Assessment of Lunar Resource Exploration in 2022

Circular 1507

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Buzz Aldrin's bootprint during the famous July 20, 1969, walk on the Moon with fellow astronaut Neil Armstrong. National Aeronautics and Space Administration photograph.

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Assessment of Lunar Resource Exploration in 2022

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Abstract

The idea of mining the Moon, once purely science-fiction, is now on the verge of becoming reality. Taking advantage of the resources on the Moon is part of the plans of many nations and some enterprising commercial entities; demonstrating in-situ (in place) resource utilization near the lunar south pole is an explicit goal of the United States' Artemis program. Economic extraction and sustainable management of these resources require understanding the nature, quantity, and quality of each resource. This publication aims to provide a relatively simple, but technically rigorous, assessment of the status of lunar resource exploration in 2022.

Building on the experience of the U.S. Geological Survey in conducting resource assessments for Earth, we propose a general methodology for quantitative lunar resources assessments. Lunar resources can be categorized as energy, mineral, and water and classified with respect to their certainty and their recoverability. The portion of the technically recoverable resource that can be converted to a commodity within budgetary and other mission constraints can be classified as a "reserve."

For energy resources, solar energy is known to be especially abundant along some high ridges near the lunar poles and the technology to exploit it is mature. Mineral resources, largely in the form of loose rock powder that covers the surface of the Moon, are also widely accessible in large quantities. Many different technologies to convert this material into useful commodities (such as landing pads and oxygen) are currently being developed and are likely to be available for industrial-scale application within 30 years. Water ice almost certainly exists in the polar regions of the Moon but there are fundamental unanswered questions about when and how the ice formed—leaving us without knowledge of the form, quantity, quality, and distribution of lunar ice. Until rover missions bring new ground truth data, lunar ice will remain a highly speculative resource that may be both limited and non-renewable.

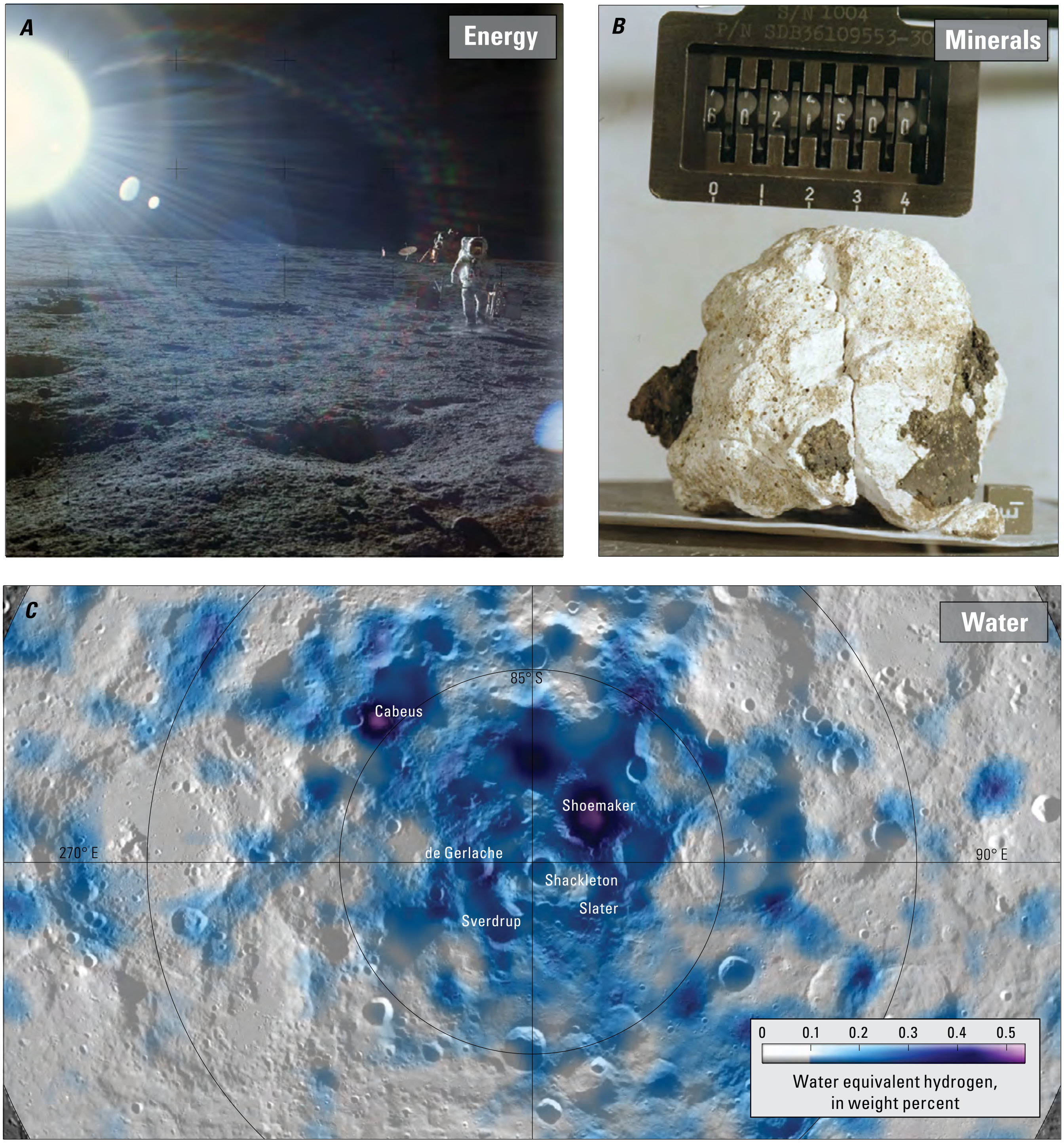
Introduction

This report provides a brief overview of the state of lunar resource exploration in 2022 within the framework of the U.S. Geological Survey's (USGS's) more than 100 years of experience in conducting resource assessments on Earth. It focuses on how close we are to conducting quantitative assessments of lunar resources that would meet the USGS's high standards for rigor and transparency. This report is intended to fill a gap between the popular and technical information currently available on this topic. We also note that, while the exploration of the Moon is an international endeavor, we focus on efforts by the United States, in general, and the National Aeronautics and Space Administration (NASA) Artemis program, in particular.

