that implementing sustainable development approaches to lunar development would result in a more calculated and conservative approach to lunar surface activities. This investigation seeks to go beyond continuity of operations as a sufficient indicator of sustainability in spaceflight missions. A conservative approach would prevent any one entity from abusing, contaminating, or overusing the scientific and material resources present on the moon and around cis-lunar space while preserving the same resources for use by future exploration endeavors. Due to these realities, Williamson, Galli, and Losch have suggested that the space environment could be added as an 18th United Nations Sustainable Development Goal (SDG) [4], [6], [7]. Sustainable development applied to the space environment would be beneficial to achieving long-range space operations while ensuring a degree of conservation and protection of space environment.

The problem of waste is another great concern in the space environment, and Williamson reminds us that in the Apollo area, waste was left on the surface of the moon "to reduce the lift-off weight of the lunar module." The waste remains, with no erosion factors to weather it apart from solar winds [2]. For future missions, it is important to quantify and address the significance of both resource utilization and waste generation in lunar mission planning to prepare for the boom in lunar landings forthcoming in the next decade. Graedel et al. maintain that a balance between terrestrial constraints and aspirations would require “[dealing] with such factors as optimizing internal recycling during manufacture, minimizing waste disposal requirements, and minimizing the incorporation of materials whose toxic properties or resource limitations argue against their use.”

In an Earth-Moon system, there is a need for a framework that addresses the existing gaps in the space exploration mission design methodology by evaluating availability, recoverability, and accessibility metrics for planetary resources pursuits [4]. Furthermore, the concern of overexploitation due to under-regulation is a clear capability gap in current space systems engineering, mission design, and planetary sustainability approaches for space resource-focused missions. For example, resource-focused missions can be tailored according to resource classification methods, thereby preventing foreseeable problems such as (1) diminishing or non-existent research yields due to cross-planetary contamination (depreciation of lunar real estate) or (2) permanent aesthetic changes (from an Earth observer vantage point) of the lunar surface due to uncontrolled mining. An intentional framework can avoid the negative outcomes of a more laissez-faire approach, as evidenced from the longstanding orbital debris problem [2]. The intent is to avoid unchecked exploitation of the space environment.

Mission Context

In 2017, a Presidential Memorandum on Reinvigorating America’s Human Space Exploration Program was issued by President Donald J. Trump and unveiled *Space Policy Directive –1*, which directs the US to “lead an innovative and sustainable program of exploration” with additional emphasis on “long-term exploration and utilization” of the Moon, Mars, and other destinations [8]. In 2019, NASA detailed the following vision for space exploration: “As NASA embarks on its renewed commitment to lead in space, we must overcome significant technical challenges to achieve the goal of a sustainable return to the surface of the Moon.” Even more recently, in April 2020, the latest report outlining sustainability called *NASA's Plan for a Sustained Lunar Exploration and Development*, stated that the "U.S. will establish a predictable and safe process for the extraction and use of space resources under the auspices of the Outer Space Treaty" [9], [10]. Interestingly, the report specifically calls for a predicable and safe process for resource extraction and use. A major focus of current NASA efforts, especially those leading up to and within the Artemis Program, includes resource prospecting efforts. Resource prospecting is considered the first step in accessing resources in the lunarscape. Prospecting is a term utilized most in the mining and extractive industries and, by definition, is a means of experimental drilling and excavation. Prospecting, however, is not the same as classifying. When terrestrial (Earth-based) resources are evaluated on various measures – availability, recoverability, accessability – the resources are also evaluated along a range of uncertainty (ROU) pertaining to resource reserve estimates [11]. Resource prospecting is more invasive than resource classification, although resource prospecting can advance resource classification efforts. An understanding of the distribution and prevalence of resources on the lunar surface can inform planned resource prospecting missions, thereby avoiding the risk of exploiting large swaths of untouched lunarscape. There is an additional area of concern voiced by Heldmann et al. (2019) and Baker (2019) regarding the construction of a viable space economy around space resources, particularly those of the moon [12], [13].

Primary Objective

The objective of this investigation was to establish a working framework to classify resources on the moon according to useful, multidisciplinary metrics, which will inform the mission design of resource prospecting and In-Situ Resource Utilization (ISRU) missions without decreasing the scientific or societal value of the space environment. In achieving this goal, there are specific sub-objectives:

(1) To avoid disruption of scientifically valuable lunar real estate

(2) To increase mission yields via space environmental awareness

(3) To leverage data interlinkages across resource prospecting missions

By adopting a resource classification framework applicable to interplanetary resource missions, this investigation will establish benchmarks to further sustainable mission design. The proposed resource classification framework is applied to geologic data from lunar fly-by and surface missions, thereby increasing the yield of existing mission data by incorporating benchmarks such as availability, recoverability, accessability in space resource classification processes. A composite sustainability framework should address the capability gap between current systems engineering, mission design, and planetary sustainability efforts, thus two research questions will be answered:

(1) How can multidisciplinary views shape the framework?

(2) How can supply and risk considerations improve the framework?

Given the imminent lunar exploration efforts in this decade (boots on the moon by 2024 and sustainable presence on the moon by 2028), this Master's thesis investigation responds to the call for a "sustainable and environmentally aware model for space exploration and development," a gap identified by researchers, government entities, and international councils, while directly responding to the call for "a predictable and safe process for the extraction and use of space resources" [1][2]. The framework will include multidisciplinary perspectives to address the gap which exists at the intersection of systems engineering, mission design, and planetary sustainability approaches – as demonstrated in Figure 2.

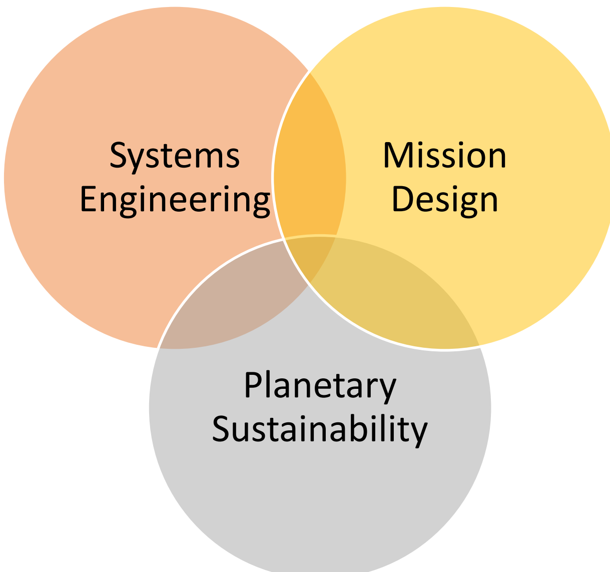


Figure 2. Capability Gap in Current Space Exploration Approaches – A Venn Diagram

Problem Statement

Space sustainability efforts should prevent any one entity from exploiting scientific real estate and material resources present in outer space while preserving the same resources for future exploration endeavors; however, current space exploration plans point to continuity of operations and mission assurance as sufficient indicators of sustainability but fail to address the sustainable use of space resources and do not include metrics on resources to be used during the mission. To date, space exploration has adhered to a model that is focused on "conquering space, exploiting its resources and largely ignoring the consequences" [2]. A degree of negligence in implementing space sustainability measures – or, at minimum, a lack of environmental awareness/foresight –

is reflected in the self-created problem of orbital debris. With over 20,000 orbital debris fragments (ranging in size from full spacecraft and upper stage fragments to micro-debris like paint and thermal insulation in Low Earth Orbit (LEO), orbital debris is considered a national security concern and has sounded an international alarm for orbital debris mitigation measures [2][3]. Concerned about this challenge, many have inquired, *How many years of debris generation and spacecraft decay can the space environment sustain before the orbital debris problem becomes a national crisis?* NASA, ESA, and DoD researchers have modeled orbital debris escalation to determine the timeframe for a looming orbital crisis and models indicate we are quickly approaching "critical mass" [14]. The danger these projectiles pose to current and future missions has influenced mission design, and additional system requirements such that "spacecraft and their launch vehicles now incorporate debris mitigation measures and existing debris is tracked continually" to reduce the probability of debris impact and mission failure [2]. Mature space mission designs developed from proactive sustainability measures – not from reactive mission requirements – will increase mission yields over the entire life cycle of the exploration campaign; additionally, this will mitigate the risk of cost overruns due to a lack of forethought. Since orbital debris is considered a national security issue, the US Strategic Command actively tracks orbital debris larger than 10 cm. The oversaturation concern could lead to an effect called the Kessler Syndrome, a scenario in which the increased density of orbital debris objects results in a "runaway chain reaction of collisions," which ultimately create more debris[14]. This eventuality makes a case for the implementation of planetary sustainability into space systems engineering and mission design for cis-lunar space, which could avoid the risk of a new orbital debris crisis around the moon.

The orbital debris predicament is just one outcome of unsustainable planetary exploration, as uncoordinated resource utilization reduces access to space resources and assets. As Galli and Losch specify, this ultimately limits access to scientific knowledge and societal benefits [4]. Williamson warns of the unfortunate consequences of this approach, asserting that "the most likely result is that the parts of the space environment with the greatest value to science and commercial development will become despoiled, degraded or simply unavailable" [2]. It is worth noting that the uncoordinated and unconstrained use of the space environment led to the orbital debris problem. Unsustainable space exploration practices endangers the space environment and inhibits the human exploration of space, a risk that is heigtened into reality as space junk approaches "critical mass" [14]. In industrial and government visions for lunar exploration, discovering, classifying, and upcycling space resources is a prerequisite to achieving economical, long-term, and sustainable presence in space. It is clear that the discovery and use of planetary resources is a focal point in industry and government visions for lunar exploration [6], [15], [16]. Avoiding surface disruption, increasing mission yields, and leveraging data interlinkages will be paramount to success in space sustainability efforts. To quantify surface disruption, mission yields, and exploration data, a new resource classification framework is needed to inform future approaches. However, to develop something for the future, one must consider the past and the present. It is thus pertinent to evaluate existing resource evaluation theories ranging from industry best practices to novel research theories, for which an expanded discussion is included in the theory chapter.

CHAPTER II:

THEORY

Natural Resource Classification in the 1920s

Natural resources have been classified in a variety of ways. Certain classification frameworks focus on what in systems engineering would be considered the *availability* of a resource and regeneration *capacity* of a resource. In a 1925 *Science issue*, N. Fenneman's *A Classification of Natural Resources* divided natural resources into four primary classes, shown in Figure 3 [17]:

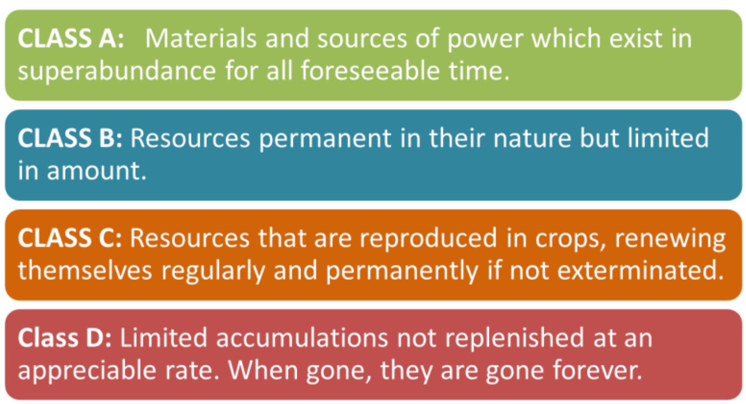


Figure 3. A Classification of Natural Resources, derived from N. Fenneman [17]

Fenneman's resource classification framework focuses on the availability, quantity, and renewability of a resource. This classification approach focuses on the exhaustability of a resource. Today's layman terminology bypasses these four classes and use of generic classifications of *renewable* and *nonrenewable* resource are more common. Further, as Nooten describes, these classifications now account for societal advances where “technology provides the possibility of finding ways to renew the supply of minerals through advances in exploration techniques, extraction processes, recycling, and substitution”[18]. From a planetary resource classification perspective, Nooten's description of "societal advances" are direct research areas under *NASA's Plan for a Sustained Lunar Exploration and Development* [9]. Indeed, the accuracy of planetary resource classifications will increase with scientific and technological advances in space exploration technology.

Petroleum Resource Classification Methods

There are specific extractive industry standards regarding resource classifications that apply to this proposed study. The Society of Petroleum Engineers (SPE) characterizes natural resources on the basis of quantity, accessibility, and producibility as explained in the *Petroleum Resources Classification System* [11]. SPE maintains that the resources will be defined and assessed according to the factors of "integrity, skill, and judgment of the evaluator" and the classification is further affected by the "geological complexity, stage of exploration or development, degree of depletion of the reservoirs, and amount of available data." SPE also reports that the definitions will improve consistency when reporting resources. SPE resource classifications include (1) Total Petroleum Initially-in-Place, (2) Discovered Petroleum initially-in-place, (3) Undiscovered Petroleum initially-in-place. The classifications under the four Recoverable categories include (a) Production, (b) Reserves, (c) Contingent Resources, and (d) Prospective Resources. Additional categories are concerned with (5) Remaining Reserves, (6) Commercial Production, and (7) Prospective Resources.

Figure 4 is a graphical representation of the definitions, as provided by SPE, who have graphed the "range of uncertainty in the estimated potentially recoverable volume for an accumulation" on the horizontal axis, and the "level of status/maturity of the accumulation" on the vertical axis. The Range of Uncertainty (ROU) is a wide enough range to account for a spectrum of technical/commercial uncertainties. It is important to note that if probabilistic methods are used to develop the range depicted along the horizontal axis in

Figure 4 (Low, Best, and High estimates), the best estimate is the mode or median as "a measure of central tendency of the uncertainty distribution (most likely/mode, median/P50 or mean)," as SPE describes.

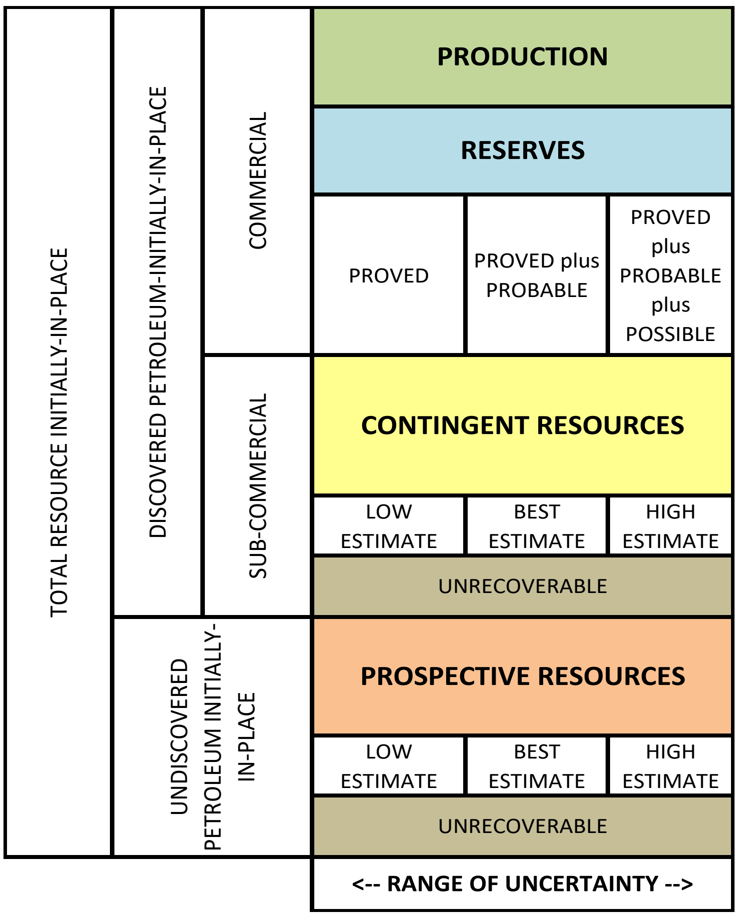


Figure 4. Petroleum Resources Classification System, derived from SPE [11]

Resource estimates mapped against a ROU, as shown above, can help visualize the production, reserve, contingent, and prospective resources, while an understanding of the unrecoverable component will increase through the appropriate advances in space resource discovery, classification, and recovery technology. This progression is supported by SPE's assertion that "Unrecoverable" resources may become "Recoverable resources" as "commercial circumstances change, technological developments occur, or additional data are acquired." For the purposes of this investigation, it is useful to remove the word "petroleum" and replace it with "resource" to expand the application of this classification approach to space resources. Of the three "Resource Initially-in-place" categories, two are considered in this framework: (1) Total Resource Initially-in-Place and (2) Discovered Resource Initially-in-Place. Furthermore, from the four recoverable categories, two are considered: (a) Production (renamed "Extracted Resources") and (b) Reserves.

While this petroleum resource classification approach is based on extraction feasibility, a space resource's classification could also account for industrial use and scientific use estimates. Estimated Ultimate Recovery (EUR) is a metric of total yields produced from a source (extracted and remaining), whereas aggregation pertains to the risk that categories (4b) Contingent Resources or (4c) Prospective Resources will "not achieve commercial production." The (4a) reserve classifications are broken down into three categories: (1P) Proved Reserves, (2P) Proved plus Probable Reserves (2P), and (3P) Proved plus Probably plus Possible reserves (3P).These classifications are relevant to long-term mission yields, which require sustainable planetary exploration approaches in the short-term. From a space exploration perspective, an interesting extrapolation by SPE is that some assessors consider that the recoverable assessment (4a-4c) is the only portion that should be considered a resource. Indeed, a resource classification framework should define what is and is not a resource. This is a key consideration for both terrestrial and space resources, where the value of a resource can depend on scientific breakthroughs that validate their worth.

General Electric Resource and Risk Assessments

To characterize the role of resources in a framework for planetary sustainability, resource classification in the framework will be guided by resource classifications set forth by the Society of Petroleum Engineers. To address the planetary sustainability component, this framework will address commodity flow concerns through an exploration of General Electric's (GE) methodology, outlined in Table 1. The framework is derived from a method established by the National Research Council called "Impact of an Element Restriction on GE", which guides resource yield classifications and achieves a more sustainable equilibrium [19]. The methodic component of GE's impact table is the characterization of "ability to substitute" for a resource, a measure of sustainability that echoes the natural resource classification method proposed by Fenneman in 1925. Additionally, the "GE % of World Supply" is an indicator that can be correlated to the SPE methodology for classification of petroleum resources.

Table 1. General Electric Resource Assessment derived from print [16]

Risk Level	GE % OF WORLD SUPPLY	IMPACT ON GE REVENUE	GE ABILITY TO SUBSTITUTE	ABILITY TO PASS THROUGH COST INCREASES
VERY HIGH	Extremely significant, > X%	> $Y Bn	Very difficult – Very unique and no substitue expected	Nearly impossible
HIGH	Very significant, 0.25X – X%	$0.25 Y – $ Y Bn	Difficult – No known substitue; extensive research	Difficult
MEDIUM	Significant, 0.05X% – 0.25X%	$0.05 Y – $0.25 Y Bn	Moderate – Possible substitutes known but not	Partially possible
LOW	Low, 0.01X% – 0.05X%	$0.01 Y – $0.05 Y Bn	Easy – Substitute known but not designed in	Relatively easy
VERY LOW	Very Low, < 0.01X%	< $0.01 Y Bn	Very easy – Substitute design ready for production	Done automatically

In the context of planetary resources, items under consideration for each resource are the projected risk levels, percentage of supply, potential impact on revenue, ability to substitute, and ability to pass through cost increases for various elements of interest on the lunar surface. For example, to interpret risk level of resources, risk awareness will be required to establish metrics for the space environment that correspond to the risk levels -- ranging from VERY LOW to VERY HIGH. However, another supplementary GE resource assessment framework combines supply and price risk factors to determine a risk rating, as shown in Table 2. The risk ratings are based on resource availability, producibility, volatility, substitutability factors. Ultimately, a combination of resource assessment and risk assessment methods could better articulate planetary protection concerns than one method alone.

Table 2. General Electric Supply Risk Assessment, derived from print [16]

RISK LEVEL	ABUNDANCE IN EARTH's CRUST (ppm)	SOURCING AND GEOPOLITICAL RISK	CO-PRODUCTION RISK	DEMAND RISK	HISTORIC PRICE VOLATILITY (5-YR PERIOD MAX)	MARKET SUBSTITUTABILITY
VERY HIGH	Very rare < 0.01	Concentrated, high risk	Co-produced but extraction method in jeopardy	New applications could significantly increase demand	> 500%	No substitutes
HIGH	Rare, 0.01 – 1%	Concentrated and/ or significant risk	Co-produced and economically insignificant	New applications could increase demand	200% – 500%	Unknown or poor substitutes
MEDIUM	Less Common, 1 – 100	Some diversity and/or risk	Co-produced but economically significant	No new apps; growth faster than GDP	100% – 200%	Known substitutes but worse performance
LOW	Common, 100 – 10,000	Very diverse and/or stable	Primary product	No apps; growth at GDP	50% – 100%	Known substitutes
VERY LOW	Very Common, > 10,000	U.S. based	–	No apps; growth less than GDP	< 50%	Easy and known substitutes

NRCS National Engineering Handbook

The US Department of Agriculture (USDA) Natural Resource Conservation Service maintains a National Engineering Handbook used for the classification of geologic resources, including rock, soil, and general earth material. For this investigation of resource classification and mission risks, Part 631 Engineering Geology is relevant. Part 631 proposes various rock and earth material classifications and specific rock characterisitcs relevant to engineering geology or geotechnical pursuits. Chapter 12 of

Part 631 (Rock Material Field Classification System) elaborates on rock material field classifications, including evaluating earth materials for exacavation [20]. For example, rock excavatability is a parameter of relevance to any resource classification method. The main question this answers is, *what degree/type of impact is required to excavate the site?* The question can be answered by site surveys to an extent, however determining the excavatability of a specific material at a site of interest is key. As a resource classification framework is developed for a lunar space resource classification approach, both the rock properties and site characteristics will be of interest to characterize sustainability.

Planetary Protection and the 1/8 Principle

One proposed planetary protection approach pertaining to resource classification and use is the "1/8 Principle," an idea coined for protecting the Martian environment [21]. This approach requires that "no more than 1/8 of the available resources" should be used to prevent "super exploitation." Milligan and Elvis examine the super exploitation concern and conclude that a resource conservation approach could be a necessary stop-gap measure. A constrained approach or a generational resource extraction cap for resource-focused missions is one path forward for on-going space exploration pursuits, and allows cross-industry discussions on "legal, ethical, and value-based considerations" time to catch up [2]. The proposition thus avoids a "Wild West" scenario where full-scale industrial mining endeavors proceed unchecked, without consideration of resource limitations or potential future needs and uses [22]. Sustainability measures should strive to balance planetary exploitation, planetary conservation, and planetary preservation. Thus, to define a relevant and informed framework, it is critical to address the dividing lines between resource exploitation, conservation, and preservation.

Systems Engineering Metrics

Systems engineering metrics characterize the effectiveness of both a product and a process [23]. In the context of resource-focused missions, this is especially true. There are a variety of systems engineering metrics, ranging from RAM analysis (Reliability-Availability-Maintainability) to usability, which are computed to characterize either a product or a process. For planetary resource extraction-focused missions, the product can be defined as the space resource of interest, while the process can be the method of accessing, recovering, and ultimately availing the space resource. In this investigation, three appropriate metrics were selected from a large list of potential systems engineering metrics. The first metric is availability. This metric is selected as it will classify the abundance of a resource, as the scarcity or abundance of a resource should be factored into a sustainability evaluation of a proposed resource extraction pursuit. Recoverability was another metric that was analyzed to better characterize sustainability of extractive pursuits on the lunar surface. This metric is concerned with the difficulty of extracting the resource. The final metric of interest is accessibility, which can quantify how accessible a selected site is. The entire investigation is focused on expanding planetary sustainability by proposing a resource classification framework to better characterize sustainability. The framework encompasses availability, recoverability, and accessibility; however, it must also include a generational sustainability factor defined by a total depletion rate. After weighing starting availability, extracted percentage, and usage percentage, we can arrive at a total resource depletion rate. It is also useful to address surface disruption caused by surface prospecting and exploration. To summarize, the primary metrics (availability, recoverability, and accessibility) will include parameters that individually characterize the sustainability of a given resource-focused mission profile.

CHAPTER III:

METHODOLOGY

Framework Formulation

The first step of the investigation is evaluating existing resource assessment frameworks for relevance to planetary resources. In a thorough literature review, at least four possible contributors were identified; these range from petroleum industry best practices to novel research ideas [11], [17], [18], [20], [21]. It is a combination of industrial standards, research propositions, and mission context that guided the formulation of a novel planetary resource classification framework, a process shown in Figure 5.

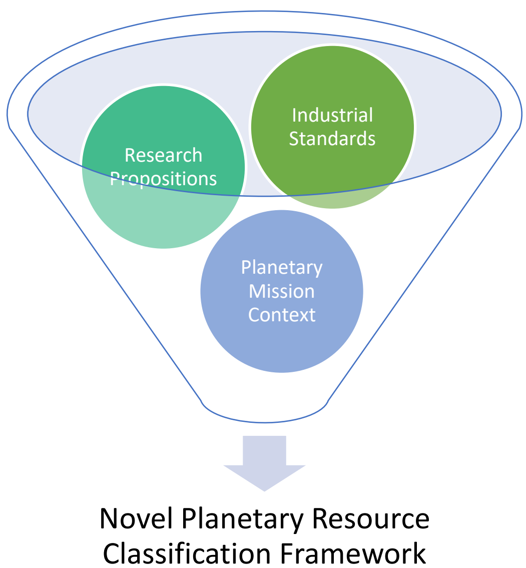


Figure 5. Basic Framework Formulation Approach

The mission context includes mission data analysis, which is discussed in the next section. Since planetary resource-based missions are multi-stakeholder ventures, it is appropriate to draw on multi-disciplinary, cross-industry insights (commercial, government, and academic). Additionally, the entire framework can be bounded by the mission context and industrial standards within space systems engineering to guide framework formulation.

Two of NASA's life cycle approaches are modeled in the *NASA Systems Engineering Handbook* and *NASA Introduction to Human Systems Integration (HSI) Handbook*. These life cycle approaches provide relevant context to bound a planetary resource problem within existing industry processes. Figure 6 illustrates the end-to-end methodology to be followed for framework formulation.

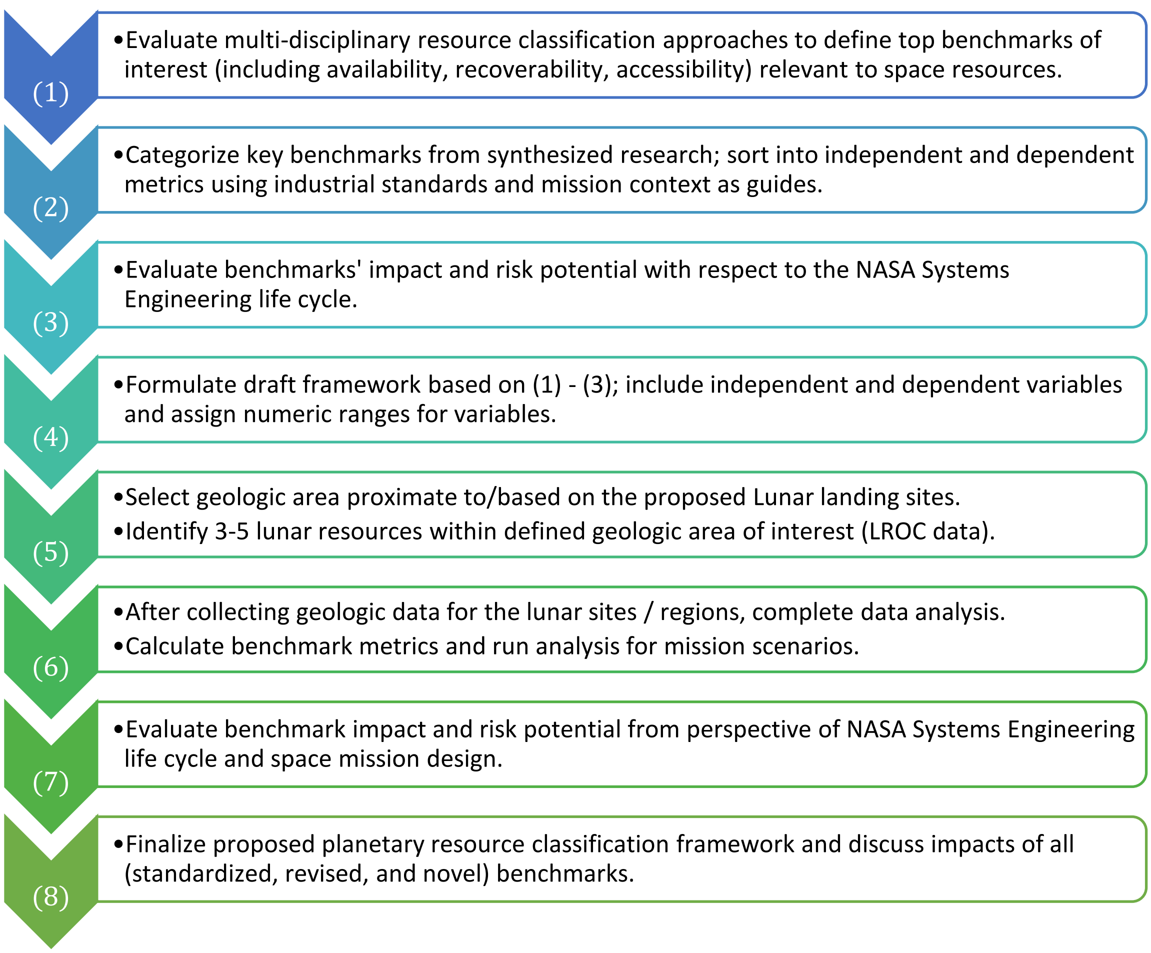


Figure 6. End-to-End Framework Formulation Methodology

Data Availability

After reviewing existing standards to document and categorize essential benchmarks, the first draft for a novel framework was prepared. The second step was to acquire existing planetary data available that is relevant for resource extraction or ISRU missions. NASA's Artemis program has identified Shakelton's Crater as a likely future landing site; therefore, using the geologic maps of the Moon's South Pole region was relevant, as this was developed by NASA and the US Geological Survey (USGS) with data from the Apollo-era the Lunar Orbiter mission [24]. Additionally, in April 2020, the USGS, in conjunction with NASA and Goddard Spaceflight Center, released a first-of-its-kind comprehensive geologic map of the moon, noting that it was "a synthesis of six Apollo-era regional geologic maps, updated based on data from recent satellite missions ... [and] will serve as a reference for lunar science and future human missions to the Moon" [25]. Similar geologic maps for Mars, a body of interest for general resource assessment purposes, are also available but were not the focus of this thesis.

The Lunar Reconnaissance Orbiter (LRO) team maintains mission data yields in interactive LROC QuickMap tool. The tool's GIS layering option enabled an investigation of individual lunar surface features (e.g. craters, terrain maps, and rock features), including an overlay the Unified Geologic Map and elemental abundance for metric assessment and resource approximation purposes [26]–[31]. The map includes data from various lunar fly-by and surface missions, including NASA's Lunar Prospector and Lunar Reconnaissance Orbiter (LRO) missions. The baseline lunar map is shown in *Figure 7*. The USGS geologic maps and LROC QuickMap tool contain significant data on the geologic composition of the lunar surface and were utilized as references to guide framework development. Raw lunar mission data sets for elemental abundance are also available on the mission websites on NASA's *Planetary Data System (PDS)* site [32]. The datasets and GIS images utilized in this thesis are summarized in Figure 7.

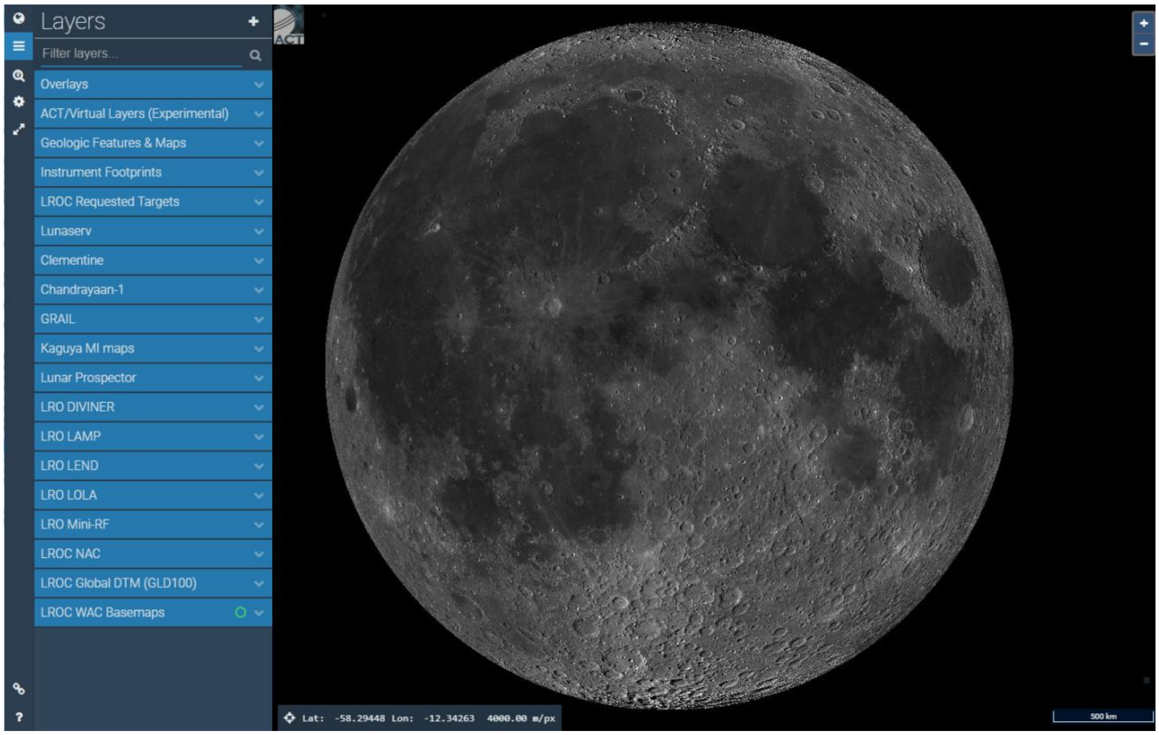


Figure 7. LRO/LROC Lunar QuickMap Tool [26]

Table 3. Mission Data Leveraged in Investigation

Mission / Data Source	Dataset	Data Collection Method	Data Credit
Lunar Prospector	Elemental Abundance	Raw Mission Data	[26], [33], [34]
LRO DIVINER *Diviner Lunar Radiometer Experiment*	Local Minimum Temperature Nighttime Soil Temperature Rock Abundance Polar Ice Depth Stability	GIS Image Analysis	[26], [35], [36]
LRO LEND *Lunar Exploration Neutron Detector*	Polar Water Equivalent Hydrogen	GIS Image Analysis	[26], [37]
LRO LOLA *Lunar Orbiter Laser Altimeter*	Slope at 100m Roughness at 100m Elevation, GLD100 (+LOLA)	GIS Image Analysis	[26], [38], [39]
USGS / NASA *Unified Geologic Map of the Moon*	Geologic Features of the Moon	GIS Image Analysis	[26], [40]

The map tool features overlays, such as the saturation of various elements and surface eccentricities. An overlay of Titanium abundance data from the Lunar Resource observator is depicted in Figure 7. Additional notes are also included with each chart; specifically, the mapping tool contains various annotations corresponding to each overlay, which will provide a map legend or gradient chart, along with other useful context for data collection purposes. For example, for the Titanium abundance overlay shown in Figure 7, the annotation states: "The data are given in units of elemental weight percent. A description of the reduction of these data products is given by Prettyman et al. [2002]. The map scale is 2 degrees per pixel."

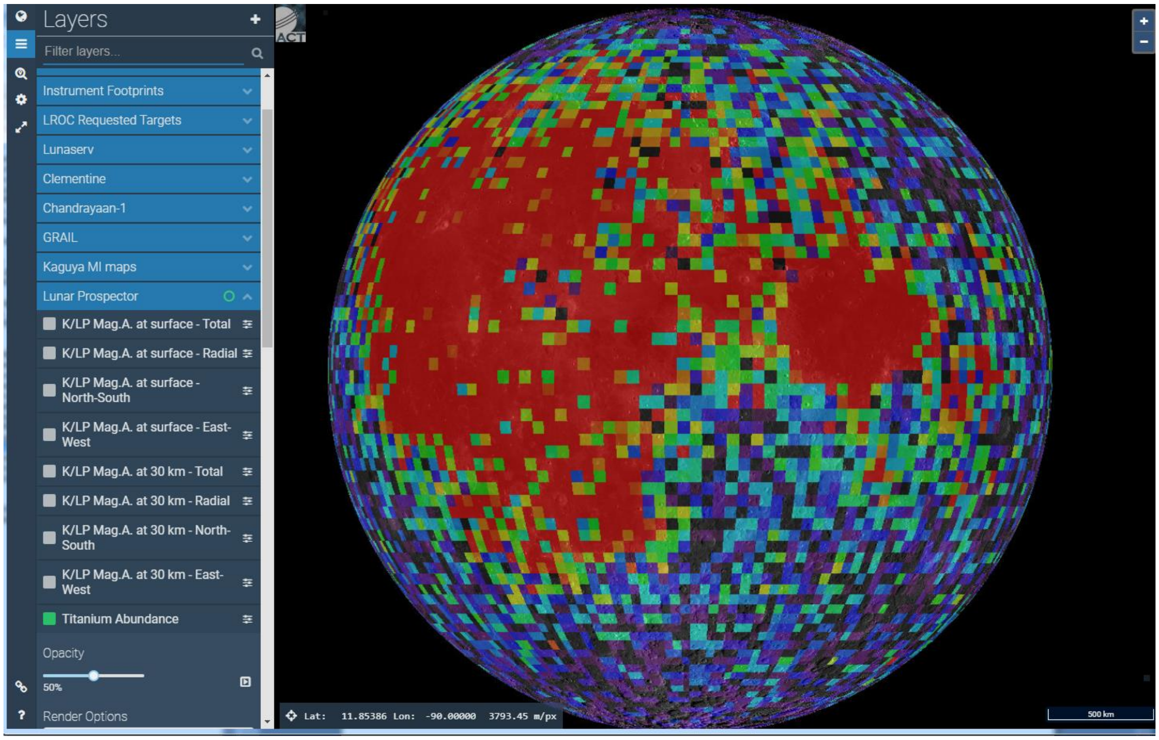


Figure 8. Titanium Abundance on Lunar Surface, Lunar Resource Prospector [26], [34]

While titanium is modeled here, note that the raw elemental abundance files for all elements evaluated were obtained from the NASA Planetary Data System for this investigation.

Novel Framework Formulation

After evaluating specific lunar resources in the context of existing resource classification frameworks and identifying any gaps, the next step of this investigation was to formulate a modified resource classification framework that addresses space resource classifications. SPE's *Petroleum Resource Classification Method* is primarily aimed at classifying resources from an extraction viability and availability perspective, while the GE Commodity Assessment approach is interested in the risk level, percentage of world supply, ability to substitute, etc [11], [19]. Different still, the 1/8th Principle aims to address maximum resource extraction limits while Fenneman's 1925 resource classification method sought to address resource abundance vs. resource depletion [17], [21]. Lastly, the classification of terrestrial rocks, soils, minerals, and materials are outlined in more traditional handbooks. The NRCS National Engineering Handbook, outlines a variety of mechanisms for the field classification of rock materials [20]. The Handbook of Mineral Science also provides useful data on mineral classification and mineral properties, which can be used for minerals on the moon's surface [33].

These theories and industrial standards were evaluated to guide framework development, however the end goal was to create a framework to address the capability gap existing at the intersection of systems engineering, mission design, and planetary sustainability efforts (recall the venn diagram in Figure 2). The novel approach of this resource classification framework is that it addresses space systems engineering concerns by proposing a framework that can be used to estimate availability, recoverability, and accessibility of space resource-focused missions. Given the complexities of lunar exploration and the numerous unknowns regarding lunar resources, the framework provides a more practical approach to lunar resource classification. It can also guide resource prospecting missions and promote planetary sustainability in a multi-user moon environment, thereby directly addressing what many space treaties hope to avoid: the over-exploitation or depletion of finite resources in the space environment.

Analysis and Modeling Tools

Once the draft framework was developed, Microsoft Excel was used to import and analyze existing geologic data for the Moon and the components required to perform resource assessments. Both MATLAB and Excel were used for further statistical analysis and graphical data reporting purposes, however, some statistical data was accessible directly from the ASU Lunar QuickMap tool. The approach for framework drafting was to model the framework using Microsoft Excel and to generate relevant systems engineering graphics using Microsoft Office. In addition to using these PC tools to develop and illustrate components of the planetary sustainability framework, readily accessible tools in the Microsoft Office suite were used for simpler illustrations – which are often more helpful than textual explanations. The novel framework is illustrated in the results section and any supporting data is reported.

Resource and Statistical Analysis Approach

The planetary resource classification framework developed was based upon the geologic data available for the moon. Early investigations of relevant systems engineering metrics, as defined by both INCOSE and in NASA's Systems Engineering Handbook, determined several possible engineering metrics that are used by systems engineering process [23], [41]. After evaluating the available datasets and engineering metrics, it was possible to reduce the list of SE metrics to only those which could increase an understanding of "system" sustainability. Here, the "system" encompasses the space resources on the moon. The goal was to ensure the planetary resource classifications accounted for the availability, recoverability, and accessibility of space resources to further sustainability. The next task was to determine which of the available geologic datasets could quantify these mission metrics in a meaningful way. While evaluating the datasets, industrial standards were essential to developing the resource classification framework so that the classificaiton methodology did not deviate from existing terrestrial classification approaches, but instead expanded upon them. Once the relevant geologic datasets were mapped to the appropriate systems engineering metric (availability, recoverability, or accessibility), the final step was to determine how the data variations within a dataset could translate to a risk category (as demonstrated in the GE methodology), to account for resource, supply, and risk classifications. A similar approach was taken to determine a composite sustainability metric, which is discussed in the results section.

For each adaptive Lunar map layer in the ASU LROC QuickMap tool, four statistical data options were available for each layered view:

- Full range of data
- Histogram 99 range {-3σ to +3σ}
- Sigma 2 range{-2σ to +2σ}
- Sigma 1 range {-1σ to +1σ}

For all availability, recoverability, and accessibility parameters derived from Lunar map layers, the bin ranges for each risk level correspond to sigma 1, sigma 2, and sigma 3 (histogram 99) range of values derived from the Lunar QuickMap tool. The overall risk defintion approach is captured in Table 4, which demonstrates how each statistical data range was tracked with respect to risk levels and risk scores throughout the framework.

Table 4. Risk Levels and Scores with respect to Data Range Definitions

Risk Level	Risk Score	Sigma 1	Sigma 2	Sigma 3
VERY HIGH	5			X
HIGH	4		X	X
MEDIUM	3	X	X	X
LOW	2		X	X
VERY LOW	1			X

The lowest and highest values correspond to the sigma 3 or histogram 99 data bins, while each more intermediate step in the risk classification was defined by either the sigma 2 range or the sigma 1 range. When the preliminary resource classification framework was complete, three sites of interests were analyzed and the geologic data for each variable of interest was logged according to the framework. With the geologic data handy, each site was assigned a overall mission risk classification according to the established ranges, ranging from *low* to *high* risk categories, distributed according to histogram 99, sigma 2, and sigma 1 ranges obtained from the LROC QuickMap. Data yields are captured in the results section.

Mission Data

Three lunar regions were surveyed – the South Pole region, Shackleton's Crater, and the Clavius Crater. These surveyed locations were assessed due to their appeal as landing sites for both space mining and Artemis missions. The Clavius Crater was a late addition due to NASA's announcement on October 26, 2020, when NASA's Stratospheric Observatory for Infrared Astronomy (SOFIA) telescope discovered water molecules on this sunlit crater on the moon [42]. The three sites are thus significant sites of interest for lunar resource prospecting and utilization. Their coordinates and boundaries in Latitude and Longitude are listed in Table 5.

Table 5. Latitude and Longitude for Evaluated Sites[26]

Location	Latitude Start	Latitude End	Longitude Start	Longitude End
South Pole Region ***Centered (0, -90)***	– 90	– 77.5	– 180	180
Shackleton's Crater Region ***Centered (0, -90)***	– 90	– 87.5	– 180	180
Clavius Crater Region ***Centered (58.4, 14.4)***	– 62.5	– 57.5	– 63	– 45

GIS Image Analysis

To analyze the data distribution (in percentage) of each parameter of the framework (for example, surface slope) at a given site, a publicly accessible color extraction tool was utilized to correlate site data from the GIS image to the establish color legends published in the Lunar QuickMap tool. While extracted images could have been evaluated by color scheme by building a MATLAB color analyzer, building a color analyzer was not the focus of this investigation; therefore, the simplest approach was to use a preexisting online color analyzer tool and determine the proportions for every parameter in the availability, recoverability, and accessibility frameworks. Once the weighted average for each parameter was determined, it would then be possible to work on the most critical element of the investigation – applying the classification framework to specific lunar sites to determine resource and risk characterizations for the sites.

Table 6 demonstrates an example of the calculated results used to determine the weighted average, minimum, and maximum values at each selected site for all availability, recoverability, and accessibility parameters.

In the example shown in this section, the step-by-step procedure used for the Shackleton's Crater image analysis for Polar Water Equivalent Hydrogen (WEH) is highlighted. Since the same process was followed for all other GIS images, the detailed steps are excluded for all other sites. The steps are identical to those followed for the Polar WEH image analysis for Shackleton's Crater. To complete the Polar WEH image analysis, the first step was to utilize the Lunar GIS QuickMap tool to focus on a specific site of interest – in this example, Shackleton's Crater. The image (shown in Figure 9) was then captured with the WEH overlay over Shackleton's Crater, and the image was bounded by the Longitude range and Latitude range identified in the mission data (reference Table 3). The image was captured using a basic screen capture tool.

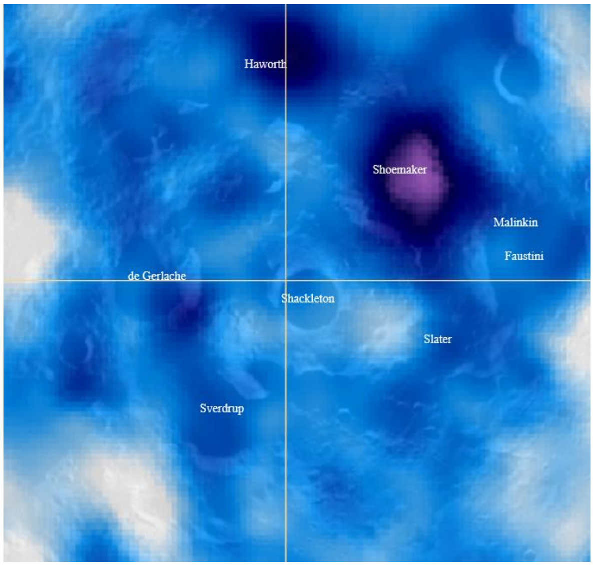


Figure 9. Shackleton's Crater Region Water Equivalent Hydrogen Map [26], [43]

After the image was captured, the online TinEye Color Extraction tool was utilized to extract the color proportions present in the site of interest. The color extraction tool is a *TinEye Lab* powered by Multicolor Engine [44] . The color legend for the specific characteristic (e.g. Polar WEH) was then consulted to determine – with some degree of visual approximation – which WEH levels corresponded to the extracted color levels. The legend for Polar Water Equivalent Hydrogen was obtained from the ASU LROC QuickMap tool and is shown in Figure 10.

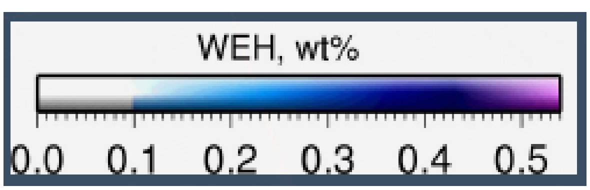


Figure 10. Legend for Polar Water Equivalent Hydrogen (WEH)

The image of the selected site was then uploaded to the TinEye color extraction tool, which returned results as shown in Figure 11.

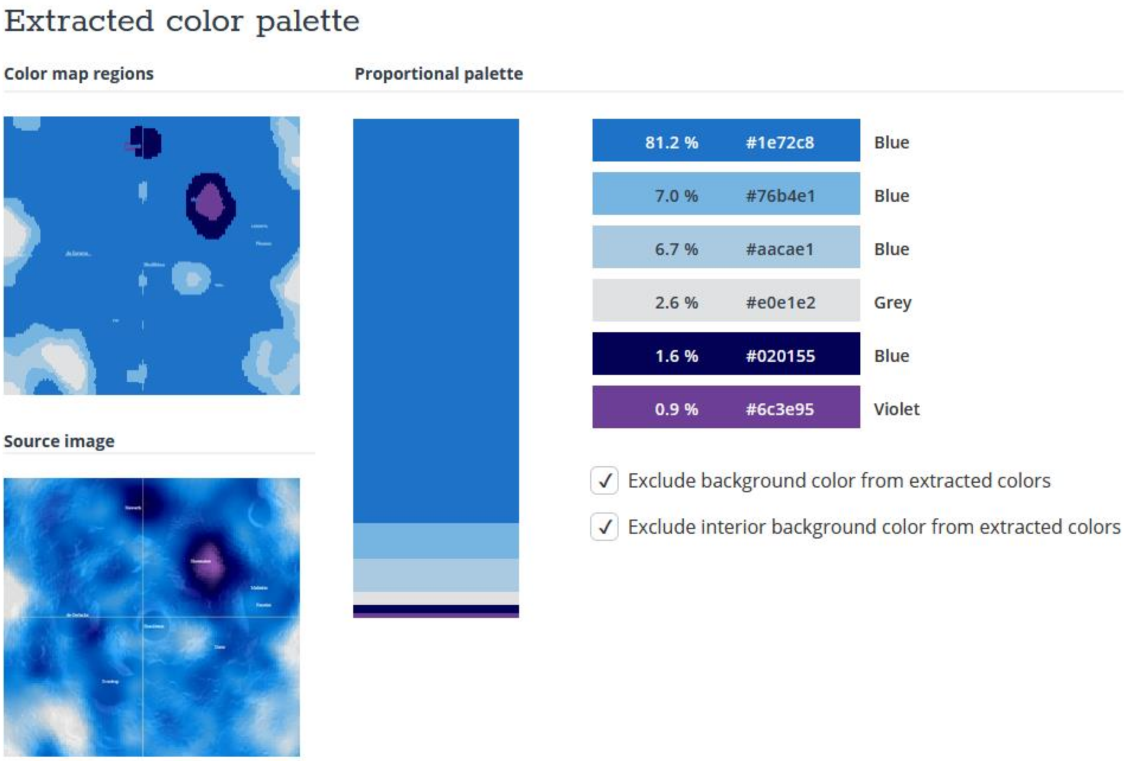


Figure 11. TinEye Color Extraction Results for Polar Water Hydrogen Equivalent at Shackleton's Crater [44]

From the extracted color palette, a proportions table was created which correlated each color proportion to the legend, as shown in Table 6. The weighted average of the site of interest was then calculated.

Table 6. Data for Shackleton's Crater Polar WEH Image Analysis

Site Selection	Water Equivalent Hydrogen (WEH, Weight %)	Color Map Palette Percentage	Fraction Form	Weighted Score
Shackleton's Crater	0.30	81.20	0.8120	0.2436
	0.25	7.00	0.0700	0.0175
	0.15	6.70	0.0670	0.0101
	0.00	2.60	0.0260	0.0000
	0.40	1.60	0.0160	0.0064
	0.45	0.90	0.0090	0.0041
	Totals:	*100.00*	*1.0000*	*0.2816*

The weighted score for each WEH level present in the color image was then combined to yield a total weighted average for Shackleton's crater. This weighted average value was utilized to determine the risk level per the resource classification framework that is elaborated upon in the following sections. In this case, a WEH weighted average of 0.2816 (weight percent, wt. %) was calculated for Shackleton's Crater.

CHAPTER IV:

RESULTS

Availability Parameters

Elemental Abundance is defined by weight percent (parts per million for smaller quantities) and indicates the prevalence of any given element on the lunar surface. From the NASA Planetary Data System, raw datasets for aluminum, calcium, iron, magnesium, oxygen, and titanium were analyzed [32], [34]. The datasets used are from the Lunar Prospector Mission [reported in weight percent, as described by Prettyman et al. (2002) for each element]. For each element, average elemental abundance values for three lunar sites of interest were derived – namely Shackleton's Crater, Clavius Crater, and the South Pole. The longitude and latitude start and end for each of the sites were reported earlier (Table 5). These latitude and longitude ranges coincide with available elemental abundance data, therefore the definitions for each of these sites were selected to ensure that the scope for each site did not expand beyond the bins of data available for each element. Once the bin range (latitude start to latitude end, longitude start to longitude end) were fully defined, the elemental abundance for each element in the site's bin was averaged to arrive at an average weight percent. The final weight percent data is reported in Table 7. Earth's elemental abundance values are also included as reference values.

Table 7. Elemental Abundance Data [33], [34]

Element	Elemental Abbreviation	Earth Weight Percent	South Pole Weight Percent	Shackleton's Crater Weight Percent	Clavius Crater Weight Percent
Aluminum	Al	8.13	14.559	15.151	13.161
Calcium	Ca	3.63	11.956	11.456	10.503
Iron	Fe	5.00	3.771	3.623	4.625
Magnesium	Mg	2.09	3.642	3.517	4.587
Oxygen	O	46.60	45.041	45.289	45.215
Titanium	Ti	< 1	0.150	0.170	0.289
Polar WEH	H_2O	N/A	0.228	0.329	N/A

The elemental abundance values for each element was within +/- 1% across the three selected sites. With this elemental abundance information, it was possible to evaluate each site-element combination with respect to risk rating, according to the proposed resource availability framework. This will be discussed in the next section.

Another important criteria to characterize availability of resources on the moon is polar water equivalent hydrogen (WEH), defined by weight percent (wt. %) and reported as the last line item in Table 7. The South Pole was the primary polar region of study in this investigation. The North Pole was not evaluated. A map layer of the South Pole Water Equivalent Hydrogen (WEH) depicted in Figure 12 is defined from 75 – 90 S Latitude and is "derived from the collimated sensors of the Lunar Reconnaissance Orbiter's Lunar Exploration Neutron Detector (LEND)" and is based upon Sanin et. al.'s translation of the LEND neutron counting rate into WEH abundance [43].