Lunar Resources

Even before the first Apollo astronauts blasted into space in 1968, it was clear that taking advantage of lunar resources would be essential for a sustained human presence on the Moon (Lowman, 1966). The United States' current plans to return humans to the Moon, the NASA Artemis program, distinguishes itself from Apollo by aiming to establish sustainable lunar exploration (NASA, 2019). For this reason, Artemis is focused on establishing a base near the lunar south pole and one of its major goals is to demonstrate in-situ resource utilization—that is, the ability to generate useful products using local resources (NASA, 2020). In-situ resource utilization is also a rapidly expanding component of other government space programs as well as prospective commercial endeavors (International Space Exploration Coordination Group [ISECG], 2021).

Following the framework used by the USGS for resources on Earth, it is helpful to consider lunar resources in three major categories: energy, minerals, and water (fig. 1). Though each of these are discussed in this report, some background is needed first. When the USGS uses the term "resource," it is referring to a concentration of a naturally occurring material in such form and amount that economic extraction of a commodity is feasible (U.S. Bureau of Mines and U.S. Geological Survey, 1980). For decades, a major stumbling block for developing in-situ resource utilization technology was that it was widely held that the 1967 Outer Space Treaty prohibited extraction of commodities from the Moon. However, national laws providing explicit legal permission for using space resources have been recently passed by some nations (for example, the Unites States in 2015, Luxembourg in 2017, and Japan in 2021). To end hypothetical discussions and establish a clear legal precedent, on August 23, 2021, NASA made a $0.10 payment to a commercial provider for a lunar commodity (Turner, 2021). The lack of legal challenges to this materially trivial case is expected to mitigate future legal action when larger quantities of lunar material are put to use.



Base image mosaic from National Aeronautics and Space Administration, Arizona State University, and Applied Coherent Technology Corp. Lunar QuickMap, 0.5 and 100 meter resolution

Figure 1. Three categories of lunar resources. These are the same three categories the U.S. Geological Survey uses for resources on Earth: energy, minerals, and water. *A*, Photograph from the Apollo 12 mission showing the unfiltered sunlight that bathes the Moon. National Aeronautics and Space Administration (NASA) photograph AS12-46-6806 by Charles “Pete” Conrad on November 19, 1969. *B*, Photograph of anorthosite breccia sample 60215, similar to rocks expected near the south pole of the Moon, collected by the Apollo 16 mission. NASA photograph s72-44478. *C,* Map of water-equivalent hydrogen around the south pole of the Moon (from the Lunar Reconnaissance Orbiter’s Lunar Exploration Neutron Detector; data available in the Lunar QuickMap and method to calculate water-equivalent hydrogen from Sanin and others, 2017).

As legal issues are being addressed, technical barriers to in-situ resource utilization are also being tackled. Currently, the maturity of the technology to extract and utilize lunar resources is varied. For example, the use of solar power for operations on the lunar surface was first accomplished by Luna 9 in 1966, and the related technologies have steadily improved on Earth and in space. The technologies for extracting minerals and water from the Moon are not as mature, but development efforts are underway across many entities including several new commercial endeavors and several national space programs (the European Space Agency, the China National Space Administration, the Israel Space Agency, the Indian Space Research Organization, and Roscosmos to name a few). NASA's Space Technology Mission Directorate has multiple programs that fund a broad array of research into in-situ resource utilization technologies (Sanders, 2021). NASA has been investigating an architecture to process at least 15 metric tons of ice from near the lunar south pole to produce at least 10 metric tons of oxygen and 2 metric tons of hydrogen by the year 2030 (Kleinhenz and Paz, 2020). Technology for constructing landing pads out of the lunar regolith (the layer of pulverized rock that covers the Moon's surface) is another high priority for NASA (NASA, 2020). A variety of active technology development efforts are working toward using a mix of lunar resources that would sustain a human presence on the Moon (fig. 2).

As legal and technological challenges are being actively addressed, the remaining open issue is what lunar resources exist, where they can be found, and if they are in sufficient quantity and quality to make use of. There are two fundamentally different approaches to discovering resources: prospecting and exploration (fig. 3). Prospecting relies on a modicum of scientific knowledge and a great deal of luck to find economically viable deposits. Though risky, this approach may be the only viable option if very little information is available. In contrast, resource exploration is a multidisciplinary campaign that systematically identifies and reduces uncertainties and risk leading up to the decisions of if, where, how, and when to extract a resource. For the Moon, a coordinated international resource evaluation campaign may be the most practical way to obtain the large amounts of data required for this approach (Neal and others, 2022). The output of the resource exploration process is typically presented as a report, called an assessment. If the assessment provides estimated amounts of the resource, and the uncertainties in those amounts, it is classified as a "quantitative resource assessment." For major commercial endeavors in recent decades, this type of assessment is typically considered a prerequisite for making key decisions related to resource extraction. For industrial-scale lunar in-situ resource utilization to become a reality, obtaining quantitative assessments of lunar resources is arguably of similar importance as solving the legal and technological challenges.