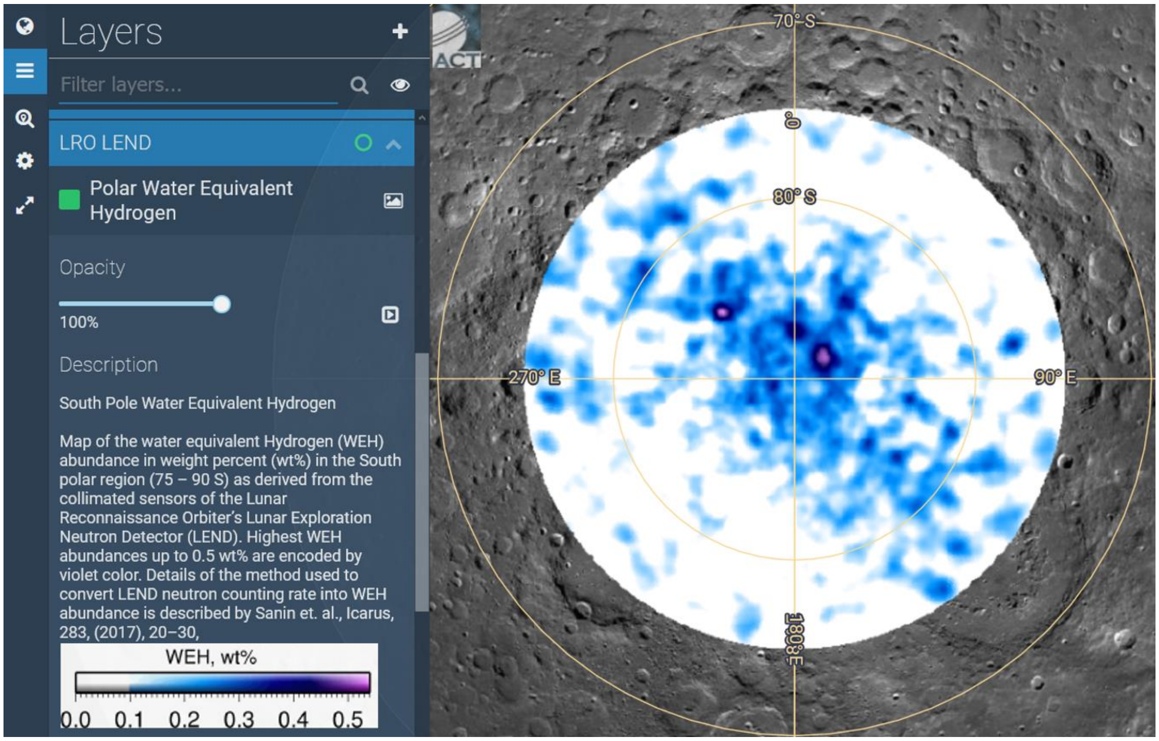


Figure 12. South Pole Water Equivalent Hydrogen with Legend [26], [43]

The rock abundance is another critical availability parameter. It is defined as a comparison of rock fraction to fine grain soil based upon the temperature comparison of lunar rocks compared to lunar regolith [26], [36]. Since rocks retain more heat than regolith overnight, rock abundance can then be characterized by using a heat map on a lunar night. A nearside GIS image of the rock abundance is depicted in Figure 13, while a polar image overlay is depicted in Figure 14.

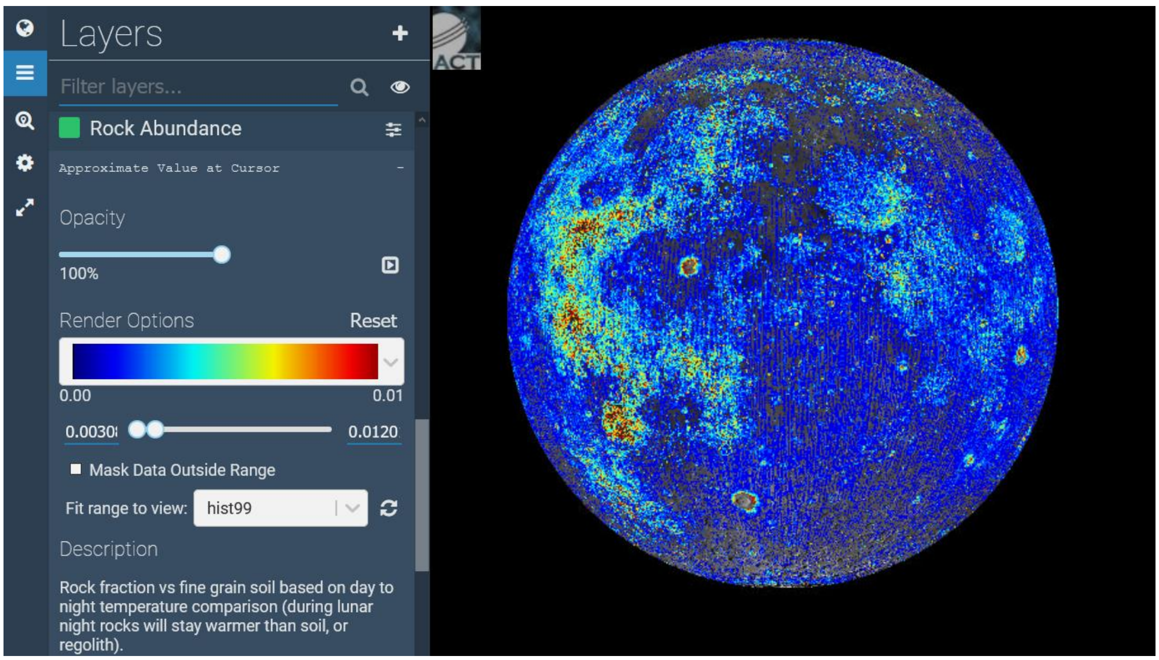


Figure 13. Lunar Rock Abundance with Legend [26], [36]

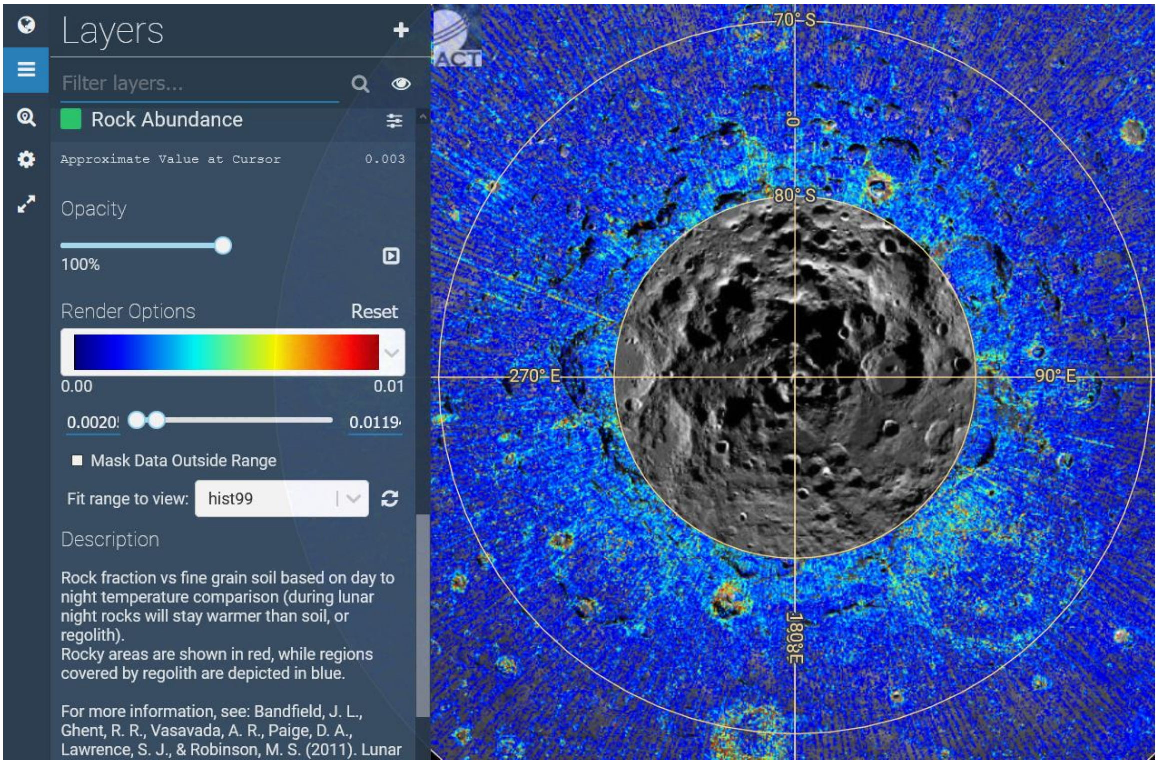


Figure 14. Polar Proximate Rock Abundance with Legend

Due to data availability limitations at the Shackleton's crater site, the closest approximate crater was utilized to approximate the rock abundance and utilize its data for the Shackleton's Crater site. The selected crater, Schomberger A, is shown in Figure 15.

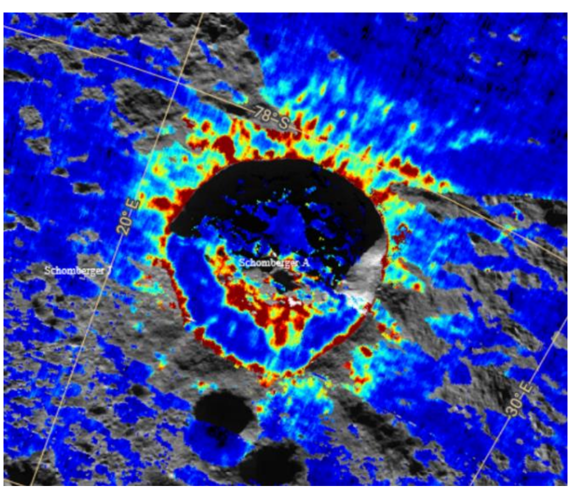


Figure 15. Schomberger A Crater Rock Abundance Map

Availability Metric and Risk Classification

In this section, the proposed resource and risk classification ranges are outlined. All parameters in this section relate to an assessment of the availability of space resources on the lunar surface. The first parameter in Table 8 should look very familiar, as GE's Resource and Risk methodology specifically outlines elemental abundance within the various risk levels.

Table 8. Elemental Abundance Index [19]

Risk Level	Description	Elemental Abundance (Weight %)	Elemental Abundance (ppm)
VERY HIGH	Very Rare	< 0.000001 %	< 0.01
HIGH	Rare	0.000001 – 0.0001%	0.01 – 1
MEDIUM	Less Common	0.0001 – 0.01%	1 – 100
LOW	Common	0.01 – 1	100 – 10,000
VERY LOW	Very Common	> 1 %	> 10,000

The next parameter risk classification range defined was the Polar Water Equivalent Hydrogen Index. In this case, a bin size of 0.1 (weight percent) was established to account for the established ranges reported by Sanin et. al [43]. Qualitative descriptions ranging from *very rare* to *more common* were maintained as in the Elemental Abundance Index.

Table 9. Polar Water Equivalent Hydrogen Index

Risk Level	Description	Polar Water Equivalent Hydrogen (WEH) Range (Weight %)
VERY HIGH	Very Rare	< 0.2
HIGH	Rare	0.2 – 0.3
MEDIUM	Less Common	0.3 – 0.4
LOW	Common	0.4 – 0.5
VERY LOW	More Common	> 0.5

The final parameter for the availability framework is rock abundance. To establish a rock abundance range appropriate for the relative lunar risk profile, the sigma 1, sigma 2, and sigma 3 (histogram 99) ranges were evaluated from the LROC QuickMap tool. Thus, the *medium* level of risk contains the sigma 1 range, while the sigma 2 range range spans *low* to *high* levels of risk. Finally, the sigma 3 range spans from *very low* to *very high*.

Table 10. Rock Abundance Index

Risk Level	Description	Rock Abundance Range
VERY HIGH	Least Abundant	< 0.0002
HIGH	Less Abundant	0.0002 – 0.0026
MEDIUM	Abundant	0.0026 – 0.0074
LOW	More Abundant	0.0074 – 0.0098
VERY LOW	Most Abundant	> 0.098

Availability for Selected Sites

After conducting an image analysis for each of the three selected sites, the risk profiles were determined for each data-driven availability parameter. The results are shown in Table 11.

Table 11. Recoverability Indices for Selected Sites

Location	Elemental Abundance in Crust	Polar Water Equivalent Hydrogen	Rock Abundance
South Pole *Centered (0, -90)*		**4**	**3**
Data Result	Varies by Element	0.2275	0.0055
Shackleton's Crater *Centered (0, -90)*		**3**	**3**
Data Result	Varies by Element	0.3288	0.0055
Clavius Crater *Centered (58.4, 14.4)*			**4**
Data Result	Varies by Element	N/A	0.0019

Recoverability Parameters

Another metric essential to classifying space resources is recoverability. Recoverability is concerned with the ease of obtaining the resource from its present environment and state. To characterize recoverability, it was determined that that the elemental, mineral, and rock properties data would best characterize the existing recoverability range of a specific resource. The environmental factors relevant to characterizing recoverability include the lowest expected soil temperatures (or the polar minimum temperatures) and the actual rock mass stability (or ice stability). The lowest expected (winter, nighttime) temperatures should pose the highest challenge to extraction technology, while low rock stability or ice stability will pose challenges for resource extraction equipment.

Soil temperature and polar minimum temperature data from the LRO DIVINER experiment was available via the LROC QuickMap tool. The nighttime soil temperature is available for nearside/farside regions and excludes polar data. To cover the polar temperature data, the worst-case polar winter minimum temperature data can be used for polar sites of interest. This temperature classification is important especially to classify the harshest lower bounds of moon temperatures, which are more likely to pose challenges for resource recovery technology (especially in permanetly shadowed regions or during lunar night operations). Additionally, mineral tenacity fluxuates with temperature since material stress changes with respect to temperature; as temperature increases, materials trend towards having more ductile response to stress, whereas colder temperatures cause materials to trend towards a brittle response to stress [33]. One important note is that for nighttime soil temperatures, these will apply for a longer duration depending on fluxations in what percentage of the moon is sunlit.

Nighttime soil temperatures were explored using the QuickMap tool, for which a lunar GIS image is depicted in Figure 16.

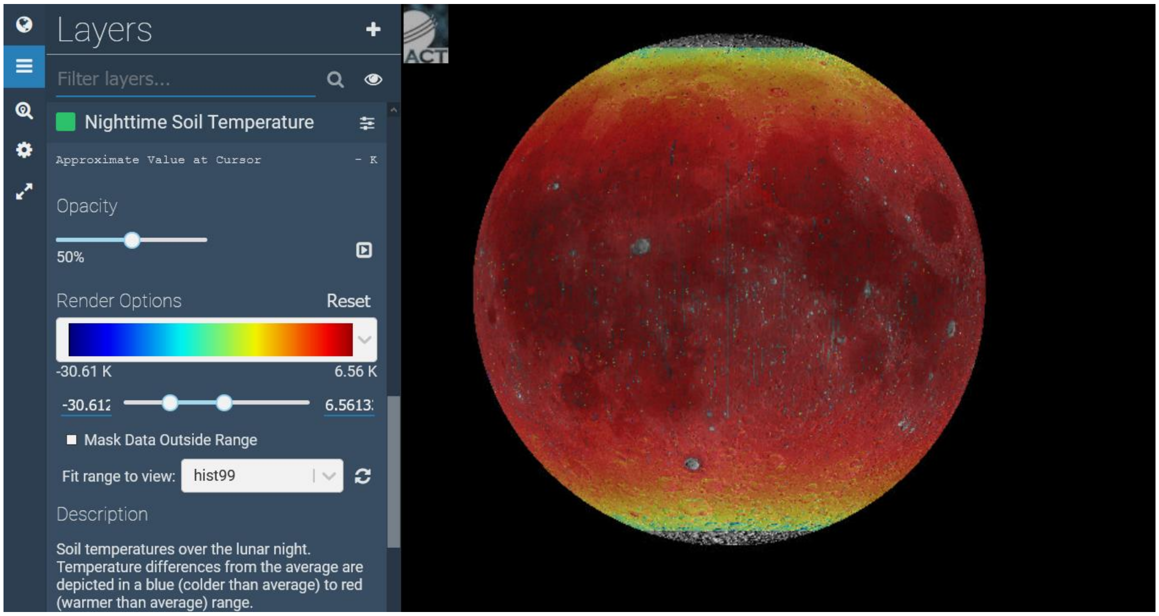


Figure 16. Nighttime Soil Temperatures with Legend [26], [36]

The nightime soil temperature data was not defined for polar sites, thus the winter minimum temperatures was used as a replacement. The South Pole winter minimum temperature is shown in Figure 17.

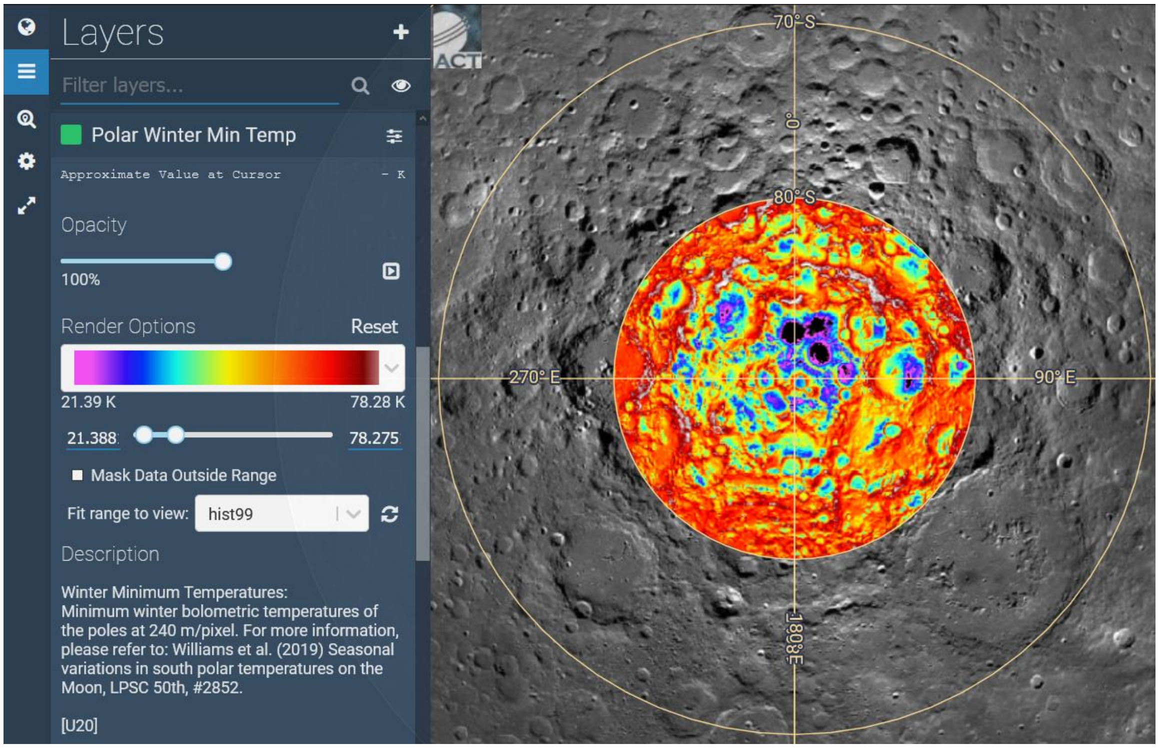


Figure 17. Polar Winter Minimum Temperatures with Legend [26], [45]

Ice stability data was available for the polar regions of the moon and are defined as ice stability depth in meters. This parameter is important from a recoverability perspectice, as greater ice stability depth indicates greater available ice depth for extracton and use. The ice stability GIS image for the South Pole is depicted in Figure 18.

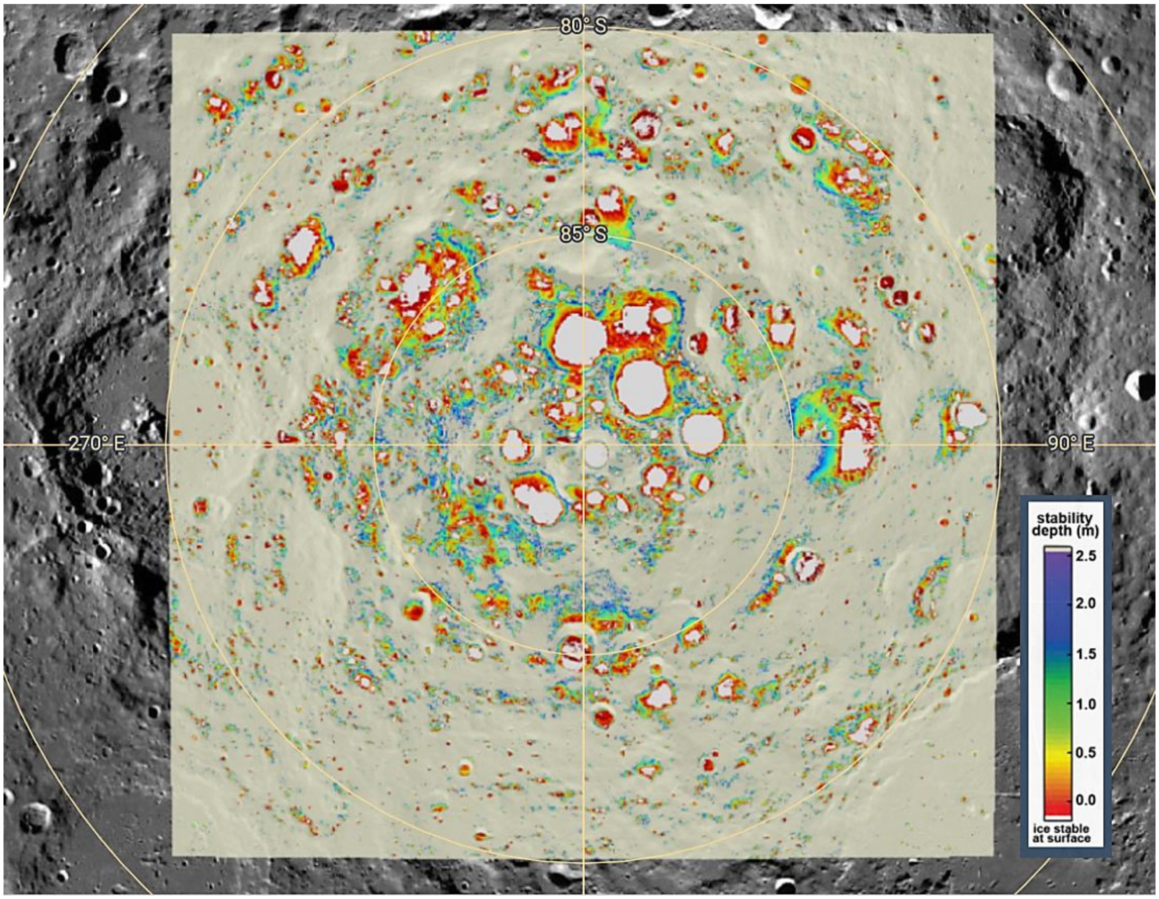


Figure 18. South Pole Ice Stability Depth with Legend [26], [46]

In terms of rock properties, the mineral hardness and tenacity will determine the recoverability of a resource. Mineral hardness can be described by Moh's Scale of Hardness, which is essentially an assessment of its internal bond strength of a mineral [33]. Mineral tenacity is also related to bond strength and characterizes how a mineral reacts (breaking or deforming) to stresses such as crushing, bending, breaking, or tearing which leads to a tenacity classification of brittle, ductile, malleable, sectile, flexible, or elastic [33].

Given these recoverability variables, rock properties data was collected for each element of interest on the Moon. The data for each element studied in this investigation are reported in Table 12.

Table 12. Rock Properties Data [33], [47]

Element	Elemental Abbreviation	Occurs in:	Chemical Formula	Absolute Hardness	Mineral Tenacity
Aluminum	Al	Anorthite [An]	$CaAl_2Si_2O_8$	6	Brittle
Calcium	Ca	Anorthite [An]	$CaAl_2Si_2O_8$	6	Brittle
Iron	Fe	Pyroxene Olivine [Ol] Ilmenite [Ilm]	$X_2Si_2O_6$ $((Mg, Fe)_2SiO_4)$ $FeTiO_3$	5.0 – 6.0 6.8 5.0 – 6.0	Brittle
Magnesium	Mg	Pyroxene Olivine [Ol]	$X_2Si_2O_6$ $((Mg, Fe)_2SiO_4)$	5.0 – 6.0 6.8	Brittle
Oxygen	O	Iron Oxide (Lunar Regolith)	FeO	5 – 5.5	Brittle
Titanium	Ti	Ilmenite [Ilm]	$FeTiO_3$	5.0 – 6.0	Brittle
Water	H_2O	Water Ice	H_2O	1.5	Brittle

Elements rarely exist in pure form on the moon and instead are found in specific minerals, therefore it was important to document the minerals in which elements are likely to be found. Determining the most common minerals served two purposes: first, to document the likely origin of elements for in-situ resource utilization (ISRU) activities relating to extracting a specific element, and second, to determine the rock properties of a specific mineral. After obtaining mineral classifications, it was possible to determine the hardness of a mineral (per Moh's Scale of Hardness) and the mineral tenacity of the mineral. In the case of all elements above, the mineral tenacity is brittle, which indicates the mineral is easy to break into fragments when hammered/crushed [33] . While this recoverability parameter is constant for the entire data set under consideration in this investigation, in future investigations of other resources it may vary. Thus, the mineral tenacity is an important parameter to consider in future investigations of resourece extraction and processing.

The final recoverability parameter is rock mass stability, for which no current data was available. There are some ongoing investigations of lunar regolith characteristics, ice characteristics, and even crater manuvering technologies, however these do not characterize rock mass stability according to the standards defned in Chapter 12 of Part 631 in the National Engineering Handbook for rock material field classifications. Rock mass stability will need to be defined at a later date. However, it is possible to ascertain a mission resource risk profile based on a user input to a rock mass stability parameter. Therefore, rock mass stability is included in the final recoverability assessment, although it is currently a user input and not a mission data-driven parameter.

Recoverability Metric and Risk Classification

Temperature impacts the recoverability of a resource, while also impacting the operations of extraction technologies. To capture the impact of temperature on recoverability, a nighttime soil temperature index was developed along with a polar winter temperature range. Both recoverability parameters are captured in Table 13 and Table 14, however neither dataset covered the entire moon. Thus, both parameters are used in combination here to cover both the polar winter minimum temperatures and the typical nighttime soil temperatures on the nearside of the moon. Nighttime soil temperatures from the dataset are reported as a deviation from the global average, where negative values are colder than average and positive values are warmer than average [26], [36].