USGS Resource Assessments

The USGS was established by Congress under the Organic Act of 1879 and charged with the "classification of public lands and the examination of the geological structure, mineral resources, and products of the national domain" (43 U.S.C. 31 et seq.). Over its history, the USGS has become internationally recognized as a leader in providing reliable assessments of energy, minerals, and water resources (U.S. Geological Survey World Energy Assessment Team, 2000; Schulz and Briskey, 2003; Miller and others, 2021). This has been achieved by developing, and continually improving, methods to provide rigorous and transparent quantitative assessments in a format that can be understood by decisionmakers with varied technical expertise. In 1962, the mandate to assess resources was expanded to "...outside the national domain..." (Public Law 87-626), which opened the door to assessing international as well as extraterrestrial resources. In 2017, the USGS published a study showing the feasibility of assessing resources in near-Earth asteroids with only modest modification of the methodologies used for assessing mineral resources on Earth (Keszthelyi and others, 2017). The USGS has

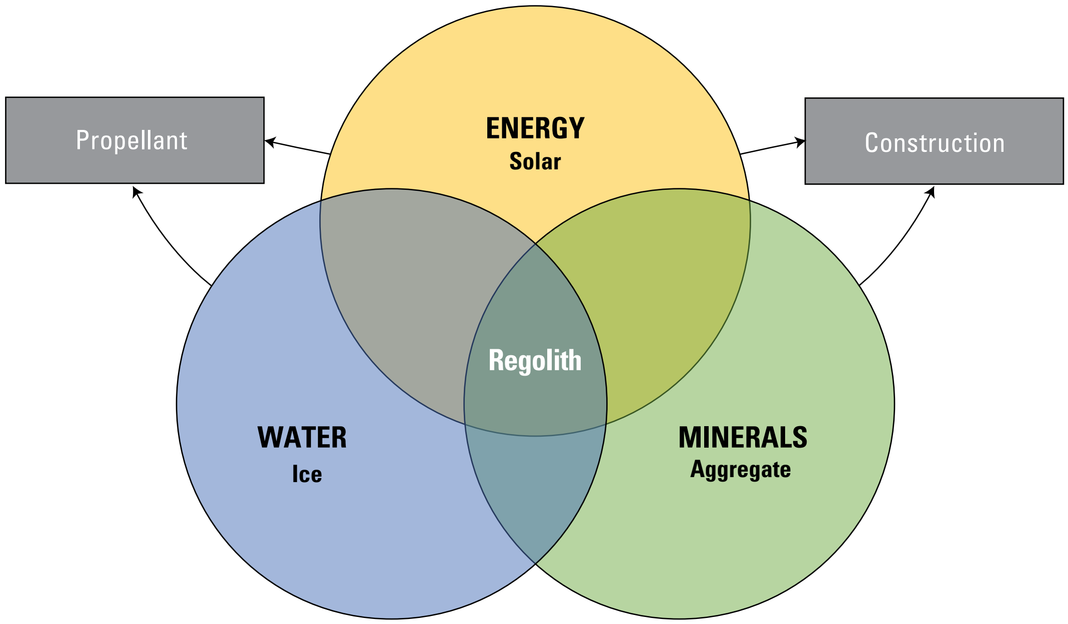


Figure 2. Diagram showing different lunar resources and their uses. Energy is needed to convert water and mineral resources into useful commodities such as propellant and construction materials. All these resources can be found in the pulverized rock (regolith) that covers the lunar surface.

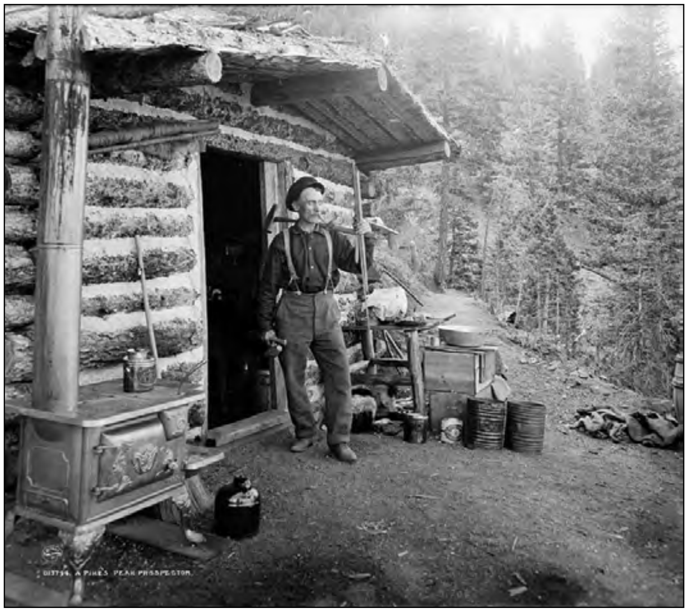
also investigated how its resource assessment methodologies could be applied to the Moon (Keszthelyi and others, 2018, 2021, 2022).

Although there are differences in the details of the USGS assessments conducted for energy, minerals, and water, there are also important fundamental principles that are consistent across all quantitative resource assessments.

- Rigorous—the most appropriate scientific and statistical methods are applied.
- Transparent—each assumption and step in the analysis is fully described.
- Quantitative—numerical values of key quantities (and uncertainties) are provided.
- Understandable—the key points are explained in terms all stakeholders understand.

The combination of these properties allows users of the assessment to verify that it is unbiased and trustworthy.

A. **Resource prospecting**



B. **Resource exploration**

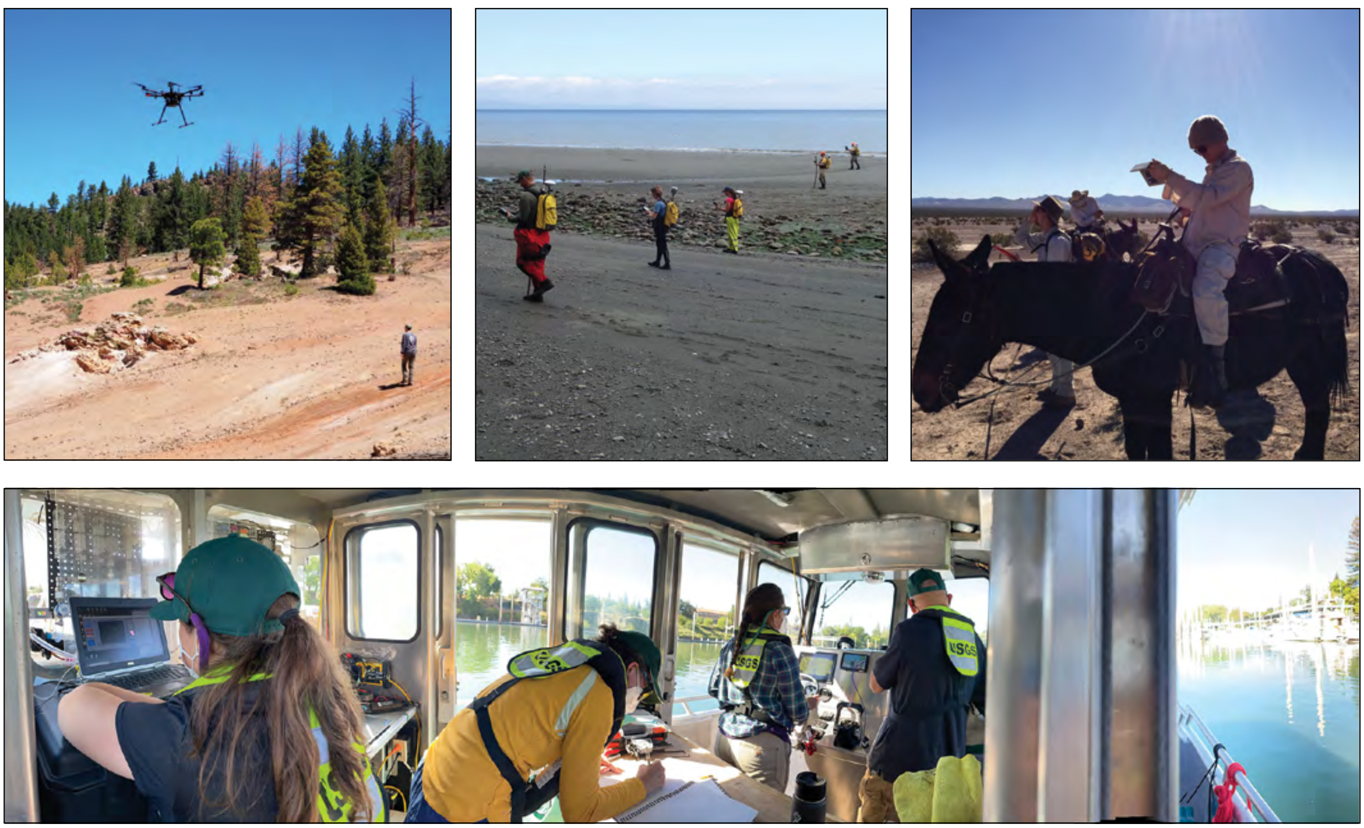


Figure 3. Resource prospecting versus exploration. *A*, Prospector on Pike's Peak, Colorado, around 1900. While the role of the individual prospector has been romanticized, few prospectors were supported beyond a minimum subsistence level (U.S. Forest Service, 1995). Photograph by William Henry Jackson, from the Detroit Publishing Company collection of the U.S. Library of Congress. *B,* Resource exploration is conducted by interdisciplinary teams of professional specialists, paving the way for large resource extraction operations that produce most commodities on Earth (U.S. Forest Service, 1995). Photographs by Jonathan Glen, U.S. Geological Survey (USGS) (top left); USGS (top middle); Andrew Cyr, USGS (top right); USGS (bottom).

Developing Quantitative Lunar Resource Assessments

We have recently used the framework of the established USGS resource assessment methodologies to consider lunar resources (Keszthelyi and others, 2018, 2021, 2022). In general, we find much of the USGS terminology from mineral resource assessments to be directly applicable to the Moon but do recommend some simplification and borrowing of terminology from energy assessments.

Resource Classification

Before discussing how to quantify lunar resources it is helpful to establish a classification system that provides the language to describe how usable a resource is (fig. 4). There are two key considerations: (1) do we know where the resource is, and (2) do we know how to convert the resource into a useful commodity (U.S. Bureau of Mines and U.S. Geological Survey, 1980). To describe the confidence in our knowledge of a resource, we use the terms “speculative” to mean there are theoretical and indirect reasons to expect deposits of the resource in the area, “inferred” to mean the properties of the deposits in the area are estimated by extrapolating from other well-studied regions, and “measured” to mean the properties of the deposits have been directly measured within the area being assessed.