Table 13. Nighttime Soil Temperature Index

Risk Level	Temperature Deviation Classification	Nighttime Soil Temperature (Deviation from Average)
VERY HIGH	Significantly Lower than Average	< -49.8 K
HIGH	Lower than Average	-49.8 K to -19.3 K
MEDIUM	Average	-19.3 K to 11.2 K
LOW	Higher than Average	11.2 K to 21.4 K
VERY LOW	Significantly Higher than Average	> 21.4 K

Table 14. Polar Winter Minimum Temperature Index

Risk Level	Temperature Classification	Polar Winter Temperature Range
VERY HIGH	Extremely Low	< 41.02 K
HIGH	Very Low	41.02 to 74.30 K
MEDIUM	Low	74.30 to 140.85 K
LOW	Moderately Low	140.85 to 172.84 K
VERY LOW	Moderate	> 172.84 K

As shown in Table 13 and Table 14 above, it is clear that the worst-case polar winter minimum temperature index is lower than the nighttime soil temperature of other regions. This allows for each unique region to be defined according to its local dataset when determining a temperature risk factor that contributes to the overall recoverability metric. Thus, for a polar site of interest, the polar winter minimum temperature index should be used as the primary benchmark for the temperature risk factor. Conversely, for non-polar sites, the nighttime soil temperature index is a better benchmark when determining the temperature risk index.

The GE resource classification approach lists access as a potential indicator for sustainability. The NRCS National Engineering Handbook characterizes excavatability of earth materials on the basis of an earth material ripping index. Given that much of the lunar surface will be excavated to some extent and that the only variation will be the power required to excavate a given material, it is appropriate then to define a material ripping index and risk profile for space resources also. Table 15 demonstrates the material ripping index proposed for lunar resources.

Table 15. Excavatability Index [20]

Risk Level	NEH Rock Material Field Classification System Class	Ripping Index (Excavatability)	Excavated Material Hardness	Ripping Index (Kn) or Headcut Erodability Index (Kh)	Seismic Velocity (ft/s)	Equipment needed for excavation (hp)
VERY HIGH	Class III	> Very Hard Ripping to Blasting	Very hard rock to Extremely hard rock	> 10,000 1000 – 10000	> 8,000	> 350
HIGH	Class II	Hard Ripping	Moderately hard rock through hard rock	100 – 1000	7000 – 8000	> 250
MEDIUM	Class I	Easy Ripping	Soft through moderately soft rock	1.0 – 10	5000 – 7000	> 150
LOW	—	Power Tools	Stiff cohesive soil or dense cohesion-less soil throughvery soft rock orhard, rock-like material	0.10 – 1.0	2000 – 5000	> 100
VERY LOW	—	Hand Tools	Very soft through firm cohesive soilor very loose through medium dense cohesionless soil	< 0.10	< 2000	—

The material ripping index is a user-entered argument that impacts the recoverability score of a material. The class categories (Class I-III) are derived directly from the Chapter 12 of Part 631 of the National Engineering Handbook (NEH), which defines the excavatability field classifications of rock materials [20]. The material ripping index is derived from the NEH definitions, and accounts for the excavatability of a metric. Allowing a user to define their intended extracton method is the best approach, as this enables a focused assessment of this factor for a particular risk profile.

The rock mass stability at the surface is also of concern when assessing the recoverability of rock material. Rock mass stability is a common geotechnical classification and therefore it is relevant to pull all related geotechnical metrics to guide future resource classification approaches. Although rock mass is clearly related to rock masses and not soils (or lunar regolith), in areas where more rocky features prevail on the moon the rock mass stability classification is applicable. The rock mass stability index proposed in Table 16, is derived from the NRCS Part 631 Engineering Geology Handbook and captures the NEH rock material class, the rock mass strength, the rock hardness, rock quality designation, number of joint sets in the rock mass, and a stability description. These are correlated to 3 levels of risk: very low (1), medium (3), or very high (5). The intermediate risk levels of (2) and (4) are not currently defined, however as more distinct data on space resources becomes available this risk classification could expand to allow for more granularity.

Table 16. Rock Mass Stability Index [20]

Risk Level	NEH Rock Material Field Classification System Class	Rock Mass Strength	Rock Hardness	Rock Quality Designation (ASTM D6302/D6032)	Number of Joint Sets in Rock Mass (include bedding plane partings)	Index Description
VERY HIGH	Class III: Unstable	< 12.5 MPa	Moderately soft to very soft rock	< 25	> 3 interconnecting joing sets; and at least 1 set contans adverse component of dip	Rock material has significant potential for instability. All conditions met.
MEDIUM	Class II: Potentially Unstable	12.5 - 50 MPa	Moderately hard rock	25 – 75	< 2 joint sets plus random fractures; no set contains adverse component of dip	Rock material has potenial for instability. At least one condition met.
VERY LOW	Class I: Stable	> 50 MPa	Hard to extremely hard rock	> 75	1 joint set and random fractures, or rock mass intact and massivel no adverse component of dip	Rock material has very low potential for instability. At least one condition met.

The next classification of interest is ice stability depth for areas where water ice exists, where this index is the "depth at which water ice will sublimate at a rate of 1 mmGyr^{-1}" as defined by Siegler et. all (2016) [46]. The Ice Stability Depth focuses on risk based upon ice stability depth, while also assigning a qualitative classification as shown in Table 17. Bin sizes of 0.5 m depth are defined for all risk levels, except for the MEDIUM (Potentially Unstable) category, which spans a 1.0 m – 2.0 m range.

Table 17. Ice Stability Depth Index

Risk Level	Classification	Ice Stability Depth
VERY HIGH	Very Unstable	< 0.5 m
HIGH	Unstable	0.5 – 1.0 m
MEDIUM	Potentially Unstable	1.0 m – 2.0 m
LOW	Stable	2.0 – 2.5 m
VERY LOW	Very Stable	> 2.5 m

Moh’s scale of hardness is a standard mineral classification approach that is relevant to calculating the recoverability of a resource. As hardness increases, the difficulty of obtaining or recovering the bulk resource will increase. Therefore, the established Moh’s Scale of Hardness is captured in Table 18 and mapped to specific risk levels.

Table 18. Rock Hardness Index (Moh's Scale of Hardness) [33]

Risk Level	Moh's Scale of Hardness Value	Index Description	Reference Mineral
VERY HIGH	8, 9, 10	Scratches glass very easily (8), cuts glass (9), or used as a glass cutter (10).	Topaz (8), Corundim (9), Diamond (10)
HIGH	6, 7	Cannot be scratched with a knife (6), but scratches glass, or scratches glass easily (7)	Orthoclase (6), Quartz (7)
MEDIUM	4, 5	Easily scratched with a knife but not as easily as calcite (4), scratched with a knife, with difficulty (5)	Fluorite (4), Apatite (5)
LOW	2, 3	Can be scratched by the fingernail (2), very easily scratched with a knife and just scratched by a copper coin (3)	Gypsum (2), Calcite (3)
VERY LOW	1	Very easily scratched by a fingernail; has a greasy feel (1)	Talc (1)

Recoverability for Selected Sites

After conducting an image analysis for each of the three selected sites to determine the weighted score for each parameter, the risk profiles were determined for each data-driven recoverability parameter. The results are shown in Table 19.

Table 19. Recoverability Indices for Selected Sites

Location	Temperature	Rock Mass or Ice Stability	Rock Hardness	Mineral Tenacity
South Pole *Centered (0, -90)*	3	4	3	1
Data Result	116.76	0.5428	5.6	Brittle
Shackleton's Crater *Centered (0, -90)*	3	4	3	1
Data Result	111.79	0.6611	5.6	Brittle
Clavius Crater *Centered (58.4, 14.4)*	3		3	1
Data Result	-5.49	User Input	5.6	Brittle

Accessibility Parameters

Accessibility is a key factor when determining the long-term sustainability of a space resource economy. *How accessible is the resource?* This is a question that frequently limits terrestrial use of petroleum and mineral resources, and thus is a relevant question for space resources. To classify resources, the most critical parameters included geologic features of a site, surface roughness, surface slope, and absolute elevation change. To characterize geologic features, the USGS Unified Geologic Map of the Moon (released in 2020) was utilized. This map was rich with information about various moon landscaping features, ranging from craters to ridges, flat floors to smooth plains, and grooves to sinuous ridges. A nearside view of this map is depicted in Figure 19, while the South Pole view is depicted in Figure 20.

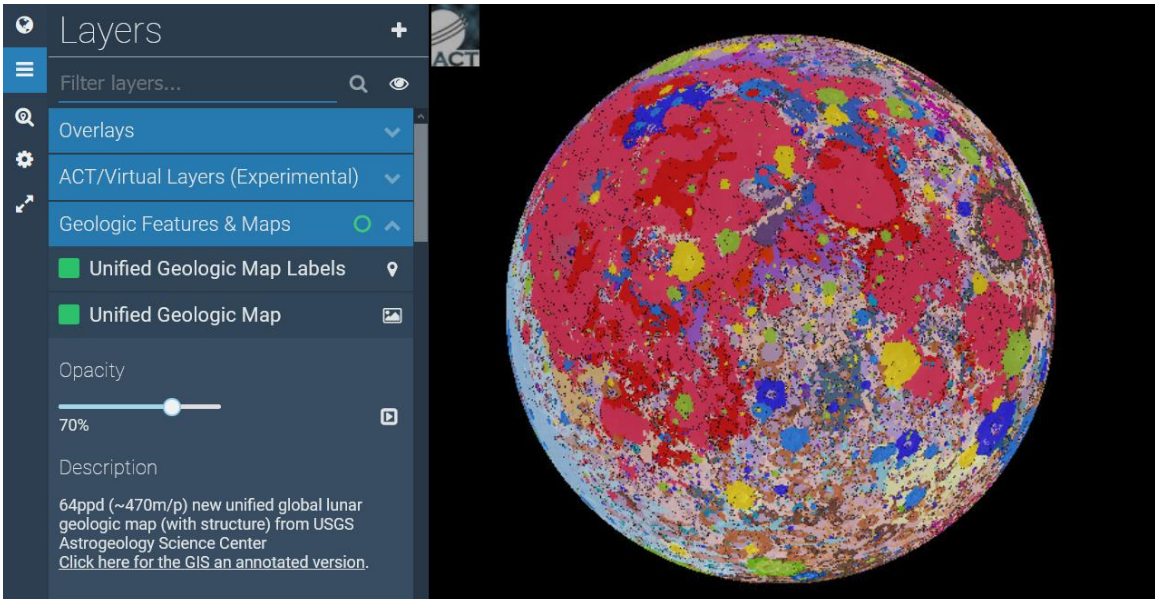


Figure 19. Nearside Unified Geologic Map of the Moon [25], [26]

Figure 20. South Pole Unified Geologic Map [25], [26]

These Unified Geologic Map features were classified into accessibility risk profiles and were comprised of 49 distinct geologic codes. These codes are reported below, in Figure 21. Additionally, the long form descriptions for all 49 codes are included in Appendix A.

Figure 21. Unified Geologic Map Regions of the Moon

The remaining three parameters of surface roughness, slope, and absolute elevation were derived from the GIS Lunar QuickMap tool. Surface roughness was defined by the LRO LOLA instrument at 100m scale as a map layer in the GIS tool. The data and GIS images from the tool are based on mission phase LRO_SM_17 [26], [38]. The range for a nearside projection of the QuickMap tool is depicted in Figure 22.

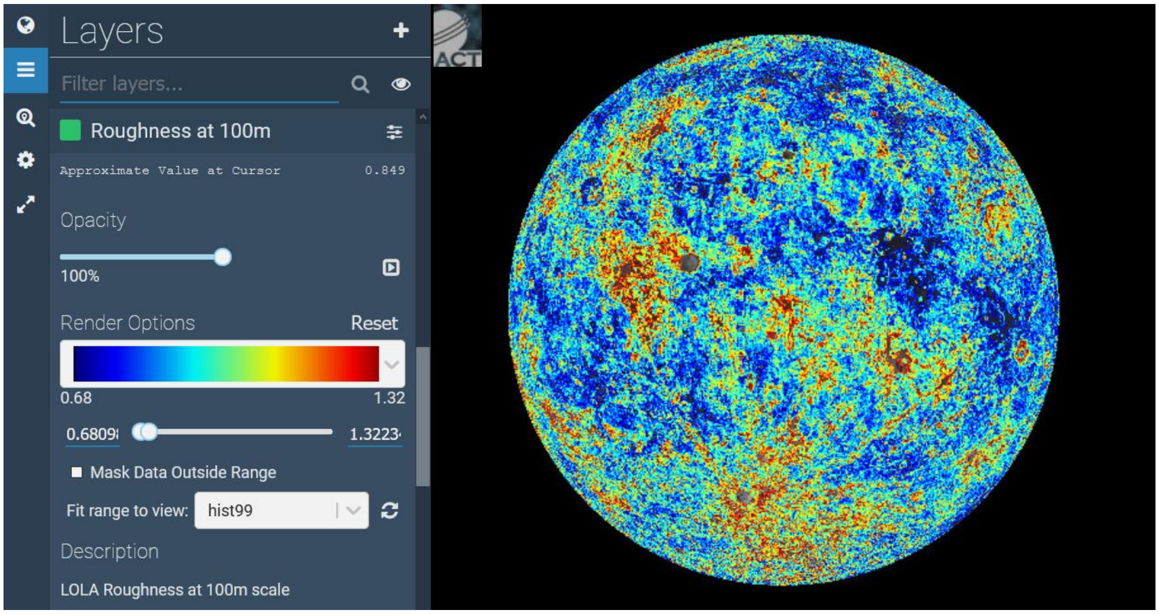


Figure 22. LOLA Surface Roughness at 100m scale with Legend [26], [38]

Surface slope data was also captured by the LRO LOLA instrument. The "LOLA Slope at 100m scale" depicts the roughness of the moon per the mission phase LRO_SM_17 dataset [38].

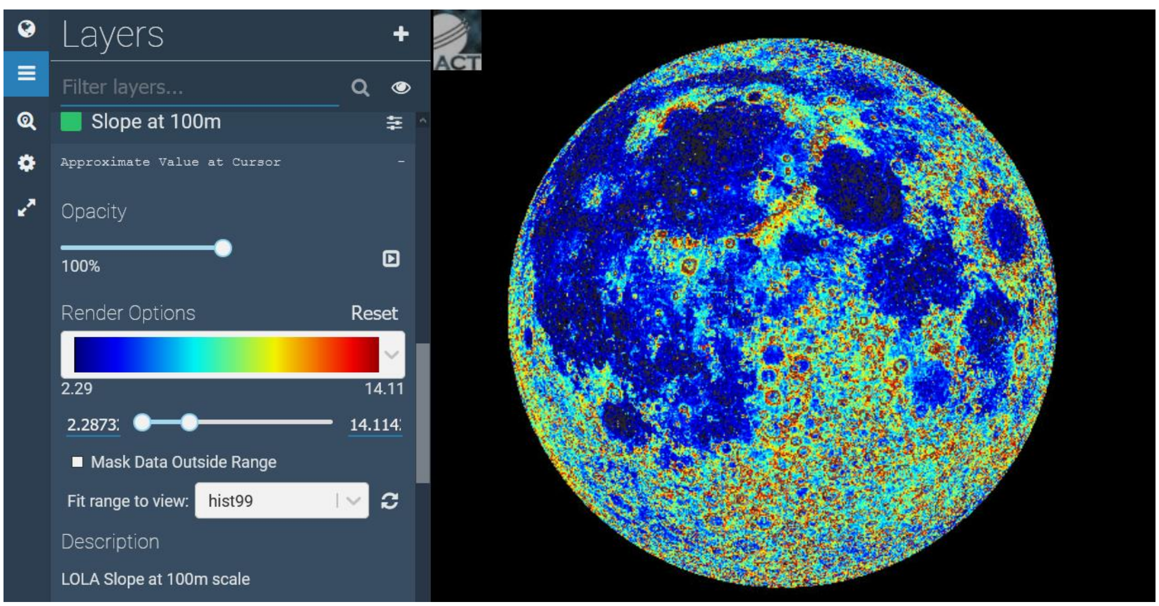


Figure 23. LOLA Slope at 100m with Legend [26], [38]

The final accessibility parameter is elevation change. From the GLD100 and LOLA mission data, a global Digital Terrain Map (DTM) is available on the QuickMap tool. From this DTM, we can determine the elevation variations on the moon.

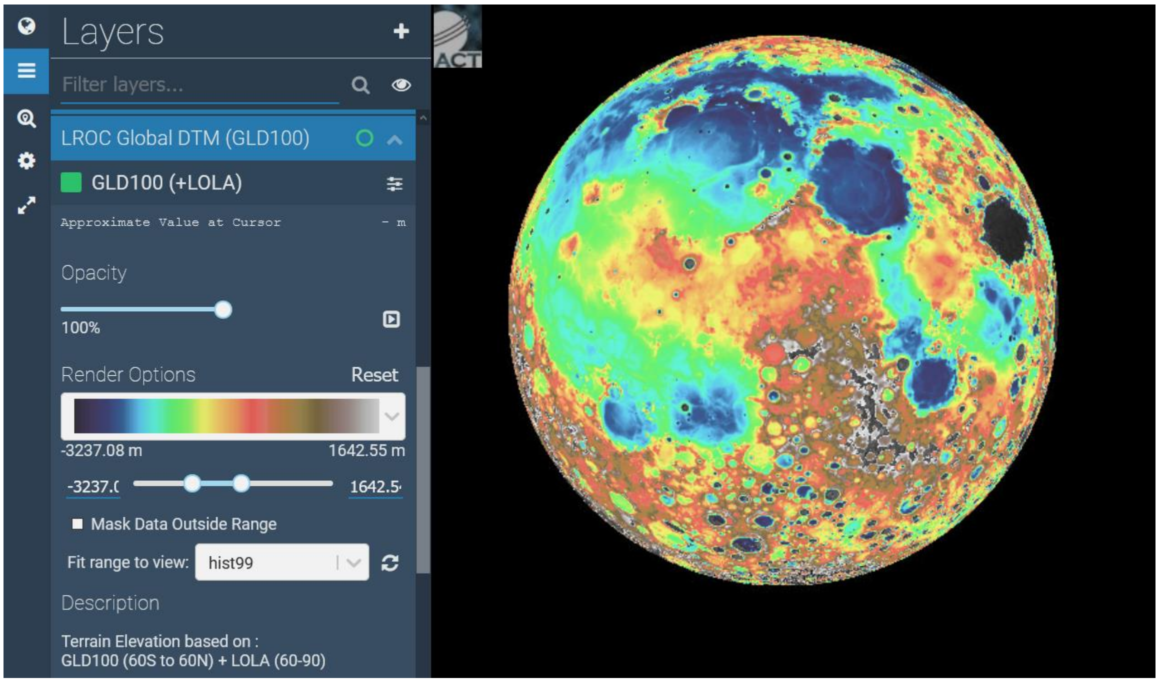


Figure 24. GLD100 (+LOLA) Digital Terrain Map with Legend [26], [38], [39]

Accessibility Metric and Risk Classification

Accessibility is the third metric of concern and characterizes ease of access to a selected region or mission site. The key here was to compute a composite score that would indicate how accessible a region of interest is. The best approach to defining a Geologic Features Index that accounts for relative risk was to evaluate the long-form qualitative descriptions that accompanied the USGS Unified Geologic Map of the Moon. These long form descriptions are included in APPENDIX A. Each map code was categorized depending on specific keywords associated with *low* to *very high* risk levels. A visual assessment of a full-size USGS Unified Geologic Map of the Moon was also conducted for each map code. The final classification framework corresponding to each map code and classification is shown in Table 20.

Table 20. Geologic Feature Index – Unified Geologic Map Codes

Risk Level	Geologic Features	Unified Geologic Map Code	Keywords
VERY HIGH	Very Complex	Cc, Csc, Ec, Isc, Ibm, Iia, Iiap, Iic, Iif, Iork, Nbl, Nbm, pNt	Densely packed craters; rugged blocks; sinuous ridges; rolling and chaotic materials; sharp raised edges
HIGH	Complex	Elp, Ic, Ic1, Ib, Ip, INp	Deeply sloping; intensely fractured plains; clusters of overlapping depressions
MEDIUM	Moderately Complex	Ccc, Ic2, Icc, Icf, Id, Ig, Im2, Iohi, Ioho, Ios, Iorm, Int, Nb, Nt, Ntp, pNb, pNc	Radial grooves on rims and walls (craters); flat; smooth surfaces, numerous ridges
LOW	Moderate	Ecc, Esc, Em, Im1m Imd, Iom, Nbsc, pNbm	Broad flat floors; gently rolling to hilly terrain; smooth, flat; moderate surface to high density of superposed craters
VERY LOW	Simple	It, Itd, Nc, Nnj, Np, Np	Smooth inner flanks; muted topographic relief; rolling subdued terrain; generally flat

To establish a surface slope range appropriate for the relative lunar risk profile, the sigma 1, sigma 2, and sigma 3 (histogram 99) ranges were evaluated from the Lunar QuickMap tool. Thus, the *medium* level of risk contains the sigma 1 range, while the sigma 2 range spans *low* to *high* levels of risk. Finally, the sigma 3 range spans from *very low* to *very high*. Table 21 depicts the surface slope index for risk classification.

Table 21. Surface Slope Index

Risk Level	Description	Surface Slope Range
VERY HIGH	Steep Grade	> 17.27
HIGH	Moderately Steep Grade	13.17 – 17.27
MEDIUM	Moderate Grade	4.99 – 13.17
LOW	Low Grade	2.72 – 4.99
VERY LOW	Flat Grade	< 2.72

To establish a rock abundance range appropriate for the relative lunar risk profile, the sigma 1, sigma 2, and sigma 3 ranges were evaluated from the Lunar QuickMap tool. Thus, the *medium* level of risk contains the sigma 1 range, while the sigma 2 range spans *low* to *high* levels of risk. Finally, the sigma 3 range spans from *very low* to *very high*.

Table 22. Surface Roughness Index

Risk Level	Description	Surface Roughness Range
VERY HIGH	Very high sinuosity	> 1.309
HIGH	High sinuosity	1.122 – 1.309
MEDIUM	Medium sinuosity	0.749 – 1.122
LOW	Low sinuosity	0.562 – 0.749
VERY LOW	Very low sinuosity	< 0.562

To characterize the Elevation Change Index, GIS images and statistical information from the GLD100 + LOLA High Resolution Lunar topography was utilized. The color bins ranged from less than 500 m up to 4000 m [39]. Since these data bins could be evenly distributed, the bins were defined using both a quantitative and qualitative approach.

Table 23. Elevation Change Index

Risk Level	Elevation Change Description	Elevation Range
VERY HIGH	Severe Elevation Changes	> 4000 m
HIGH	Significant Elevation Changes	2000 – 4000 m
MEDIUM	Moderate Elevation Changes	1000 – 2000 m
LOW	Elevation Changes Present	500 – 1000 m
VERY LOW	Elevation Changes Present but not Severe	< 500 m

Accesibility for Selected Sites

After conducting an image analysis for each of the three selected sites and calculating the weighted average of each parameter, the risk profiles were determined for each data-driven accessibility parameter. The results are shown in Table 24.

Table 24. Accessibility Indices for Selected Sites

Location	Geologic Features	Surface Slope	Surface Roughness	Absolute Elevation Change
South Pole *Centered (0, -90)*	**3**	**3**	**5**	**3**
Data Result	2.91	7.9769	1.042	1129.24
Shackleton's Crater *Centered (0, -90)*	**3**	**3**	**4**	**3**
Data Result	2.85	7.5958	0.9242	1208.6
Clavius Crater *Centered (58.4, 14.4)*	**4**	**3**	**1**	**1**
Data Result	3.98	7.1056	0.0067	102.73

Metrics are computed and required for space systems engineering project and range from reliability to availability to maintainability. The metrics most relevant to the classification of planetary resources were availability, recoverability, and accessibility. The following section captures the inputs to each mission metric, to supplement the descriptions in the preceding sections, while elaborating on the rationale for the MATLAB application introduced in a later section.

Overall Sustainability Metric and Risk Classification

Determining the availability, recoverability, and accessibility of a selected site provides mission metrics that are focused on the surface of the moon. The sustainability composite score is concerned with humanity's plans for the surface of the moon. In this case, it becomes relevant to pull in human inputs, such as drilling tools in use, extraction rate, usage rate, and depletion rate. The sustainability score accounts for availability, recoverability, and accessibility, but must also account for specific mission constraints such as surface disruption (surface contact type), extraction method (tool in use), and total projected depletion rate of a resource (generational availability).

The depletion rate is an important addition to the sustainability metric, as overall resource availability corresponds to proven reserves, extraction rate indicates extracted and obtained reserves, which must be updated as they are depleted through a usage rate, also known as production. Thus, sustainability is calculated as a weighted average of availability, recoverability, and accessibility (each with a 1/5 scale factor, totaling 3/5), and the remaining (2/5) scale factor is distributed over surface disruption, extraction method, and total depletion rate.

There are two remaining risk classification tables that must be discussed to complete the sustainability assessment. The first is the surface disruption index. This will account for the preservation of pristine space environments by assigning a risk level to the degree of disruption caused by a specific category of surface prospecting. The table is captured in Table 25. In the case of severe, widespread excavation – the kind that would cause permanent, aesthetic changes to the moon – a risk level of VERY HIGH (5) is assigned. The risk severity decreases as surface impacts to pristine lunar real estate decreases; thus, a VERY LOW (1) risk score applies for resource prospecting via remote sensing and other contactless technologies.

Table 25. Surface Disruption Index

Risk Level	Surface Disruption	Disruption Extent
VERY HIGH	Surface Prospecting (contact, extensive excavation)	Severe, widespread excavation
HIGH	Surface Prospecting (contact, widespread rovers)	Moderate local excavation, widespread roving beyond local site
MEDIUM	Surface Prospecting (contact, local rovers)	Limited local excavation, local surface prospecting
LOW	Surface Prospecting (contact, crew)	Crew field investigations, local surveys
VERY LOW	Surface Prospecting (contactless, satellites, hovercraft)	Satellite surveying and remote sensing by contactless technologies

Finally, a risk classification was developed to account for the depletion rate, which is calculated using user-defined parameters of total availability, extracted percentages, and usage percentage. The classification table for depletion rate is shown in Table 26 and was classified on the basis of how many generations will pass before the resource is fully depleted. In this framework, one generation is defined as 25 years. The fewer the generations before depletion, the greater risk.

Table 26. Generational Depletion Index

Risk Level	Depletion Description	Generational Resource Depletion Rate
VERY HIGH	More than 15% depleted in 1 generation; fully depleted in less than 6 generations	> 15 %
HIGH	10 – 5% depleted in 1 generation; fully depleted in 6 – 10 generations	10 – 15%
MEDIUM	5 – 10% depleted in 1 generation; fully depleted in 10 – 20 generations	5 – 10%
LOW	1 – 5% depleted in 1 generation; fully depleted in 20 – 100 generations	1 – 5%
VERY LOW	Less than 1% depleted in 1 generation; fully depleted in more than 100 generations	< 1%

The surface disruption index and generational depletion index risk indices provide a quantitative mechanism with which to characterize sustainability based upon a defined mission profile.

Overall Sustainability for Selected Sites

The Mission Risk Profiles are generated as a component of the planetary sustainability framework. The risk profiles shown below are obtained from a MATLAB mission scenario with simulated user mission inputs (reference Table 27). A worst-case generational depletion rate (risk score 5) and surface disruption factor (risk score 5) is assumed in the scenario below to calculate an overall sustainability risk.