The recoverability, that is the maturity of technologies to convert lunar resources into useful commodities, is the other key consideration (fig. 4). We adopt the concept of a “technically recoverable” resource that is used in assessments of petroleum resources on Earth. Petroleum assessments found that it was important to limit consideration of new technologies to those that are likely to be available for commercial-scale production in a 30-year timeframe (Schmoker and Klett, 2005), and we suggest that this translates well to discussions of lunar resources as well. In terms of the widely used Technical Readiness Levels defined by NASA (fig. 5), this 30-year timeframe can be translated as technologies that are currently at level 3 or higher (that is, the concept has been proven to be viable at least in the laboratory). We use the term “unrecoverable” to mean the technology to convert the resource into a commodity does not currently exist and is not likely to exist within the next 30 years.

On Earth, the term “reserve” is limited to the portion of the resources that can be economically extracted (U.S. Bureau of Mines and U.S. Geological Survey, 1980). For the Moon, we currently cannot rely on market forces to define what is economical. Instead, we propose that for a deposit to be considered a reserve, the conversion to a commodity must be not just technically possible but also achievable within mission constraints. Space missions are constrained by

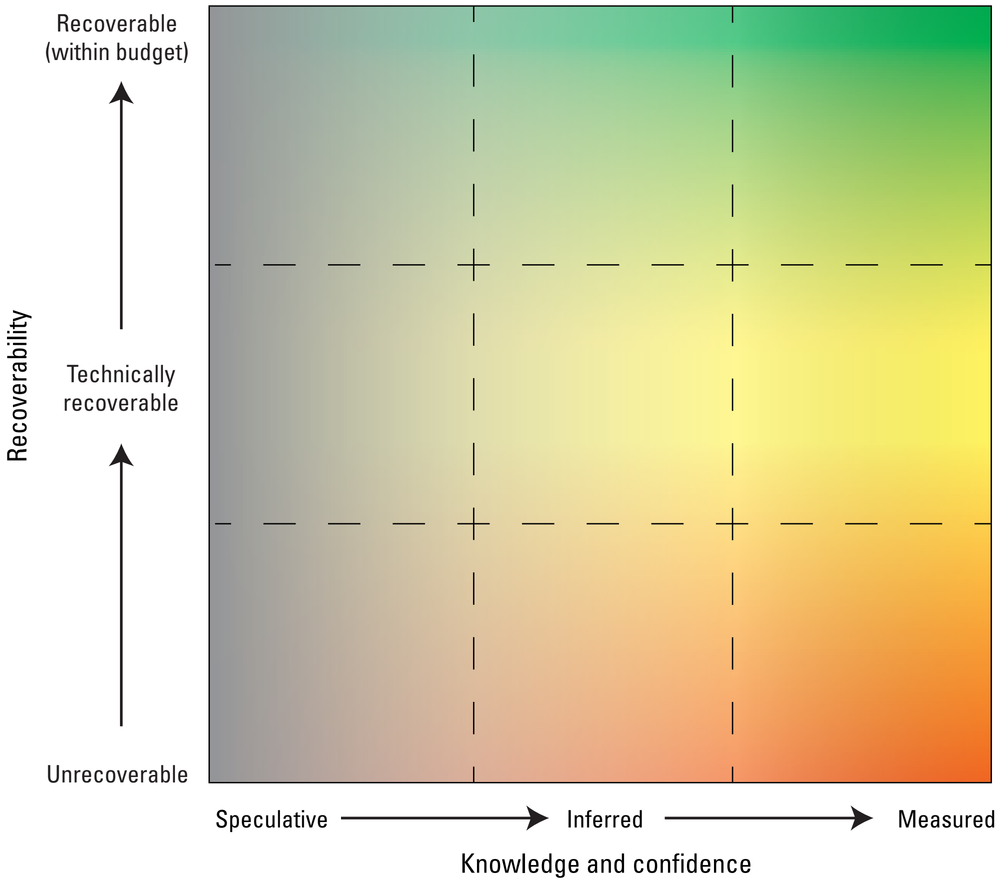


Figure 4. Diagram of proposed classification of lunar resources. Terminology combines and simplifies terms used by the U.S. Geological Survey for mineral and energy resources.

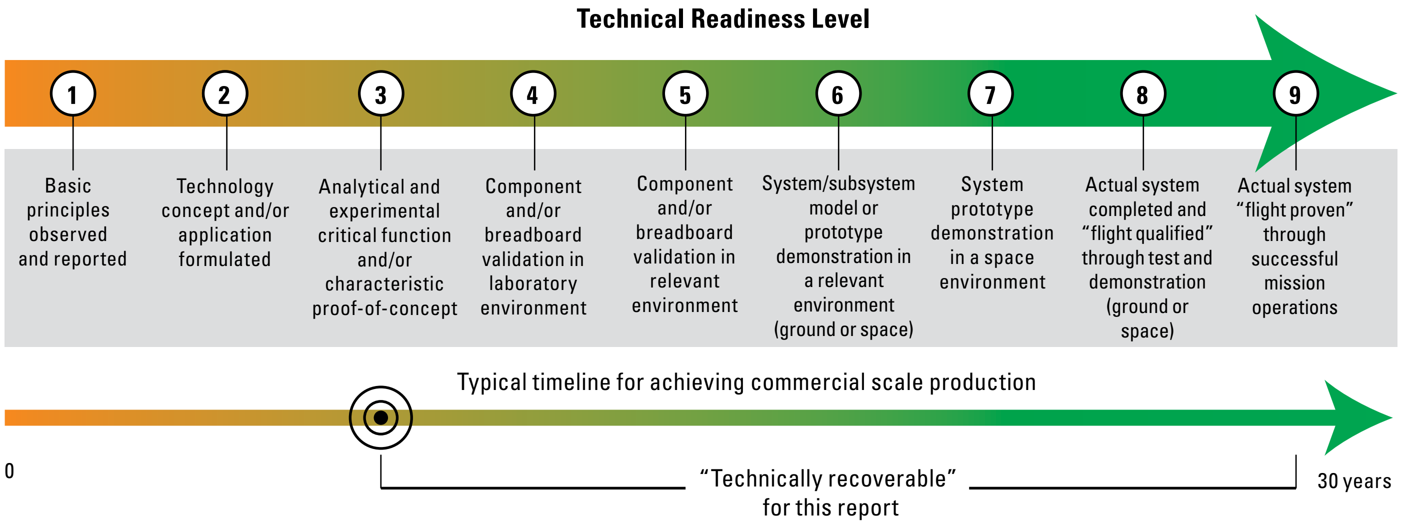


Figure 5. Diagram of Technical Readiness Levels as defined by the National Aeronautics and Space Administration (NASA). In practice, this system has become an international standard. Modified from NASA.

multiple factors, including power, mass, volume, schedule, cost, and risk. Typical space missions do not have sufficient risk budgets to consider speculative or inferred deposits as reserves. However, there are exceptions. For example, it may be considered acceptable for a technology demonstration mission to go to a site that has only inferred deposits.

Quantitative Lunar Resource Assessment Methodology

A general methodology for conducting a quantitative lunar resource assessment can be derived from the three-part USGS quantitative mineral resource assessment methodology (Singer, 2007). This proposed methodology (fig. 6) provides a systematic process that breaks the problem into discrete segments, or models, that lead to a final report intended for a wide variety of decisionmakers and stakeholders.

As on Earth, a robust quantitative assessment of any lunar resource must start with an understanding of the processes that created each type of deposit of that resource. Note that we use the term "deposit" in a very generic sense meaning any occurrence of a resource; sunlight striking the surface of the Moon or a pocket of buried ice would be "deposits" of solar energy and water, respectively, in this terminology. The understanding of processes identifies the geologic and geographic settings in which the resource can be found, and which combination of measurements are most reliable in finding those settings. This thorough, qualitative understanding of the nature and context of the resource is necessary because, without it, an assessment could mix different types of deposits of a resource, a proverbial mixing of apples and oranges that leads to statistical errors and incorrect conclusions. This understanding can be captured in a qualitative descriptive model in a standard format derived from descriptive models for mineral deposits on Earth (Heran, 2000). Once the fundamental characteristics of a specific type of deposit of the resource are understood, it is possible to delineate the locations, or tracts, where such deposits are plausible. This spatial model is what ties the subsequent statistical analyses to specific locations on the Moon.

A quantitative resource assessment builds upon detailed analysis of one or more representative areas that contains the type of deposit being assessed. If the resource is found in discrete deposits, it is essential to determine the number of deposits in the area, leading to a deposit density model. However, the concept of a deposit density model is not readily applicable to many lunar resources, especially those that are derived from the regolith. Lunar regolith forms a nearly global layer that has consistent properties across large regions of the Moon except where punctured by recent impact craters. This is analogous to some petroleum resources on Earth, like shale gas, which are distributed relatively evenly across very wide areas (Schmoker, 2005). In such cases, the term "continuous deposit" is used. The experience from energy resource assessments indicates that, in these cases, it is not useful to provide an estimate of the total amount of the resource in a regional (or global) layer. Instead, there is more value in providing estimates of the amount of the resource per unit area of the surface. This is also in line with how solar energy, another widely distributed lunar resource, is typically quantified.

Whether the deposits are discrete or continuous, it is necessary to evaluate the variability in the quantity and

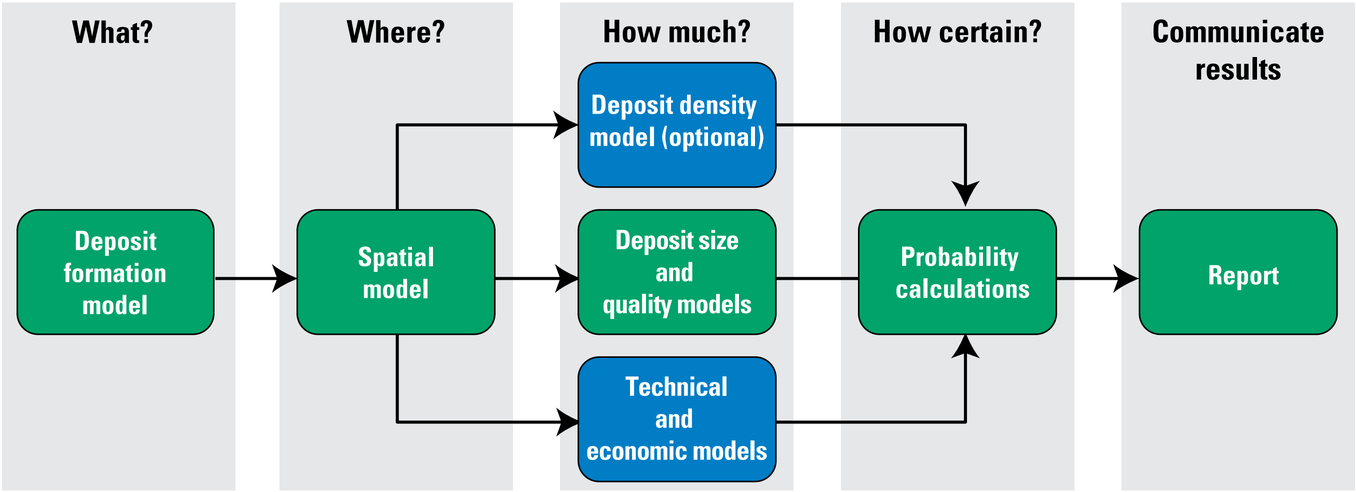


Figure 6. Schematic diagram of the quantitative lunar resource assessment methodology. This is a modest modification of the U.S. Geological Survey (USGS) quantitative mineral resource assessment methodology (Singer, 2007), including relevant concepts from USGS energy resource assessments and terms more common in lunar science. The steps shown in green are essential, but the ones in blue may be skipped in some cases.