Table 27. Overall Mission Metrics for Lunar Sites of Interest

Location	Availability Risk	Recoverability Risk	Accessibility Risk	Sustainability Risk
South Pole ***Centered (0, -90)***	**3**	**3**	**4**	**3**
Shackleton's Crater ***Centered (0, -90)***	**2**	**5**	**3**	**4**
Clavius Crater ***Centered (58.4, 14.4)***	**2**	**3**	**2**	**3**

When cross-referencing the results with geologic maps and lunar GIS images for the three surveyed sites, the results make sense. Shackleton's Crater has the most severe topography and would likely require the most surface disruption (sustainability metric) and the most involved extraction technology (recoverability). Comparatively, the Clavius Crater has much more subtle topography and is much more accessible due to its larger diameter as crater. Finally, the South Pole is simply a larger slice of region surrounding Shackleton'c Crater. It is plausible that the risks for the South Pole are in-between the ranges seen for Shackleton and Clavius Craters. These results are feasible and demonstrate how the planetary resource classifications could be conducted for upcoming and future space missions based upon the composite availability, recoverability, and accessibility frameworks can be used to classify overall sustainability.

The composite frameworks for availability, recoverability, and accessibility are captured in the following tables: Table 28, Table 29, Table 30, and Table 31.

Table 28. Final Accessibility Framework

Risk Level	Elemental Abundance (Weight %)	Elemental Abundance (ppm)	Polar WEH Range (Weight %)	Rock Abundance Range
VERY HIGH	< 0.000001 % Very Rare	< 0.01 Very Rare	< 0.2 Very Rare	< 0.0002 Least Abundant
HIGH	0.000001 – 0.0001% Rare	0.01 – 1 Rare	0.2 – 0.3 Rare	0.0002 – 0.0026 Less Abundant
MEDIUM	0.0001 – 0.01% Less Common	1 – 100 Less Common	0.3 – 0.4 Less Common	0.0026 – 0.0074 Abundant
LOW	0.01 – 1 Common	100 – 10,000 Common	0.4 – 0.5 Common	0.0074 – 0.0098 More Abundant
VERY LOW	> 1 % Very Common	> 10,000 Very Common	> 0.5 Very Common	> 0.098 Most Abundant

Table 29. Final Recoverability Framework – Part 1

Risk Level	Nighttime Soil Temperature (Deviation from Average)	Polar Winter Temperature Range	Ice Stability Index	NEH Rock Material Field Classification System Class	Ripping Index (Excavatability)	Excavated Material Hardness	Ripping Index (Kn) or Headcut Erodability Index (Kh)	Seismic Velocity (ft/s)	Equipment needed for excavation (hp)
VERY HIGH	< -49.8 K Significantly Lower than Average	< 41.02 K Extremely Low	< 0.5 m Very Unstable	Class III	> Very Hard Ripping to Blasting	Very hard rock to Extremely hard rock	> 10,000 1000 – 10000	> 8,000	> 350
HIGH	-49.8 K to -19.3 K Lower than Average	41.02 to 74.30 K Very Low	0.5 m – 1.0 m Unstable	Class II	Hard Ripping	Moderately hard rock through hard rock	100 – 1000	7000 – 8000	> 250
MEDIUM	-19.3 K to 11.2 K Average	74.30 to 140.85 K Low	1.0 m – 2.0 m Potentially Unstable	Class I	Easy Ripping	Soft through moderately soft rock	1.0 – 10	5000 – 7000	> 150
LOW	11.2 K to 21.4 K Higher than Average	140.85 to 172.84 K Moderately Low	2.0 m – 2.5 m Stable	—	Power Tools	Stiff cohesive soil or dense cohesion-less soil throughvery soft rock orhard, rock-like material	0.10 – 1.0	2000 – 5000	> 100
VERY LOW	> 21.4 K Significantly Higher than Average	> 172.84 K Moderate	>2.5 m Very Stable	—	Hand Tools	Very soft through firm cohesive soilor very loose through medium dense cohesionless soil	< 0.10	< 2000	—

Table 30. Final Recoverability Framework – Part 2

Risk Level	NEH Rock Material Field Classification System Class	Rock Mass Strength	Rock Hardness	Rock Quality Designation (ASTM D6302/D6032)	Number of Joint Sets in Rock Mass (include bedding plane partings)	Index Description	Moh's Scale of Hardness Value	Index Description	Reference Mineral
VERY HIGH	Class III: Unstable	< 12.5 MPa	Moderately soft to very soft rock	< 25	> 3 interconnecting joing sets; and at least 1 set contans adverse component of dip	Rock material has significant potential for instability. All conditions met.	8, 9, 10	Scratches glass very easily (8), cuts glass (9), or used as a glass cutter (10).	Topaz (8), Corundim (9), Diamond (10)
HIGH	—	—	—	—	—	—	6, 7	Cannot be scratched with a knife (6), but scratches glass, or scratches glass easily (7)	Orthoclase (6), Quartz (7)
MEDIUM	Class II: Potentially Unstable	12.5 - 50 MPa	Moderately hard rock	25 – 75	< 2 joint sets plus random fractures; no set contains adverse component of dip	Rock material has potenial for instability. At least one condition met.	4, 5	Easily scratched with a knife but not as easily as calcite (4), scratched with a knife, with difficulty (5)	Fluorite (4), Apatite (5)
LOW	—	—	—	—	—	—	2, 3	Can be scratched by the fingernail (2), very easily scratched with a knife and just scratched by a copper coin (3)	Gypsum (2), Calcite (3)
VERY LOW	Class I: Stable	> 50 MPa	Hard to extremely hard rock	> 75	1 joint set and random fractures, or rock mass intact and massive no adverse component of dip	Rock material has very low potential for instability. At least one condition met.	1	Very easily scratched by a fingernail; has a greasy feel (1)	Talc (1)

Table 31. Final Accessibility Framework

Risk Level	Geologic Features	Unified Geologic Map Code	Keywords	Surface Slope Range	Surface Roughness Range	Range (Absolute)
VERY HIGH	Very Complex	Cc, Csc, Ec, Isc, Ibm, Iia, Iiap, Iic, Iif, Iork, Nbl, Nbm, pNt	Densely packed craters; rugged blocks; sinuous ridges; rolling and chaotic materials; sharp raised edges	> 17.27 Steep Grade	> 1.309 Very High Sinuosity	> 4000 m Severe Elevation Changes
HIGH	Complex	Elp, Ic, Ic1, Ib, Ip, INp	Deeply sloping; intensely fractured plains; clusters of overlapping depressions	13.17 – 17.27 Moderately Steep Grade	1.122 – 1.309 High Sinuosity	2000 – 4000 m Significant Elevation Changes
MEDIUM	Moderately Complex	Ccc, Ic2, Icc, Icf, Id, Ig, Im2, Iohi, Ioho, Ios, Iorm, Int, Nb, Nt, Ntp, pNb, pNc	Radial grooves on rims and walls (craters); flat; smooth surfaces, numerous ridges	4.99 – 13.17 Moderate Grade	0.749 – 1.122 Medium Sinuosity	1000 – 2000 m Moderate Elevation Changes
LOW	Moderate	Ecc, Esc, Em, Im1m Imd, Iom, Nbsc, pNbm	Broad flat floors; gently rolling to hilly terrain; smooth, flat; moderate surface to high density of superposed craters	2.72 – 4.99 Low Grade	0.562 – 0.749 Low Sinuosity	500 – 1000 m Elevation Changes Present
VERY LOW	Simple	It, Itd, Nc, Nnj, Np, Np	Smooth inner flanks; muted topographic relief; rolling subdued terrain; generally flat	< 2.72 Flat Grade	< 0.562 Very Low Sinuosity	< 500 m Elevation Changes Present but not Severe

MATLAB Application

A MATLAB application was developed to demonstrate how user inputs were incorporated with the mission data analysis. This GUI represented a method through which the user could enter mission profile information (human decisions) into the existing scientific data imported for use in availability, recoverability, accessibility, and sustainability calculations. User options include mission material (element of interest), site selection (currently limited to the three sites evaluated in this thesis), total availability percentage, extracted percentage, usage percentage, location (nearside/farside or polar), extraction method, surface disruption level, and rock mass stability. Additionally, users can select which risk factors to include in the availability, recoverability, and accessibilty calculations. The tool also computes a basic weekly extraction late, weekly usage rate, and total annual depletion rate based on starting availability defined by the user. This assumes that the total availability is known from prospecting efforts or assumed per available planetary data. The intent here is to document how much of the available resources an entity is planning to extract and to place the concept of depletion rate alongside the calculated risk metrics for availability, recoverability, accessibility, and sustainability. Additionally, the user is asked to input a maximum cap on the total availability (percent, %), while specifying the intended percent (%) consumption (usage) of the total extracted from the total available. For the maximum cap, systems engineers should not independently establish a total availability cap for planetary resources, as this is a much more macroscopic limit for the entire moon system. This limit will need to be established via international space law and policy efforts to advance generational sustainability in a multi-user moon environment.

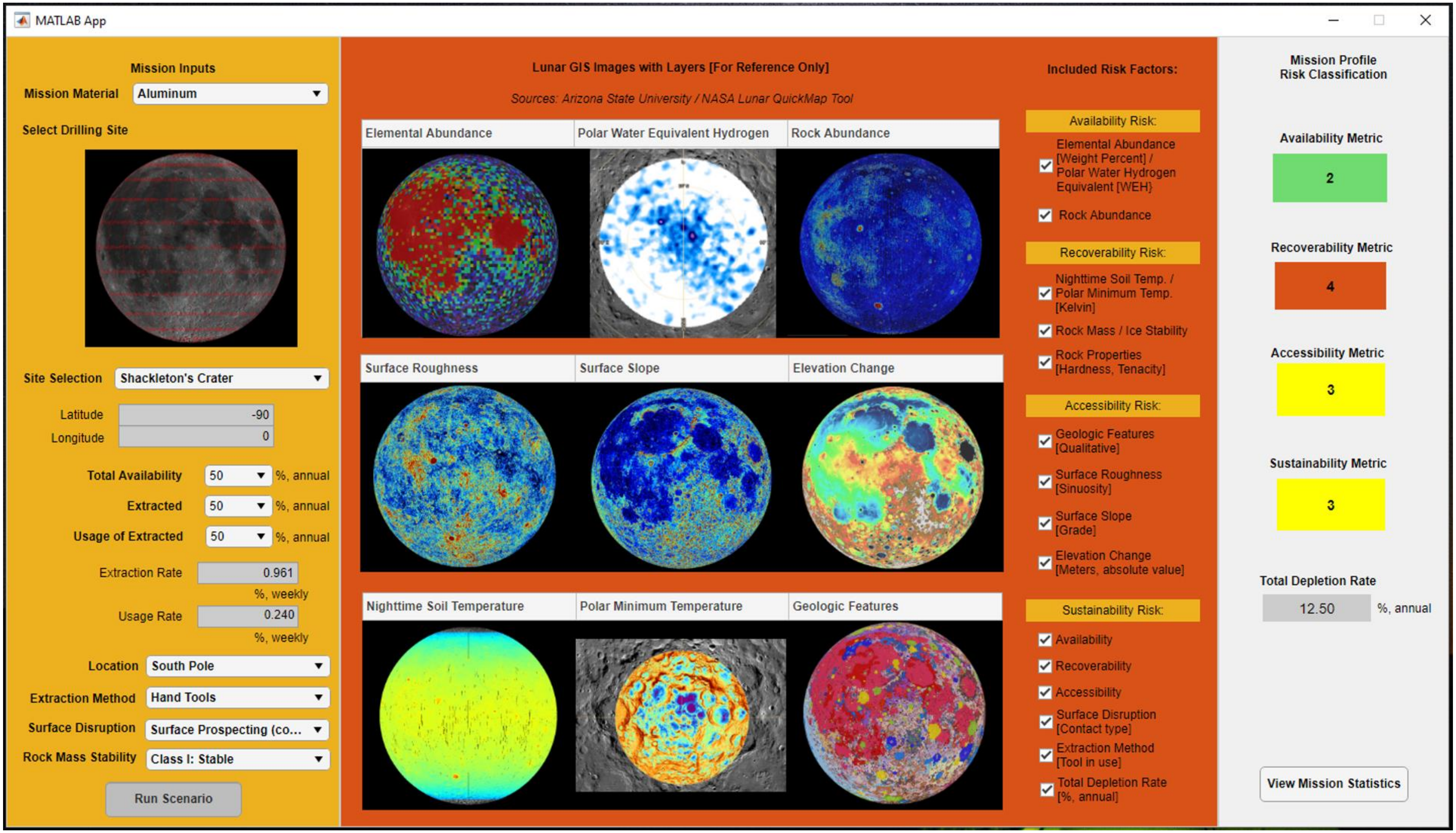


Figure 25. MATLAB Resource and Risk Assessment Interface

GUI Component	Description	GUI Component	Description
1	Mission Inputs – Panel for primary user inputs.	8	Extraction Method – Select primary resource extraction tool to be used.
2	Mission Material – User enters resource of interest.	9	Surface Disruption – Enter the degree of surface disruption planned during mission.
3	Site Selection – User selects drilling or excavation site of interest.	10	Rock Mass Stability – Enter the prospective or surveyed field classification of RMS.
4	Total Availability – User enters total percentage of starting resource availability.	11	**RUN SCENARIO** – User pushes this button to run mission risk assessment.
5	Extracted – User enters percentage of starting resource to be extracted.	12	Risk Factors Panel – User can toggle individual risk factors ON/OFF in final risk classification.
6	Usage of Extracted – User enters percentage of their extracted total to be utilized (depleted).	13	Mission Profile Risk Classification – Overall mission metric calculations are displayed here.
7	Location – User selects primary region of interest (Nearside, Farside, South Pole, North Pole).	14	**VIEW MISSION STATISTICS** – Opens the logged mission statistics for each run scenario.

Figure 26. Legend for MATLAB Resource and Risk Assessment Interface

To tie in the concept of planetary protection under the “1/8 Principle,” (which is an idea coined for protecting the Martian environment) it is possible to input a Total Availability cap in the MATLAB interface to ensure that “no more than 1/8 of the available resources” is used or extracted to prevent “super exploitation." [19]. As proposed by Milligan and Elvis, a resource conservation approach could be a necessary stop-gap measure. A constrained approach or a resource extraction cap for resource-focused missions is one path forward that prevents full-scale industrial mining endeavors from proceeding unchecked, without consideration of resource limitations or potential future needs and uses [20]. A planetary resource classification framework and an interactive resource and risk assessment tool (such as the proposed MATLAB tool) can enable space entities to implement sustainability measures into their early mission design and space systems engineering life cycle. By assessing resource metrics and mission risk, it is possible to characterize the fine line between planetary exploitation, planetary conservation, and planetary preservation.

Resource Classification Algorithms

Current resource utilization methods vaguley refer to “using” the moon’s resources, but few actually project resource extraction, resource reserve, resource uiltization, and resource depletion rates. To better characterize space resources, it is critical to account for the known, proven reserves on the moon. As is the case with terrestrial resources, SPE typically has classified resources on various metrics, including the total resource-initially-in-place, discovered resource-initially-in-place (includes reserves), contingent resources, undiscovered resource-initially-in-place, and prospective resources.

Total availability for space resources is the the known, proven reserves of a resource. Total availability can increase as new prospecting missions confirm the prevalence, recoverability, and accessibility additional resources on the moon. However, total availability should be updated as a percentage cap per year. For example, if only 10% of the available resources can be extracted in a given year, Total Availability should be defined as 10% of the true availability. Essentially, this would limit how much of a resource can be extracted in any given year. For example, currently, 100% of resources on the moon are available. However, to promote intergenerational sustainability as proposed, it would be wise to enter a limit for percentage available for extraction on an annual basis [21]. Thus, if no more than 10% of the Total Resource-Initially-In-Place should be made available in a given year, then we would enter the total availability as 10%. Mathematically, total availability is calculated as shown in [Eqn. 1].

$$Total\ Availability\ (\%) = 1 - \frac{\%\ \text{Resources Available for Extraction}}{\text{Total Resource}-\text{Initially}-\text{In}-\text{Place}} \qquad \textbf{[Eqn. 1]}$$

Once total availability is capped at a limit (in this example, 10% of all available resources), it is then important for an entity to establish what percentage of the available resources they intend to extract annually. This should be documented as *Extracted Resources*. Note that extracting a resource is not the same as using the resource, as some of the extracted resources could be placed in reserves while the rest is depleted through the planned resource utilization in a mission. Therefore, a specific entity's reserve of a resource would be the difference between the quantity extracted and the quantity utilized [Eqn 2.].

$$Resource\ Reserves = Extracted\ Resources - \text{Resources Utilized} \qquad \textbf{[Eqn 2.]}$$

Finally, it is wise to place an individual entity's extraction, reserve, and utilization in the context of the full moon resource system. Therefore, it is relevant to calculate Total Depletion Rate (annual rate) [Eqn 3.] and a Reserve Depletion Rate (%, annual) [Eqn 4.].

$$\text{Total Depletion} = \frac{Total\ Availability - Reserve\ Depletion}{Total\ Availability} \qquad \textbf{[Eqn 3.]}$$

$$Reserve\ Depletion = (\text{Extracted} * \text{Total Availability}) - (\text{Used} * \text{Extracted} * \text{Total Availability}) \qquad \textbf{[Eqn 4.]}$$

The SPE classification system distinguishes between resource reserves, production reserves, contingent reserves, and undiscovered reserves, and prospective resources. Finally, it is worth noting that these assessments can occur with the scientific knowledge available right now, with the understanding that total availability may increase or decrease as new prospecting missions prove or disprove speculative reserves (such as water ice in the polar permanently shadowed reserves).

Risk Classification Algorithms

The following section details the general algorithms utilized to generate mission metrics and evaluate the selected regions. The rationale for the standard weights are also provided. Note that in the MATLAB interface, each factor can be turned off, in which case the coefficients are distributed to the remaining factors, such that the sum of all included coeffients is 1.00.

For the availability metric, there are two parameters that influence the availability risk score: elemental abundance and rock abundance. These are equally weighted by default in the MATLAB risk calculation, unless a risk factor is unchecked by the user.

For assessments of polar water, the water equivalent hydrogen (WEH) is substituted for the elemental abundance.

$Availability$ **[Eqn 5.]**

$$Avail\ =\ \mathbf{0.5} * Elemental\ Abundance * \mathbf{0.5} * Rock\ Abundance$$

To determine the recoverability metric, the primary inputs are temperature, excavatability, rock mass stability *or* ice stability, and rock properties (function of rock hardness and rock tenacity). These are equally weighted by default in the MATLAB recoverability risk calculation, unless a risk factor is unchecked by the user. Note the rock properties equation that feeds into the *RockProp* variable.

$Recoverability$ **[Eqn 6.]**

$$Recov =\ 0.25 * Temperature * 0.25 * Excavatability + 0.25 * RockMass/IceStability + 0.25 * RockProp$$

$Rock\ Properties$ **[Eqn 7.]**

$$RockProp =\ 0.15 * Hardness + 0.10 * Tenacity$$

For the accessibility metric, the primary parameters are geologic features, surface slope, surface roughness, and elevation change. These are equally weighted by default in the MATLAB accessibility risk calculation, unless a risk factor is unchecked by the user.

$Accessibility$ **[Eqn 8.]**

$$Access =\ 0.25 * GeologicFeatures * 0.25 * Slope + 0.25 * Roughness + 0.25 * Elevation\ Change$$

The overall sustainability is a composite score of the three main parameters investigated in this thesis research. Availability, Recoverability, and Acessibility are equally weighted with a scale factor of 0.25, with the remaining 0.25 scale factor distributed between the Surface Disruption Index (0.10) and the Total Depletion rate (0.15). These weights are the default in the MATLAB accessibility risk calculation, unless a risk factor is unchecked by the user.

$Sustainability$ **[Eqn 9.]**

$$Sustain = 0.20 * Avail + 0.20 * Recov + 0.20 * Access + 0.10 * SurfaceDisruption + 0.15 * TotalDepletionRate + 0.05 * ExtractionMethod$$

Implications for Future Missions

In-Situ Resource Utilization is a high priority for both human settlement in space and surface science endeavors of the present and future generations [9], [12], [13], [48]. The planetary resource classification framework proposed in this thesis can expand sustainability efforts by front-loading the classification of space resources earlier in the space systems engineering and mission design process. This would empower all lunar exploration participants to better classify mission profiles on the basis of resource availability, recoverability, accessibility and long-term sustainability of any proposed lunar pursuit.

Understanding and promoting availability, recoverability, and accessibility metrics will enable the sustainability of space resources for generations to come. Establishing risk profiles for each mission parameter can advance the sustainability of space resource prospecting and use. Using SPE, GE, and NEH guidelines, the framework focused on availability, recoverability, and accessibility metrics. To expand the fidelity of this framework, future work could include classifying more lunar sites of interest with respect to each framework component. Once the framework is applied to a multitude of lunar sites, mission planners and analysts will be better equipped to perform a comparative analysis between sites before selecting a site with the optimal availability, recoverability, and accessibility characteristics for a resource-focused mission profile. It is plausible that the resources that are the most available, most accessible, and most recoverable will be the first to be harvested from the moon – just as this occurred for terrestrial resources.

Future space resource extraction endeavors should take a full-system or complete mission approach to evaluating space resource endeavors to ensure the sustainability of space resource missions. Additionally, as more mission data becomes available and technological advances occur, the framework could be expanded to include more engineering geology standards, such as those outlined in the Part 631 of the National Engineering Handbook. If the classification of planetary resources according to multidisciplinary metrics becomes a priority, space resource-focused missions can become a shining example of how to implement planetary sustainability in space exploration missions and how to prioritize sustainability earlier in the space systems engineering lifecycle.

CHAPTER V:

SUMMARY

The motivation for this work was a curiosity regarding how multidisciplinary metrics can help classify mission resources in space resource-focused missions, inspired by current space systems engineering concepts, mission design approaches, planetary sustainability concepts. The risks of unrestrained space exploration have raised concerns regarding the present and future of space exploration, particularly in resource-focused missions. There is an existing capability gap in space systems engineering and mission design that fails to acknowledge the risk that long-term mission yields could be sacrificed for short-sighted exploration gains. Planetary sustainability, however, requires a long-term vision for space exploration that accounts for the finite conditions in the space environment.

The research was focused on addressing the mission overlap between these three research areas (recall the venn diagram from Figure 2). Preliminary findings provide confidence that implementing systems engineering metrics to better classify space resources will advance planetary sustainability goals. Combined with broad policies and mission objectives, a technical framework that illuminates resource availability, recoverability, and accessibility can advance current planetary sustainability approaches. Of course, advances in this technical framework will also influence current indicators of sustainability, including mission assurance and long-term viability of space exploration missions.

Space exploration policy and mission design is the broader context of the future of space development. However, development without accounting for planetary sustainability is impractical. In order to classify planetary resources, it is critical to classify planetary resources and establish appropriate terms of use prior to widespread, uncontrolled use by multiple entities. A planetary resource classification framework can guide the use of space resources and enable a more informed approach to resource utilization and overall planetary sustainability. thereby upholding space exploration policy objectives and assuring mission objectives will be met for generations to come.

By leveraging existing resource classification methods, the proposed framework outlines both technical and sustainability-focused considerations to put planetary sustainability into practice earlier in the mission design process. To avoid the disruption of scientifically valuable lunar real estate, the framework can increase mission yields by accounting for resource limitations in the lunar environment. By leveraging data interlinkages across lunar prospecting missions, the investigation yields a new framework that puts space environmental awareness at the forefront of the mission evaluation process. An understanding of multidisciplinary approaches in terrestrial resource extraction on Earth guided framework development, with relevant inputs from SPE, GE, NRCS, USGS, and NASA.

The scope of impact extends beyond improving resource classification efforts, as the framework can be used early in the systems engineering and mission design cycle to improve resource awareness and advance planetary sustainability. The proposed planetary resource classification framework can further sustainability in space exploration missions by increasing mission resource awareness via multidisciplinary metrics. In the near future, an expanded framework that accounts for space resource metrics could be leveraged by space agencies, commercial entities, and policy makers to negotiate and better define space resource use within and beyond the Outer Space Treaty of 1967.

REFERENCES

[1] National Aeronautics and Space Administration, “Artemis: Humanity’s Return to the Moon,” *NASA*, 2019. https://www.nasa.gov/specials/artemis/index.html (accessed Jan. 12, 2020).

[2] M. Williamson, “Lunar exploration and development - A sustainable model,” *ACTA Astronaut.*, vol. 57, no. 2–8, pp. 161–166, Jul. 2005, doi: 10.1016/j.actaastro.2005.02.002.

[3] J. C. Mankins, “Stepping stones to the future: Achieving a sustainable lunar outpost,” *Acta Astronaut.*, vol. 65, no. 9–10, pp. 1190–1195, Nov. 2009, doi: 10.1016/j.actaastro.2009.03.060.

[4] A. Galli and A. Losch, “Beyond planetary protection: What is planetary sustainability and what are its implications for space research?,” *Life Sci. Space Res.*, vol. 23, pp. 3–9, 2019, doi: 10.1016/j.lssr.2019.02.005.

[5] UN General Assembly, *2222 (XXI). Treaty on Principles Governing the Activities of States in the Exploration and Use of Outer Space, including the Moon and Other Celestial Bodies*. 1966.

[6] M. Williamson, “Lunar exploration and development—A sustainable model,” *Acta Astronaut.*, vol. 57, no. 2–8, pp. 161–166, Jul. 2005, doi: 10.1016/j.actaastro.2005.02.002.

[7] A. Losch, “Interplanetary Sustainability: Mars as a Means of a Long-Term Sustainable Development of Humankind in the Solar System?,” in *The Human Factor in a Mission to Mars: An Interdisciplinary Approach*, K. Szocik, Ed. Cham: Springer International Publishing, 2019, pp. 157–166.

[8] “Presidential Memorandum on Reinvigorating America’s Human Space Exploration Program,” *The White House*. https://www.whitehouse.gov/presidential-actions/presidential-memorandum-reinvigorating-americas-human-space-exploration-program/ (accessed Nov. 09, 2020).

[9] C. Warner, “NASA Outlines Lunar Surface Sustainability Concept,” *NASA*, Mar. 25, 2020. http://www.nasa.gov/feature/nasa-outlines-lunar-surface-sustainability-concept (accessed Aug. 25, 2020).

[10] “NASA’s Plan for Sustained Lunar Exploration and Development,” National Aeronautics and Space Administration, Apr. 2020. Accessed: Aug. 20, 2020. [Online]. Available: https://www.nasa.gov/sites/default/files/atoms/files/a_sustained_lunar_presence_nspc_report4220final.pdf.

[11] Society of Petroleum Engineers, “Petroleum Resources Classification System and Definitions,” Feb. 2000. https://www.spe.org/en/industry/petroleum-resources-classification-system-definitions/ (accessed Jan. 19, 2020).

[12] J. L. Heldmann, A. C. Colaprete, R. C. Elphic, D. R. Andrews, and M. Field, “Landing Site Selection and Effects on Robotic Resource Prospection Missions,” in *Lunar ISRU 2019: Developing a New Space Economy Through Lunar Resources and Their Utilization*, 2019, p. 1.