quality of the resource within them. For minerals on Earth, the terms “grade” and “tonnage” are used, but we suggest the more generic terms of “quality” and “quantity” may be more appropriate for a generic lunar resource. It is important to emphasize that the focus is not on determining a single value for quantity but instead on understanding the variability in both quantity and quality. Without a robust understanding of how variable the deposits are, there can be no valid means to estimate the uncertainties in an assessment. The variabilities are best expressed in terms of probability distribution functions which can be readily incorporated into existing statistical tools and tests. As discussed previously, a consideration of what resources can be considered technically recoverable within a 30-year timeframe is also useful to incorporate.

The USGS has several different software tools for combining the information from spatial models, deposit density models, deposit quantity and quality models, and recoverability models to compute quantitative assessments for energy, minerals, and water. The tools vary in the specifics, especially related to data input and output formats, but they all rely on the Monte Carlo method to consider very large numbers of scenarios from which robust statistics can be calculated. Quantitative lunar resource assessments would follow a similar methodology, but as on Earth, software tools will need to be tailored to each type of resource. Depending on the nature of the deposits, it may be most appropriate and useful to report the results globally, on a tract-by-tract basis (as is typical for minerals on Earth), or on a gridded map product (as is sometimes done for continuous petroleum resources).

The final step is to report the assessment to the community of stakeholders, which for a lunar assessment, includes scientists who will review the assessment, decisionmakers within and outside of government, and those paying for the lunar exploration—investors and taxpayers. The USGS has honed its communication techniques about resources on Earth over decades, which has provided lessons that are relevant for lunar resources. One example is how the probability distribution for the quantity of resource is reported. When there is ample information and the audience is comfortable with statistics, the information can be provided as a chart or table with values for multiple levels of confidence which is the best way to illustrate skew in probabilistic models. However, if the geologic information is less complete, experience has shown that providing just the minimum, median, and maximum expected values is the most appropriate (Singer, 2007). In the case of the Moon, the 95 percent confidence level, which closely corresponds to two standard deviations in a normal distribution, seems an appropriate cut-off for the reported minimum and maximum values. We expect that lunar resource assessments will need to start at this basic level before there are sufficient data and understanding to merit reporting assessments in a more complex manner.

There are situations where a full quantitative assessment is either not warranted or not feasible. In these cases, more qualitative assessments can be completed. One example of such a product is termed a “prospectivity map,” which indicates which locations are more (or less) favorable for the presence of a specific resource. Several such maps have been recently produced and could feed into the spatial model of a quantitative assessment (for example, Kleinhenz and others, 2020; Cannon and Britt, 2020; Orgel and others, 2022; Brown and others, 2022). In the following sections, we consider how amenable different lunar resources are to being quantitatively assessed and how they can be currently classified (table 1).

Table 1. Summary of the state of several potential lunar resources for the Artemis program.

[Terms as defined in this report (fig. 4). ^{3}He, heavy isotope of helium]

Potential lunar resource	Current classification	Amenable to quantitative assessment	Recoverable with current technology	Plausible reserve in 30 years
Solar energy	Measured reserve	Yes	Yes	Yes
^{3}He	Inferred unrecoverable resource	Yes	No	Unknown
Bulk regolith	Measured unrecoverable resource	Yes	No	Yes
Regolith oxygen	Measured unrecoverable resource	Yes	No	Yes
Bound water and hydrogen	Inferred unrecoverable resource	Likely	No	Probably
Water ice	Speculative unrecoverable resource	Probably	No	Unknown

Energy Resources on the Moon

Solar Energy

Energy is required for any activity. For space missions, energy has usually been provided by solar arrays or radioisotope thermal generators. Batteries and fuel cells have been used as a primary power source only for shorter duration missions but often serve as temporary storage (Patel, 2004). There are several considerations, including cost, that make solar power generally preferrable to radioisotope thermal generators. For most locations on the Moon, solar power is available during the 2-week-long day and then unavailable for the 2-week-long night. However, near the poles, there are crater interiors that are in permanent shadow and peaks that are illuminated nearly continuously (Mazarico and others, 2011). This provides the tantalizing possibility that future exploration to the coldest, permanently shadowed, polar regions could take advantage of power generated from nearby persistently illuminated ridges (Speyerer and others, 2016).

If we consider following the quantitative resource assessment workflow (fig. 6), there is sufficient information to construct a descriptive model, and the whole Moon can be considered a single deposit that is quite uniform except near the poles. The quantity and quality of solar power available on the lunar surface can be assessed to a high degree of certainty because (1) the energy output of the Sun is well known, (2) the relative position and orientation of the Moon with respect to the Sun are known with great precision, (3) the topography of the Moon is known globally to a scale of tens of meters and about 5 meters in some localities of special interest, and (4) there are no clouds or other weather-related variability that could obstruct sunlight on the Moon. Maps that show the percent of the time each part of the Moon is illuminated already exist (fig. 7), allowing the quantity of available solar energy to be easily computed (Speyerer and Robinson, 2013). The length of time without sunlight is a key metric of the quality of the available solar power that is readily calculated from the available data. In summary, existing studies have already identified the specific areas on the Moon that are particularly valuable for solar energy recovery. This does not negate the need for detailed analysis of any specific solar energy collection facility; for example, positioning solar arrays even 2 meters (7 feet) above the surface significantly increases the duration of illumination (Gläser and others, 2018).