[13] D.C. Baker, “Lunar Resources: From Finding to Making Demand,” 2019, Accessed: Nov. 05, 2020. [Online]. Available: https://www.hou.usra.edu/meetings/lunarisru2019/pdf/5083.pdf.
[14] J. Corbett, “Micrometeoroids and Orbital Debris (MMOD),” *NASA*, Jun. 14, 2016. http://www.nasa.gov/centers/wstf/site_tour/remote_hypervelocity_test_laboratory/micrometeoroid_and_orbital_debris.html (accessed Jan. 18, 2020).
[15] A. M. Hein, M. Saidani, and H. Tollu, “Exploring Potential Environmental Benefits of Asteroid Mining,” Bremen, Germany, Oct. 2018, Accessed: Jan. 12, 2020. [Online]. Available: https://hal.archives-ouvertes.fr/hal-01910090.
[16] T. M. Pelech, G. Roesler, and S. Saydam, “Technical evaluation of Off-Earth ice mining scenarios through an opportunity cost approach,” *Acta Astronaut.*, vol. 162, pp. 388–404, Sep. 2019, doi: 10.1016/j.actaastro.2019.06.030.
[17] N. M. Fenneman, “A Classification of Natural Resources,” *Science*, vol. 61, no. 1573, pp. 191–197, Feb. 1925, doi: 10.1126/science.61.1573.191.
[18] G. A. Nooten, “Sustainable Development and Nonrenewable Resources — A Multilateral Perspective,” Reston, Virginia, 2007.
[19] S. J. Duclos, J. P. Otto, and D. G. Konitzer, “Design in an era of Constrained Resources,” *Mech. Eng.*, vol. 132, no. 09, pp. 36–40, Sep. 2010, doi: 10.1115/1.2010-Sep-3.
[20] Natural Resources Conservation Service, “Engineering Classification of Rock Materials,” in *National Engineering Handbook*, US Department of Agriculture.
[21] T. Milligan and M. Elvis, “Mars Environmental Protection: An Application of the 1/8 Principle,” in *The human factor in a mission to Mars : an interdisciplinary approach*, 2019, p. 167.
[22] M. Jah, “Space Traffic and the Tragedy of the Commons,” presented at the TEDxDayton, Dayton, OH, Feb. 17, 2017, Accessed: Jan. 15, 2020. [Online]. Available: https://www.youtube.com/watch?v=qpiCkJX_PhY&t=569s.
[23] J. Kasser and R. Schermerhorn, “Determining Metrics for Systems Engineering,” *INCOSE Int. Symp.*, vol. 4, no. 1, pp. 740–745, Aug. 1994, doi: 10.1002/j.2334-5837.1994.tb01785.x.
[24] “USGS Astrogeology Science Center.” https://astrogeology.usgs.gov/search?pmi-target=moon (accessed Aug. 25, 2020).
[25] “USGS Releases First-Ever Comprehensive Geologic Map of the Moon.” https://www.usgs.gov/news/usgs-releases-first-ever-comprehensive-geologic-map-moon (accessed Aug. 25, 2020).
[26] *LRO/LROC Lunar ACT-REACT-QuickMap*. Arizona State University, 2020.
[27] Robinson, M.S., et. al., “Lunar Reconnaissance Orbiter Camera (LROC) Instrument Overview,” *Space Sci. Rev.*, vol. 150, pp. 81–124, 2010.
[28] Humm, D.C., et. al., “Flight Calibration of the LROC Narrow Angle Camera,” *Space Sci. Rev. Online*, pp. 1–43, 2015.
[29] Mahanti, P., et. al., “Inflight Calibration of the Lunar Reconnaissance Orbiter Camera Wide Angle Camera,” *Space Sci. Rev. Online*, pp. 1–38, 2015.

[30] Speyerer, E.J., et. al., "In-Flight Geometric Calibration of the Lunar Reconnaissance Orbiter Camera," *Int. Arch. Photogramm. Remote Sens. Spat. Inf. Sci.*, vol. XXXIX-B4, pp. 511–516, 2012.
[31] Robinson, M.S., "Lunar Reconnaissance Orbiter Camera Experimental Data Record," *NASA Planet. Data Syst.*, no. LRO-L-LROC-2-EDR-V1.0, 2010.
[32] National Aeronautics and Space Administration, "NASA's Planetary Data System (PDS)." https://pds.nasa.gov/ (accessed Sep. 21, 2020).
[33] C. Klein and B. Dutrow, *Manual of Mineral Science*. Wiley, 2007.
[34] T. H. Prettyman *et al.*, "Elemental composition of the lunar surface: Analysis of gamma ray spectroscopy data from Lunar Prospector," *J. Geophys. Res. Planets*, vol. 111, no. E12, 2006, doi: 10.1029/2005JE002656.
[35] "Diviner Lunar Radiometer Experiment." https://www.jpl.nasa.gov/missions/diviner-lunar-radiometer-experiment-dlre/ (accessed Nov. 29, 2020).
[36] J. L. Bandfield, R. R. Ghent, A. R. Vasavada, D. A. Paige, S. J. Lawrence, and M. S. Robinson, "Lunar surface rock abundance and regolith fines temperatures derived from LRO Diviner Radiometer data," *J. Geophys. Res. Planets Wash.*, vol. 116, 2011, doi: http://dx.doi.org/10.1029/2011JE003866.
[37] E. A. Fisher *et al.*, "Evidence for surface water ice in the lunar polar regions using reflectance measurements from the Lunar Orbiter Laser Altimeter and temperature measurements from the Diviner Lunar Radiometer Experiment," *Icarus*, vol. 292, pp. 74–85, Aug. 2017, doi: 10.1016/j.icarus.2017.03.023.
[38] D. E. Smith *et al.*, "Summary of the results from the lunar orbiter laser altimeter after seven years in lunar orbit," *Icarus*, vol. 283, pp. 70–91, Feb. 2017, doi: 10.1016/j.icarus.2016.06.006.
[39] M. K. Barker, E. Mazarico, G. A. Neumann, M. T. Zuber, J. Haruyama, and D. E. Smith, "A new lunar digital elevation model from the Lunar Orbiter Laser Altimeter and SELENE Terrain Camera," *Icarus*, vol. 273, pp. 346–355, Jul. 2016, doi: 10.1016/j.icarus.2015.07.039.
[40] C. M. Fortezzo, P. D. Spudis, and S. L. Harrel, "Release of the Digital Unified Global Geologic Map of the Moon At 1:5,000,000- Scale," presented at the 51st Lunar and Planetary Science Conference, Lunar and Planetary Institute, Houston, TX, Mar. 2020, [Online]. Available: https://astrogeology.usgs.gov/search/map/Moon/Geology/Unified_Geologic_Map_of_the_Moon_GIS.
[41] "NASA Systems Engineering Handbook," National Aeronautics and Space Administration, NASA SP-2016-6105 Rev2, 2016.
[42] S. Potter, "NASA's SOFIA Discovers Water on Sunlit Surface of Moon," *NASA*, Oct. 26, 2020. http://www.nasa.gov/press-release/nasa-s-sofia-discovers-water-on-sunlit-surface-of-moon (accessed Nov. 06, 2020).
[43] A. B. Sanin *et al.*, "Hydrogen distribution in the lunar polar regions," *Icarus*, vol. 283, pp. 20–30, Feb. 2017, doi: 10.1016/j.icarus.2016.06.002.
[44] "TinEye Labs - Color Extraction Lab." https://labs.tineye.com/color/ (accessed Nov. 15, 2020).

[45] D. A. Paige and N. Schorghofer, “Seasonal Variations in South Polar Temperatures on the Moon.,” no. 2132, p. 2, 2019.
[46] M. A. Siegler, B. G. Bills, and D. A. Paige, “Effects of orbital evolution on lunar ice stability,” *J. Geophys. Res.*, vol. 116, no. E3, p. E03010, Mar. 2011, doi: 10.1029/2010JE003652.
[47] C. Mcleod and M. Krekeler, “Sources of Extraterrestrial Rare Earth Elements: To the Moon and Beyond,” *Resources*, vol. 6, no. 3, p. 40, 2017, doi: 10.3390/resources6030040.
[48] A. Colaprete, R. Elphic, M. Shirley, R. Beyer, Matt Siegler, “Resource Prospector: Evaluating the ISRU Potential of the Lunar Poles,” presented at the 49th Lunar and Planetary Science Conference, 2018, Accessed: Oct. 13, 2020. [Online]. Available: https://www.hou.usra.edu/meetings/lpsc2018/pdf/2698.pdf.

APPENDIX A:

UNIFIED GEOLOGIC MAP OF THE MOON DESCRIPTIONS

Table 32. Unified Geologic Map Descriptions[40]

Unit	Name	Description	Interpretation
Cc	Copernican Crater	Rim, wall and floor deposits of craters with sharp prominent rims, circular to polygonal outlines. High relative brightness and rays.	n/a
Ccc	Crater, Catena	Elongated linear clusters of overlapping circular to semi-circular.	n/a
Csc	Copernican Crater, Secondary	Small to very small diameter craters, densely spaced near and/or on the ejecta blanket of craters.	Impact crater forms derived from blocky material ejected from the primary impact.
Ec	Eratosthenian Crater	Non-rayed, circular craters with sharp to partially subdued crater rim crests, partial circumferential ejecta present, and lower albedo compared to unit Cc.	Morphology and material from a primary impact event.
Ecc	Eratosthenian Crater, Catena	Elongated linear to elliptical clusters of circular to semi-circular depressions, often overlapping.	Impact crater clusters derived ejecta from large, basin forming impacts. Possibly primary impacts.
Esc	Eratosthenian Secondary Crater	Small to very small diameter craters, densely spaced near and/or on the ejecta blanket of craters.	Impact crater forms derived from blocky material ejected from the primary impact.
Em	Eratosthenian Mare	Low relative brightness plains with relatively few craters large enough to map, patches of small domes, sharp-crested ridges, observable flow fronts.	Relatively thin, young volcanic flows or pyroclastic material.
EIp	Eratosthenian Imbrian Plateau	Forms high standing plateaus (relative to the mare surfaces in Oceanus Procellarum) with domes, cones, and dark mantling materials.	Volcanic constructs, flows, and pyroclastic materials.
Ic	Imbrian Crater, Undivided	Subdued topographic relief compared to younger impact features, generally less than 40 km in diameter, with broad flat floors, and little to no ejecta	Subdued morphology and material from a primary impact event.
Ic1	Imbrian Crater, Lower	Similar description to unit Ic, craters mantled by materials of the Orientale group.	Subdued morphology and material from a primary impact event, younger than Imbrium group materials but older than Orientale group materials.
Ic2	Imbrian Crater, Upper	Similar description to unit Ic, craters superpose materials of the Orientale group.	Subdued morphology and material from a primary impact event, younger than Orientale group materials but older than unit Im2.
Icc	Imbrian Crater, Catena	Subdued and mantled elongated linear to elliptical clusters of circular to semi-circular depressions, often overlapping.	Impact crater clusters derived ejecta from large, basin forming impacts. Possibly primary impacts.
Isc	Imbrian Crater, Secondary	Small diameter craters, densely spaced near and/or on the ejecta blanket of craters.	Impact crater forms derived from blocky material ejected from the primary impact.
Icf	Imbrian Crater, Fracture Floor	Crater floors typically domed, with furrows and/or linear to curvilinear fractures with variable widths and depths. Blocks and material between the	Brittle materials uplifted and extended.
Ib	Imbrian Basin, Undivided	Gently rolling to hilly terrain containing aggregates of subdued irregular to circular craters. Also forms outer basin and ejecta of crater Schrodinger.	Materials emplaced during the formation of multi-ringed impact basins.
Ibm	Imbrian Basin, Massif	Rugged blocks forming arcuate raised ridges within crater Schrodinger.	Material uplifted during basin formation, representing the inner ring of a multi-ringed impact basin.
Id	Imbrian Dark Mantle	Some of the lowest albedo material mapped, generally occurs near the outer margins of larger basins. Scalloped, smooth textures with small craters.	Pyroclastic material.
Ig	Imbrian Grooved	Covers craters and other terrae of pre-Nectarian through Imbrian age. Craters have radial grooves on rims and walls with some mounds.	Origin uncertain. Possibly Imbrium ejecta or result of seismic shaking.
Iia	Imbrian Imbrium Alpes Formation	Angular blocky and knobby with smooth, mantled surface. Closely spaced hills and hummocks, ~2-5 km in diameter.	Possibly eroded ejecta, structurally deformed bedrock, or both.
Iiap	Imbrian Imbrium Apenninus	Coarse blocks of material parallel to scarp bordering Imbrium basin. Smooth to undulating interblock materials.	Intensely fractured bedrock with interstitial Imbrium ejecta.
Iic	Imbrian Imbrium Crater	Individual craters <25 km diam., clusters and chains of craters <10 km diam. radial to Imbrium. Moderately subdued topographic features.	Secondaries and crater chains emplaced during Imbrium basin formation.
Iif	Imbrian Imbrium	Sinuous, curvilinear, and straight ridges draping the surface below. Surface	Ejecta from Imbrium basin and materials of the substrate.
Im1	Imbrian Mare, Lower	Forms flat, smooth surfaces. Relatively higher albedo compared to unit Im2 but lower albedo than unit Ip. High density of superposed craters.	Old basaltic lava, perhaps as old as Orientale basin.
Im2	Imbrian Mare, Upper	Forms flat, smooth surfaces. Lower albedo and crater density than unit Im1. Numerous ridges. Difficult to distinguish from unit Id.	Basaltic lava flows

Table 33. Unified Geologic Map Descriptions (continued)[40]

Unit	Name	Description	Interpretation
Imd	Imbrian Mare,	Steeply sloping, high-relief, rough domical or conical shaped edifices,	Volcanic edifices or laccoliths
Iohi	Imbrian Orientale Hevelius Formation,	Curvilinear to swirly ridges and troughs mostly radial and subradial to Orientale basin.	Continuous ejecta blanket emplaced during outward flow of hot, turbulent, mobile materials.
Ioho	Imbrian Orientale Hevelius Formation,	Swirly, lineated, hummocky and smooth materials forming a discontinuous and irregular boundary.	Thinning distal margins of Orientale basin ejecta.
Ios	Imbrian Orientale Hevelius Formation,	Overlapping crater chains and clusters radial and peripheral to the basin.	Secondary impact craters formed by ejected blocks..
Iom	Imbrian Orientale Maunder Formation	Smooth to rolling, intensely fractured plains with broad linear ridges and smooth domes.	Mostly impact melt. Ridges and domes likely original floor material modified through compression.
Iork	Imbrian Orientale Montes Rook	Knobby, hummocky, rolling and chaotic materials with interstitial irregular grooves and depressions.	Uppermost part of overturned flap of the ejecta sequence of Orientale basin.
Iorm	Imbrian Orientale Montes Rook	High-relief, smooth blocks marking the second and third rings of the basin.	Structurally uplifted bedrock, thickly veneered with late arriving ejecta.
Ip	Imbrian Plains	Smooth, flat to undulatory terrain of intermediate albedo occurring mostly in topographic lows and crater floors of Imbrian and older age.	Ambiguous origin, likely Orientale and other large impact crater ejecta.
It	Imbrian Terra	Low relief, low crater density, moderate to high albedo, moderately smooth surface.	Complex mixture of local erosional debris and crater and basin ejecta; megaregolith.
Itd	Imbrian Terra, Dome	Outlines and characteristics similar to main-sequence craters, with smooth inner flanks, paucity of ejecta, inner terracing, secondary cratering.	Possibly target material differences, or ash-flow calderas.
INp	Imbrian Nectarian Plains	Smooth, flat to undulating surface, moderate to high density of superposed craters.	Possibly materials emplaced by the formation of Imbrian and Nectarian basins.
INt	Imbrian Nectarian Terra	Gently rolling terrain, moderate to high density of craters.	Complex mixture of local erosional debris and crater and basin ejecta; megaregolith.
Nc	Nectarian Crater	Considerably muted topographic relief compared to younger impact features, with broad flat floors typically another unit, and very little to no ejecta present.	Muted morphology and material from a primary impact event.
Nb	Nectarian Basin, Undivided	Material of raided walls and slumped blocks of basins, as well as aggregates of closely spaced subdued hills and ridges.	Impact related structures and ejecta material.
Nbl	Nectarian Basin,	Sharp, raised ridges, intervening flat areas or deep troughs and smooth hills	Bedrock pervasively faulted by Imbrium impact.
Nbm	Nectarian Basin, Massif	Rugged blocks most commonly 10 to 30 km across, forms highest and most rugged parts of arcuate raised ridges.	Uplifted bedrock during the formation of Nectarian basins.
Nbsc	Nectarian Basin, Secondary Crater	Grouped in clusters, chains and groove-like chains, mostly peripheral and approximately radial to Nectarian basins.	Secondary impact craters of Nectarian basins.
Nnj	Nectarian Nectaris Janssen Formation	Rolling subdued terrain having numerous linear features including ridges, scarps, and grooves radial to Nectaris basin.	Nectaris basin ejecta equivalent to, but more degraded than, units Iif, Iohi, and Ioho.
Np	Nectarian Plains	Generally flat, moderate albedo terrain with dense population of large, old craters.	Ambiguous origin, possible ejecta from large impacts and basin forming events.
Nt	Nectarian Terra	Moderately rough surface, rolling to moderately rugged overall relief, with diverse ages of superposed and buried craters.	Complex mixture of local erosional debris and crater and basin ejecta; megaregolith.
Ntp	Nectarian Terra-Mantling and Plains	Light colored, wavy or rolling surfaces more heavily cratered than unit Ip.	Primary and secondary ejecta of Nectarian basins and large craters equivalent to units Ioho and Ip, with more erosional degradation.
pNb	pre-Nectarian Basin	Subdued, eroded mountain rings and arcuate segments of rings, rim, walls, and inner-ring materials.	Erosionally degraded impact related structures and ejecta materials.
pNbm	pre-Nectarian Basin Massif	Large mountainous landforms commonly lying along arc, both continuous and discontinuous, gradational with generally finer-scale topography.	Uplifted bedrock during the formation of basins.
pNc	pre-Nectarian Crater	Discontinuous, subdued rim crests and rounded, curved or straight rim remnants.	erosionally degraded morphology and material from a primary impact event.
pNt	pre-Nectarian Terra	Rugged, diverse terrain, degraded partial crater rims, gradational with smoother unit Nt, and rougher units pNbm and pNc.	Complex mixture of local erosional debris and crater and basin ejecta; megaregolith.

APPENDIX B:

SOUTH POLE IMAGE ANALYSIS

Color Palette Analyses for the South Pole, Shakleton's Crater, and the Clavius Crater are included in this section. A gradient legent that guided color analysis is also included.

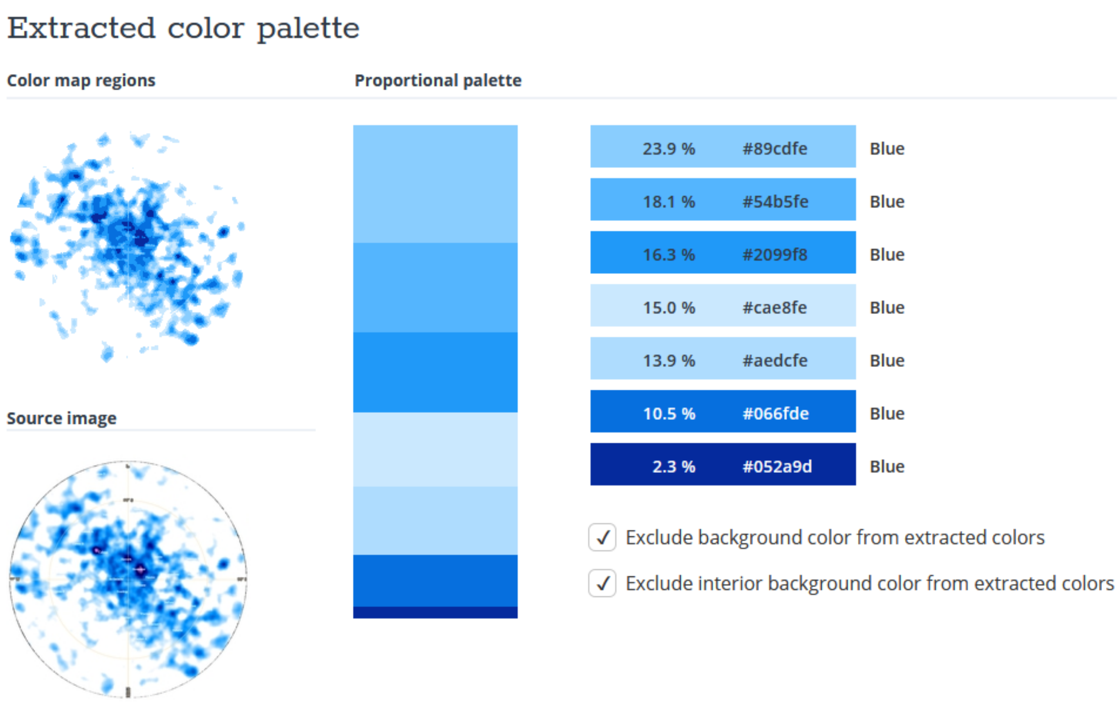
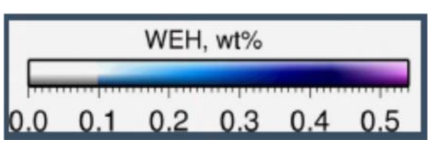


Figure 27. South Pole Polar Water Hydrogen Equivalent Percentages [26], [43], [44]



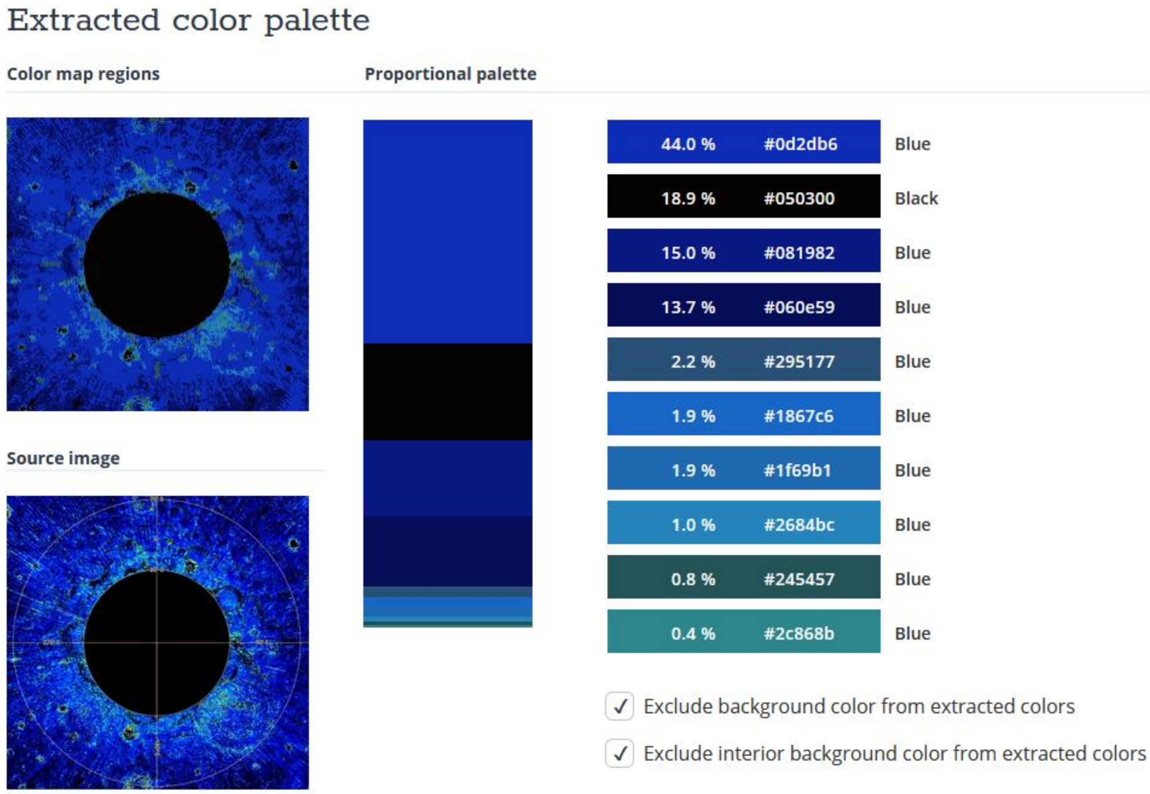


Figure 28. South Pole Rock Abundance Percentages[26], [36], [44]

Note: The black background was excluded from the weighted score.

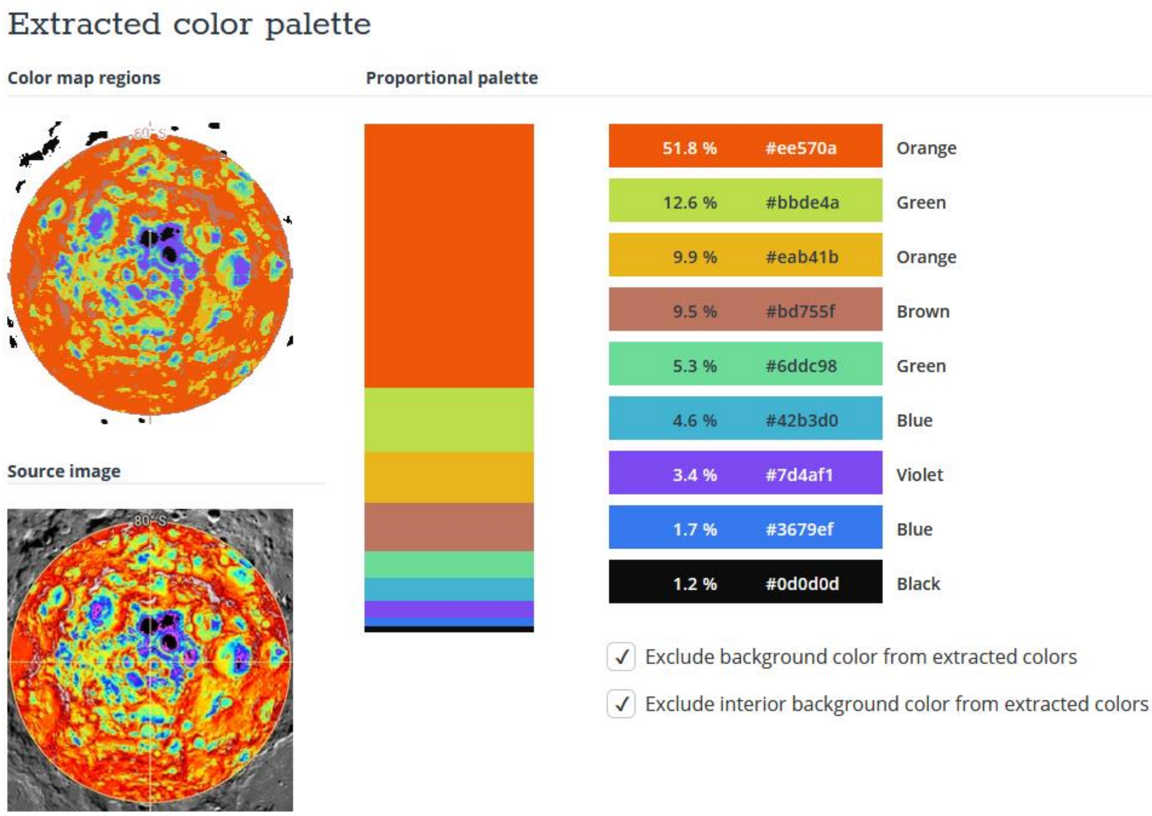


Figure 29. Polar Winter Minimum Temperature Percentages [26], [44], [45]

Note: The black background was excluded from the weighted score.

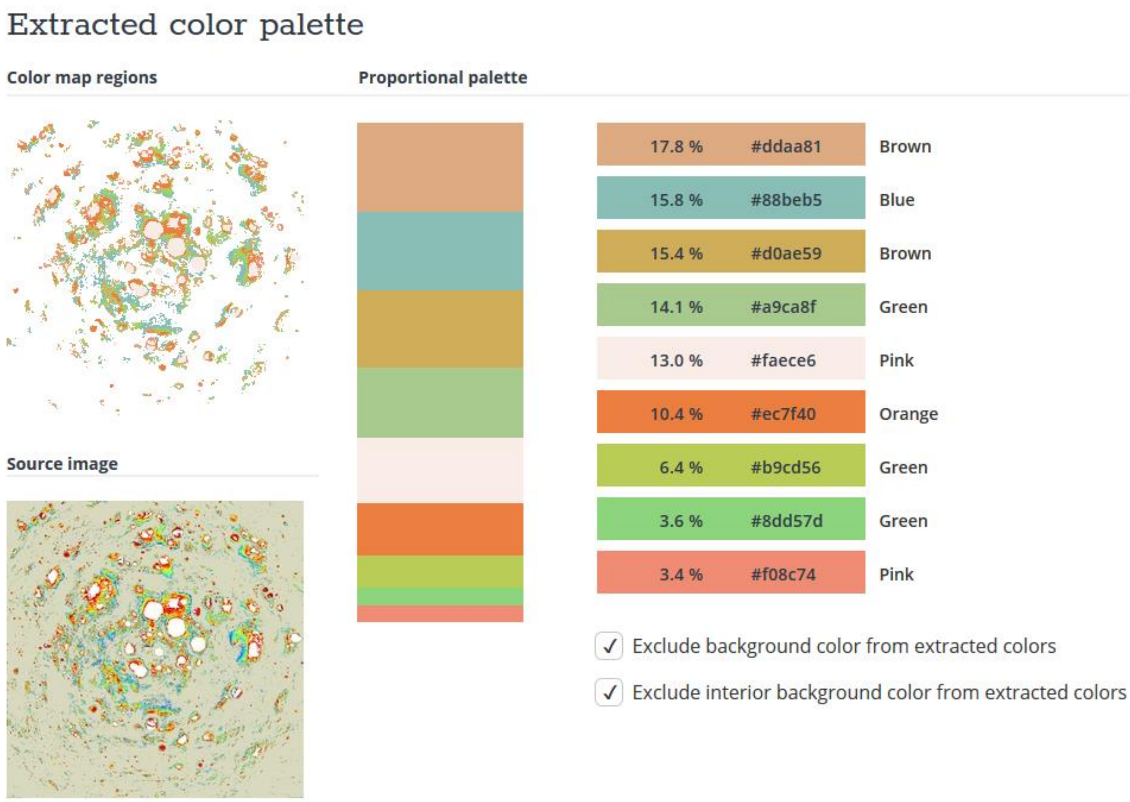
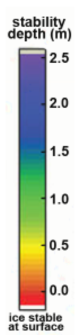


Figure 30. South Pole Ice Stability Depth Percentages [26], [44], [46]



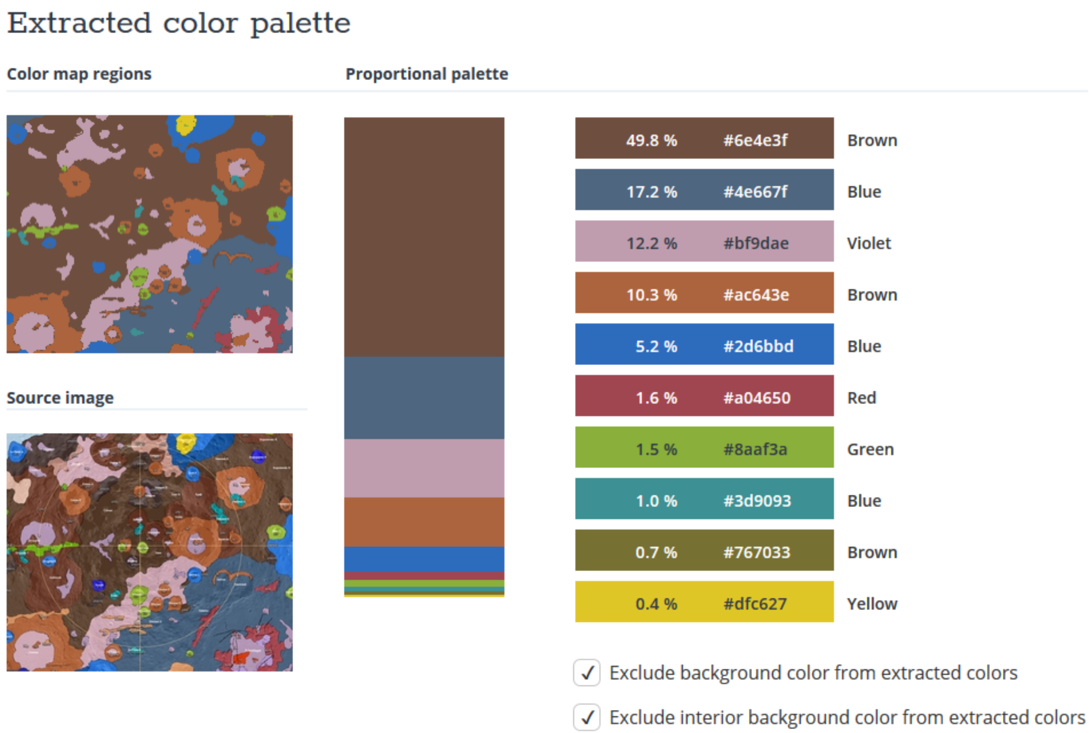


Figure 31. South Pole Unified Geologic Map Percentages

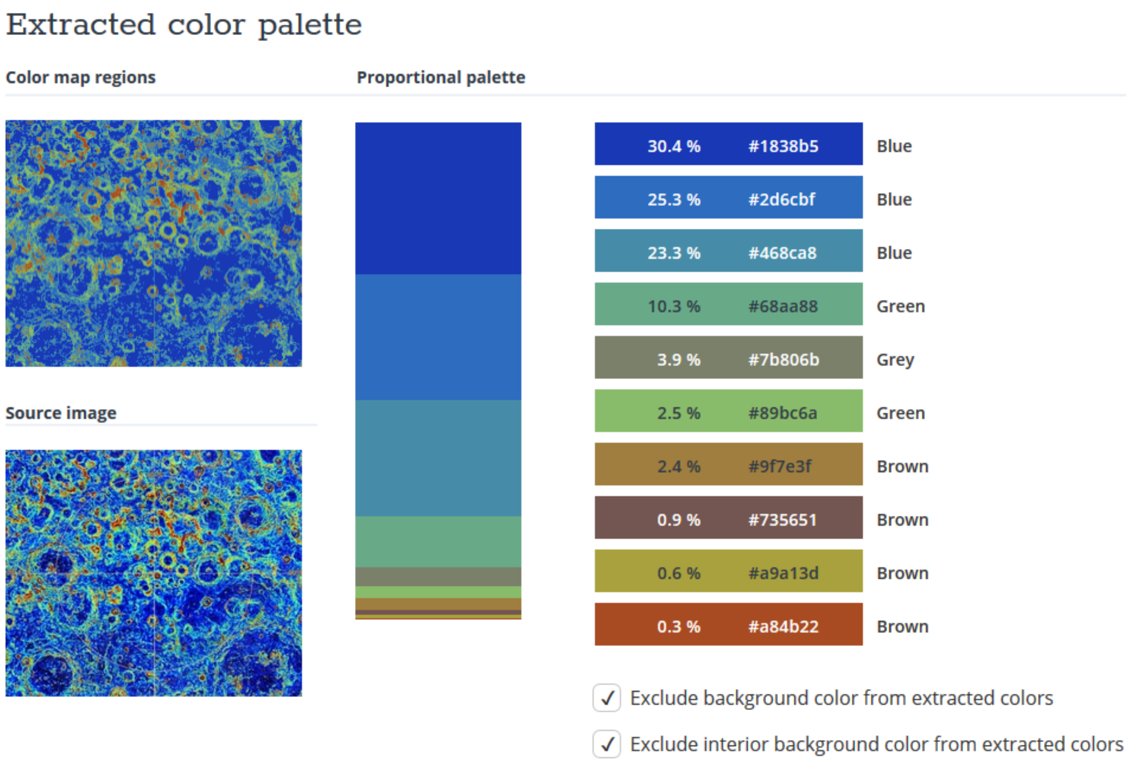


Figure 32. South Pole Surface Slope Percentages

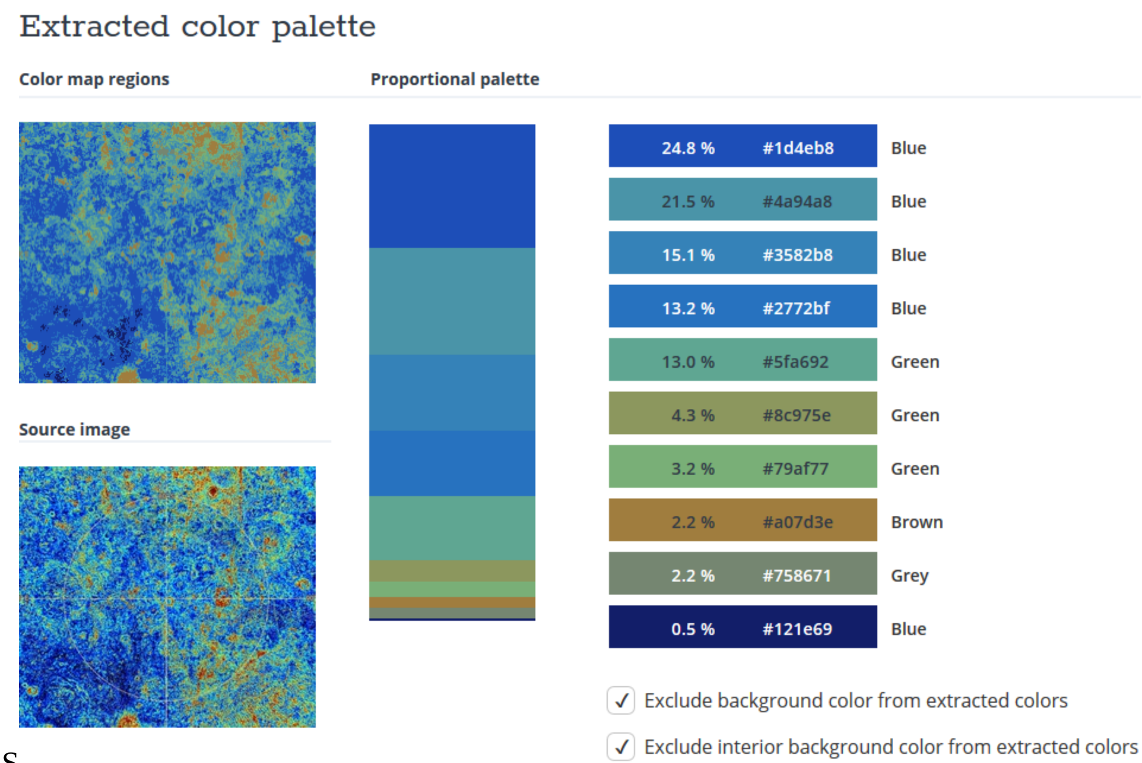


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Figure 33. South Pole Surface Roughness Percentages

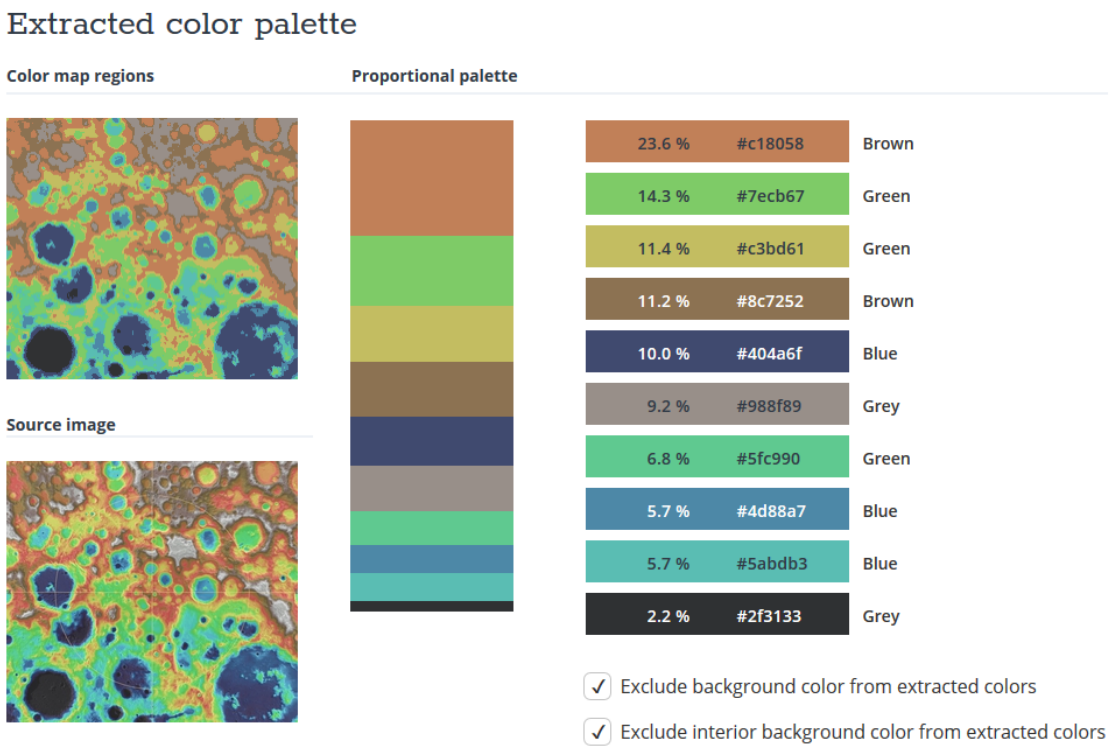


Figure 34. South Pole Elevation (GLD100 plus LOLA) Percentages [26], [39], [44]

APPENDIX C:

SHACKLETON’S CRATER IMAGE ANALYSIS

Color Palette Analyses for the Shackleton’s Crater are included in this section. A gradient legend that guided color analysis is also included.

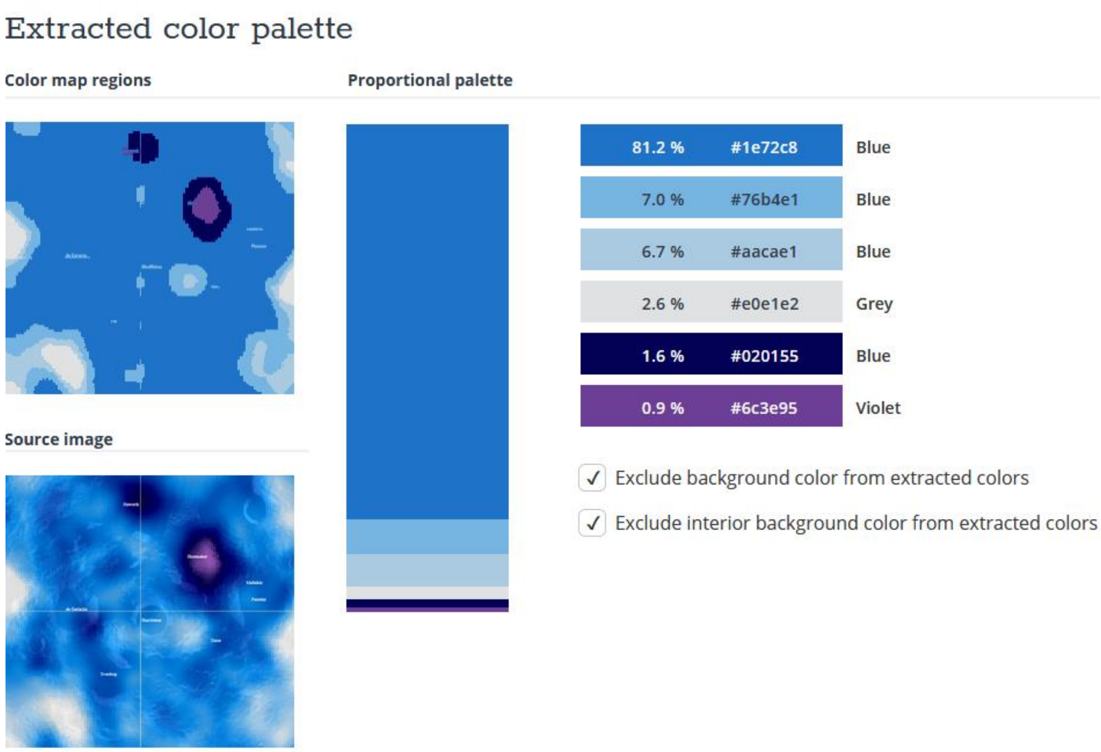
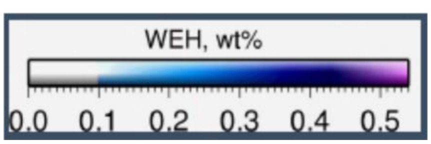


Figure 35. Shackleton’s Crater Water Equivalent Hydrogen Percentages [43]



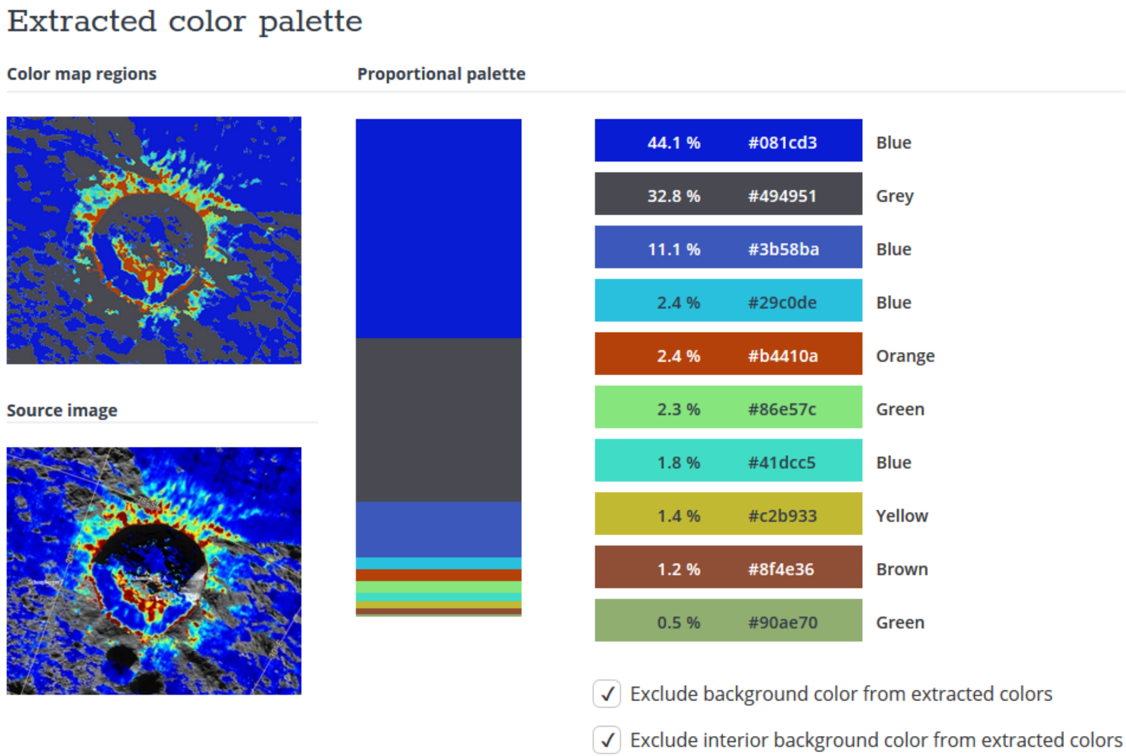


Figure 36. Schomberger A Crater Rock Abundance Percentages [26], [36], [44]

Note: Schomberger A data was substituted into Shackleton's Crater analysis, as no rock abundance data was available for the Shackleton's crater site. Additionally, the grey background was excluded from the weighted score.

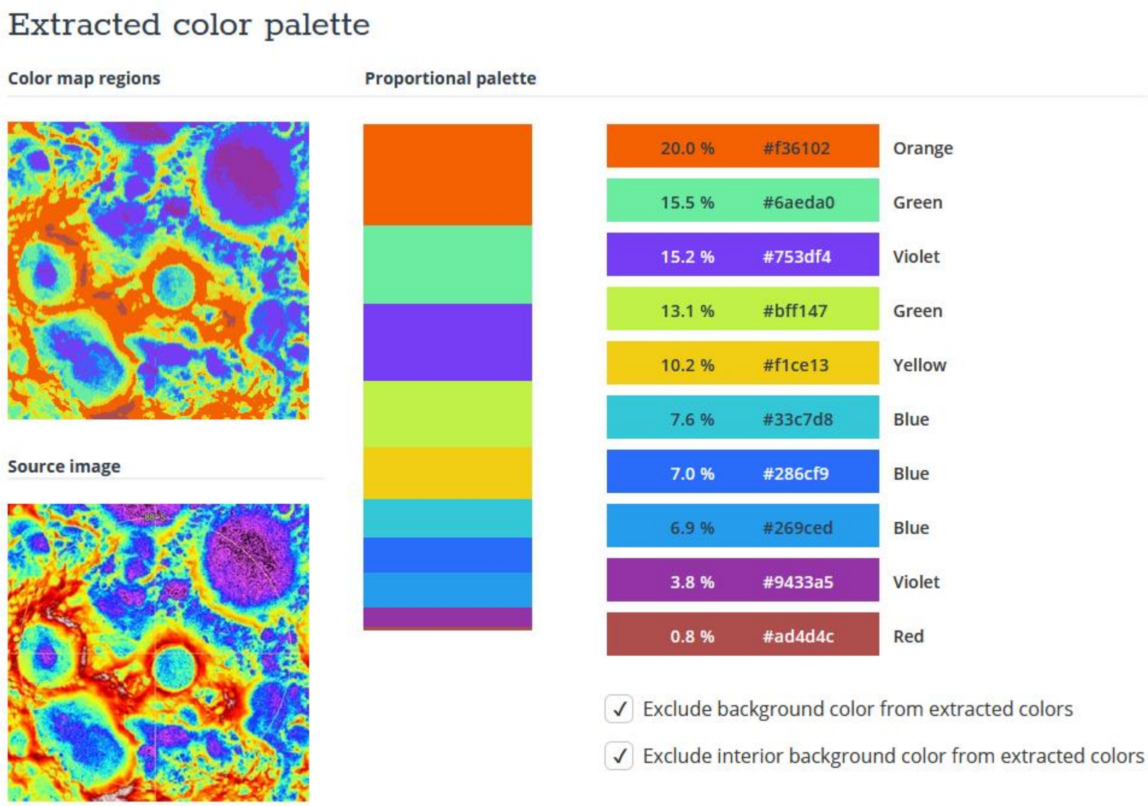


Figure 37. Shackleton's Crater Polar Minimum Temperature Percentages [26], [44], [45]

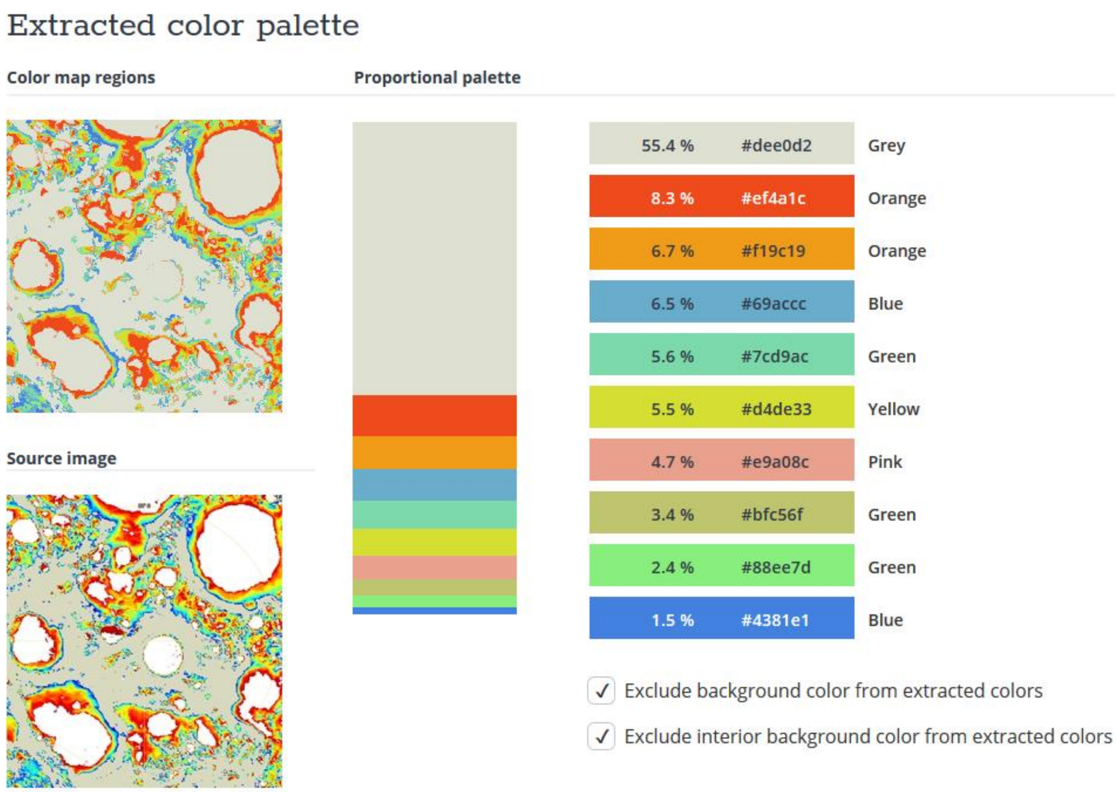
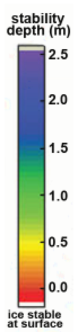


Figure 38. Shackleton's Crater Ice Stability Depth Percentages [46]



Note: The grey background was excluded from the weighted score.

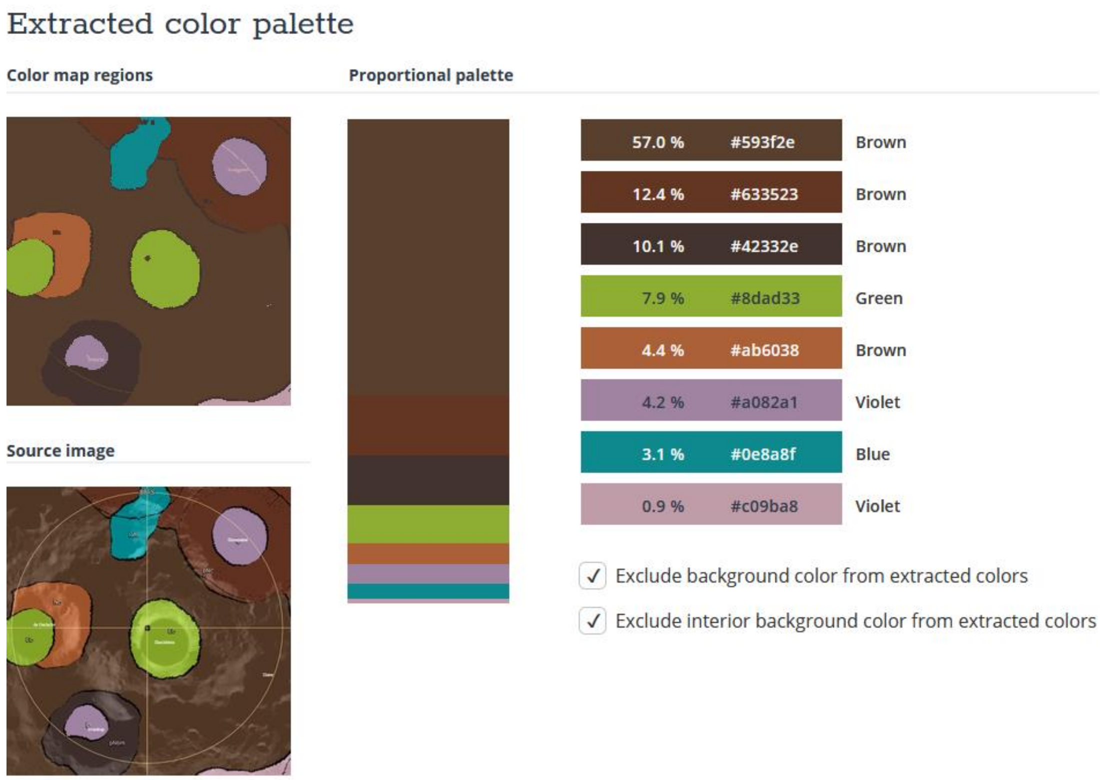


Figure 39. Shackleton's Crater Unified Geologic Map Percentages [40]

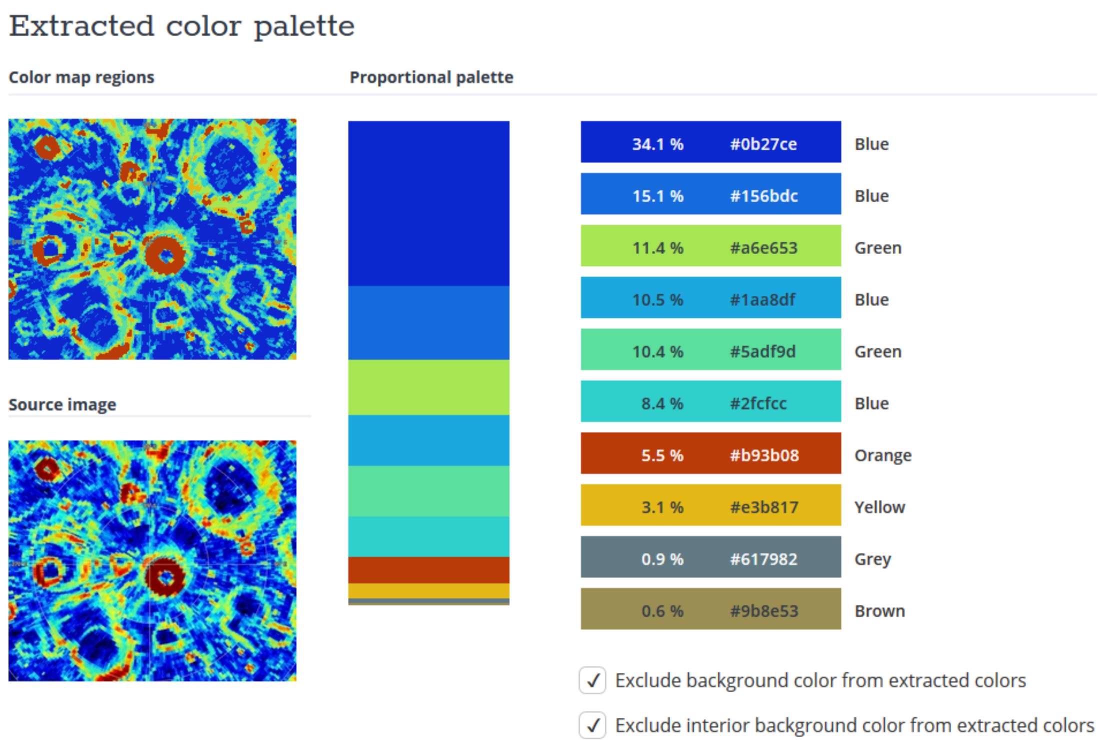


Figure 40. Shackleton's Crater Surface Slope Percentages

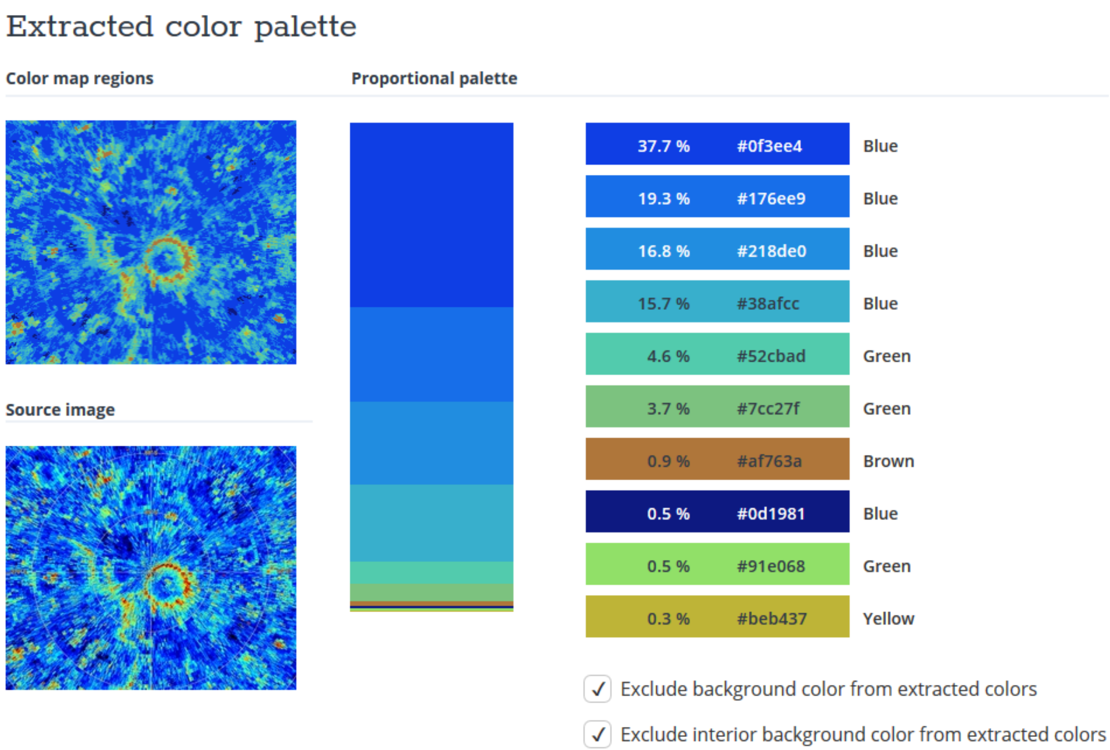


Figure 41. Shackleton's Crater Surface Roughness Percentages

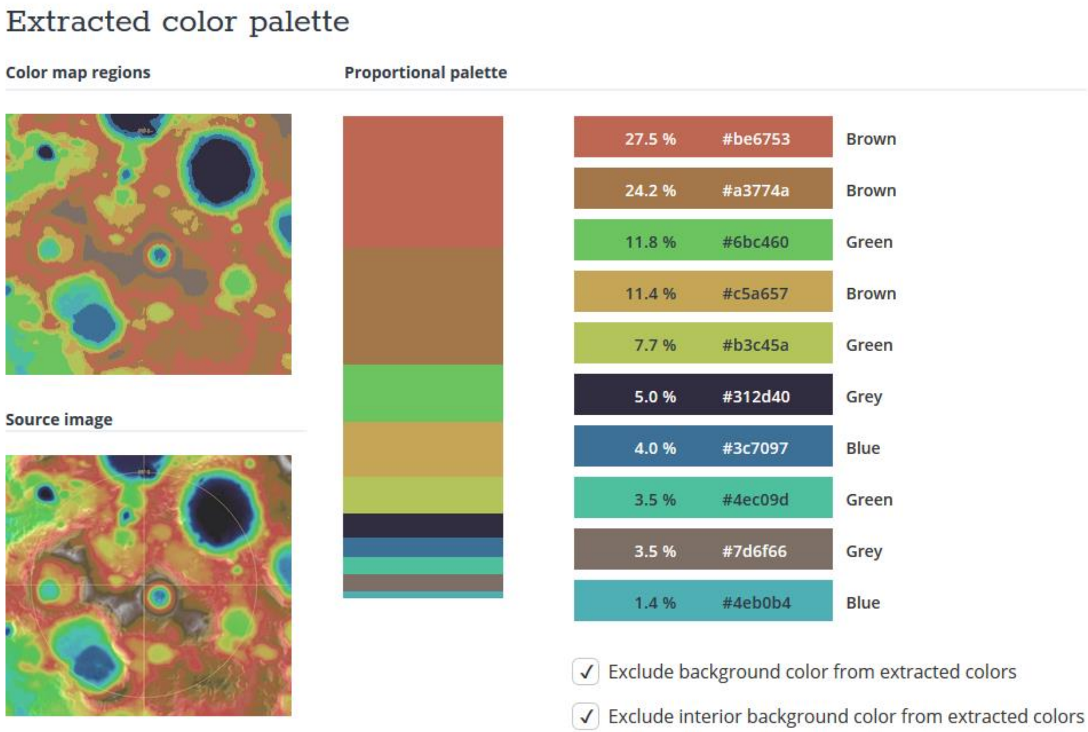


Figure 42. Shackleton's Crater Elevation (GLD100 plus LOLA) Percentages [26], [39], [44]

APPENDIX D:

CLAVIUS CRATER IMAGE ANALYSIS

Color Palette Analyses for the Clavius Crater are included in this section. A gradient legent that guided color analysis is also included.

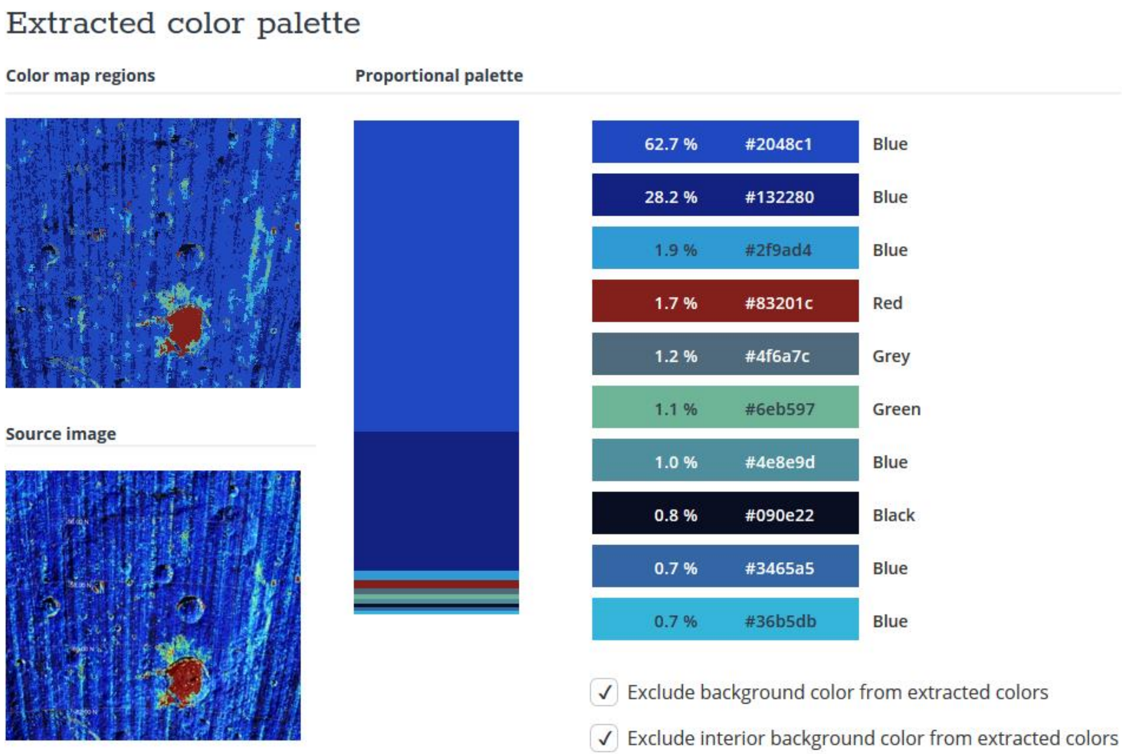


Figure 43. Clavius Crater Rock Abundance Percentages [26], [36], [44]

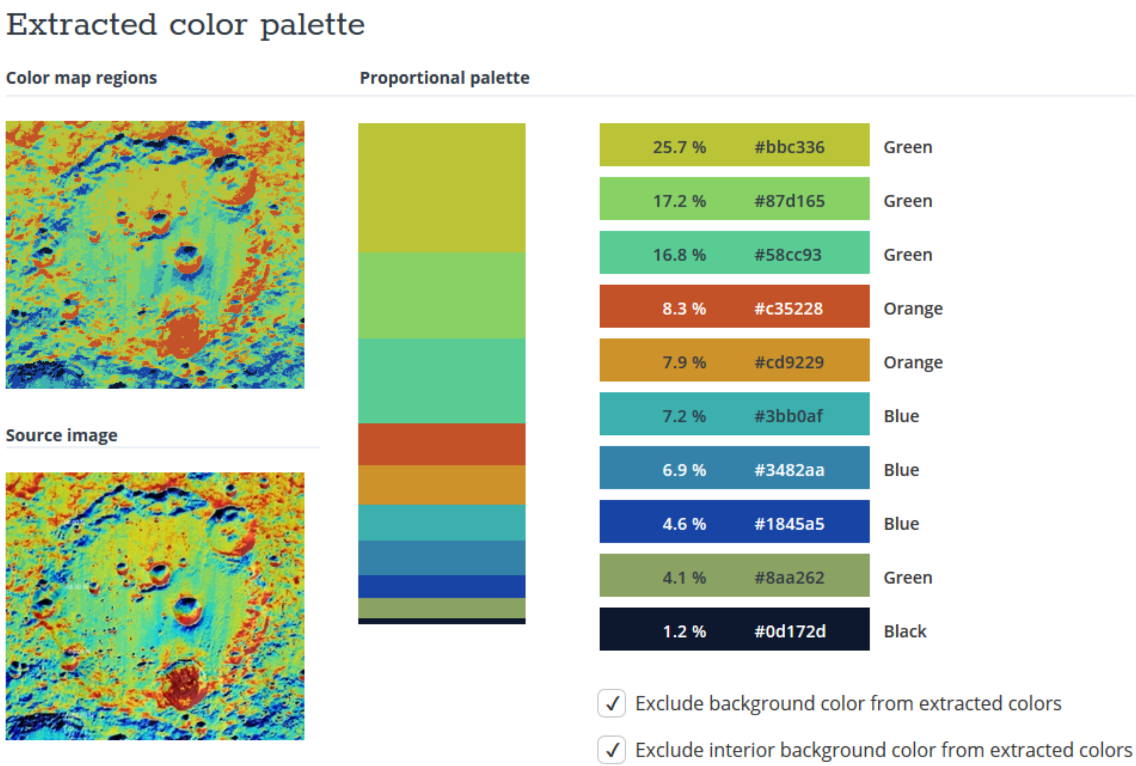


Figure 44. Clavius Crater Nighttime Soil Temperature Percentages [26]

Note: The black background was excluded from the weighted score.

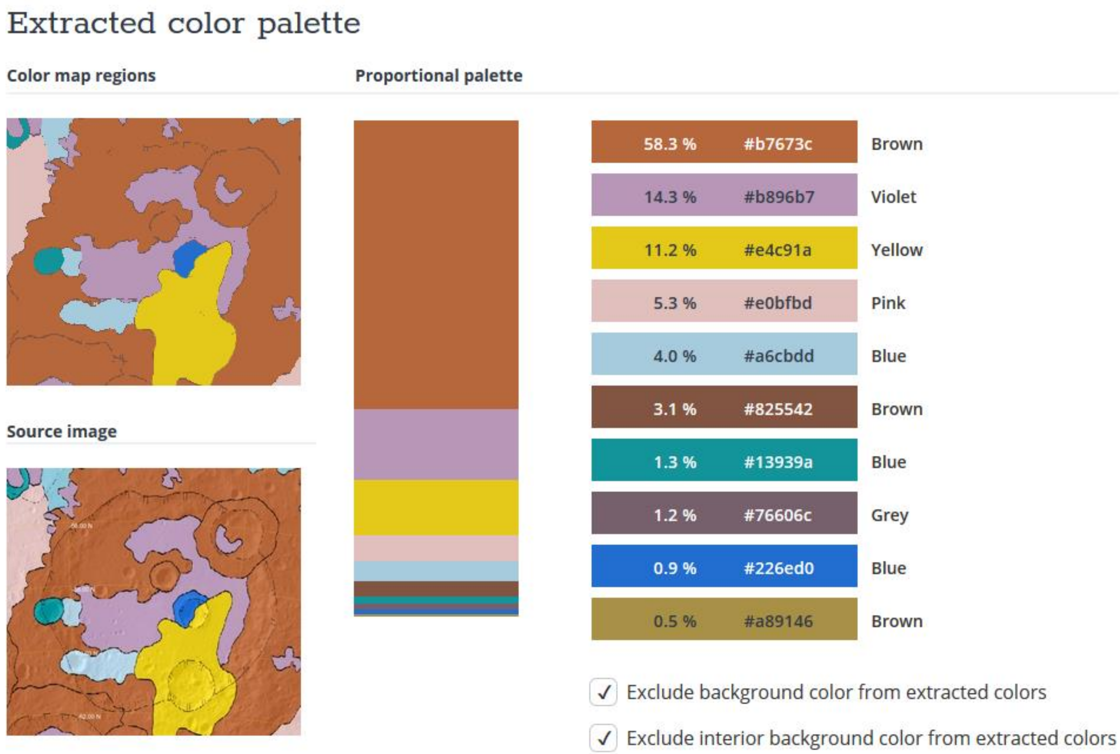


Figure 45. Clavius Crater Unified Geologic Map Percentages [26], [40], [44]

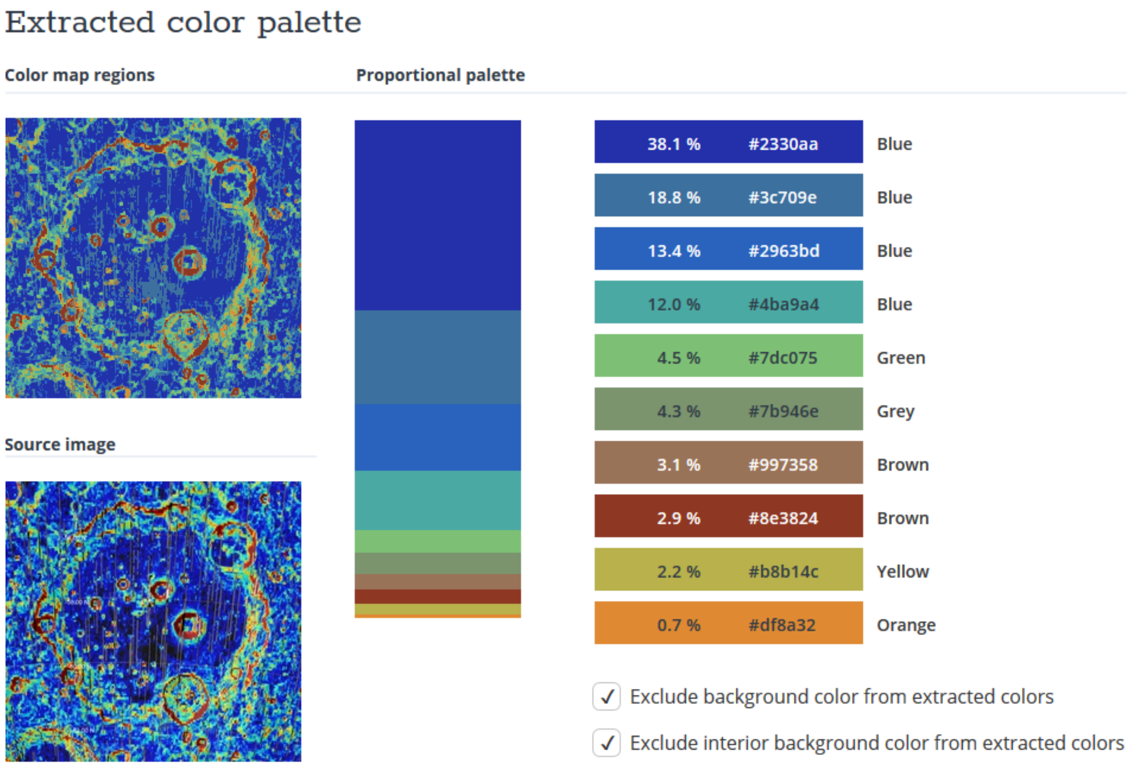


Figure 46. Clavius Crater Surface Slope Percentages

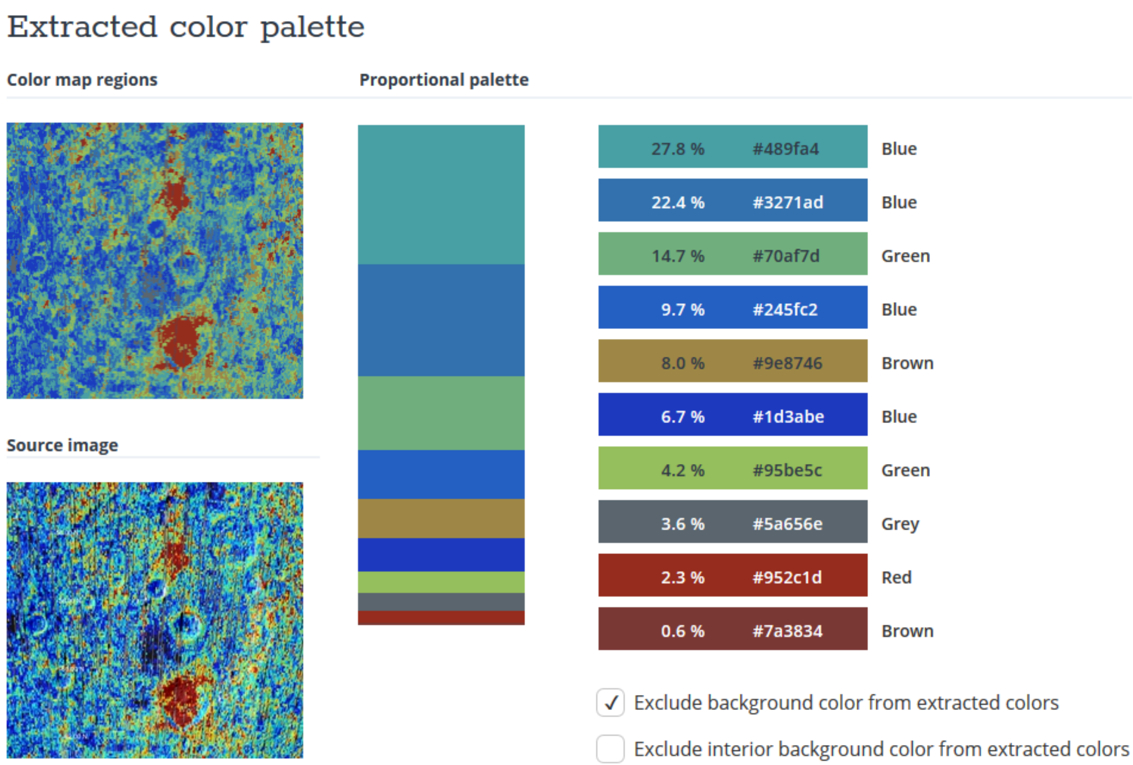


Figure 47. Clavius Crater Surface Roughness Percentages

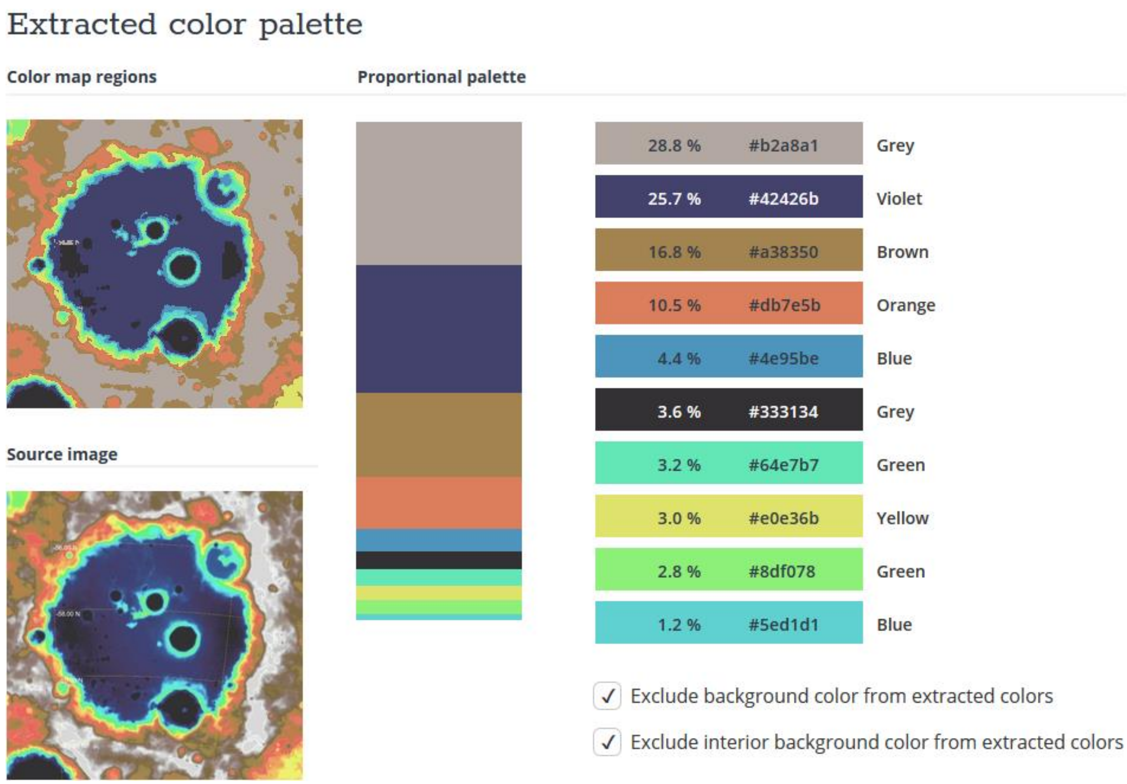


Figure 48. Clavius Crater Elevation (GLD100 plus LOLA) Percentages [26], [39], [44]