Following the terminology in figure 4, solar energy can be classified as a measured technically recoverable lunar resource (table 1). Many missions, including the upcoming NASA Volatiles Investigating Polar Exploration Rover (VIPER) mission, would go a step further and consider solar energy a reserve. The technology to convert solar energy to electricity in space is mature (Technical Readiness Level 9 of fig. 5) and its efficiency continues to improve. Current (as of 2022) space-qualified arrays can exceed 30 percent efficiency (Chamberlain and others, 2021), and can produce more than 400 watts per square meter if optimally pointed toward the Sun. Methods to deploy mirrors that concentrate solar energy are also being developed to melt or sinter (fuse a powder by heating short of complete melting) lunar materials without having to convert the energy to electricity first (Farries and others, 2021). The most challenging part of utilizing solar energy on the surface of the Moon may well be landing on the surface and deploying collectors or arrays in the desired location. Though the existing topographic maps are adequate for showing how much illumination to expect across the Moon, they are not quite at the scale of typical landers and rovers. For multiple successful landings on Mars, the topographic requirement for landing site certification is to resolve 0.6-meter-tall (about 2 feet) boulders and slopes at 2- to 5-meter (7- to 20-foot) scales (Grant and others, 2018). These requirements are met with the Mars Reconnaissance Orbiter High-Resolution Imaging Science Experiment (HiRISE) camera, which obtains images with a pixel scale of 25–30 centimeters (9.8–12 inches) per pixel (McEwen and others, 2007). The Lunar Reconnaissance Orbiter Camera (LROC) can obtain images at a comparable, 50 centimeters (20 inches) per pixel scale (Robinson and others, 2010). However, near the poles where illumination is often poor, images are typically acquired at 100–200 centimeters (40–80 inches) per pixel to improve image quality. Thus, for landings in the polar regions, the current best topographic information is approximately three to four times worse than for recent successful Mars landings. This constitutes a considerable, but not insurmountable, technical challenge.

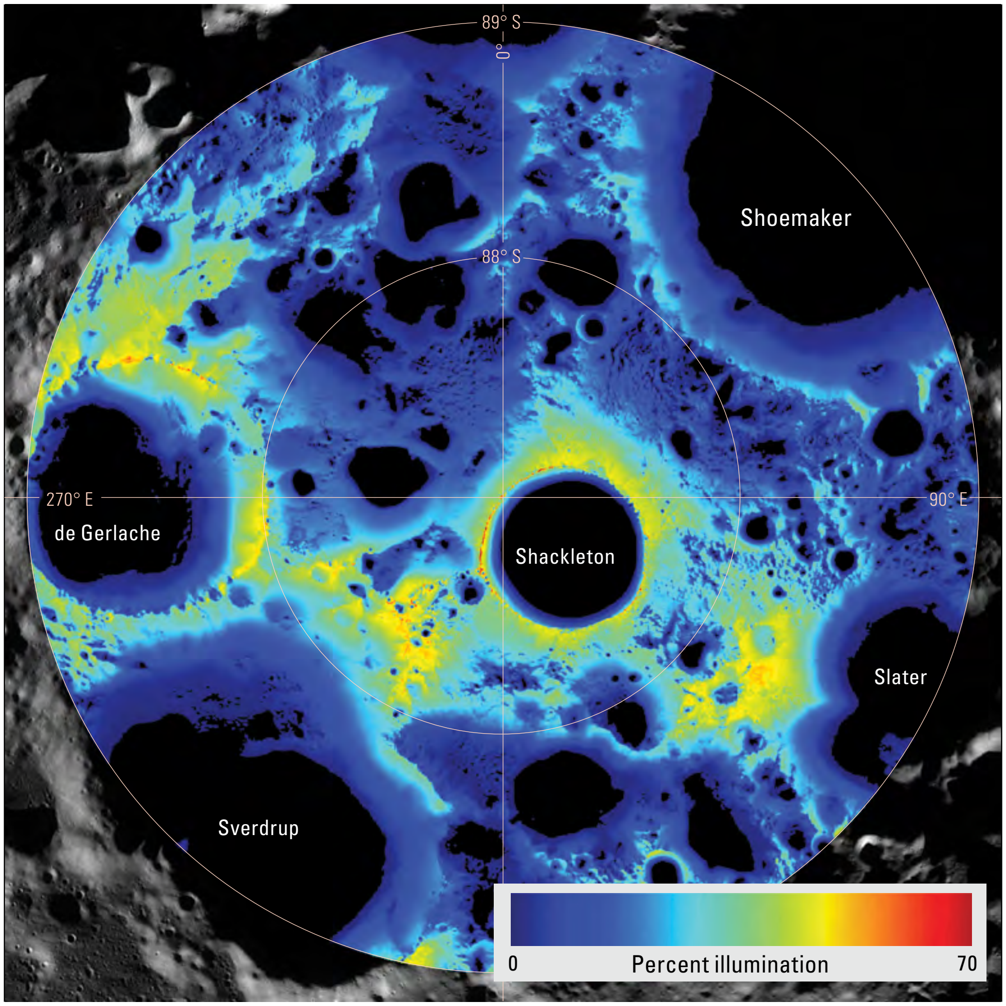


Figure 7. Illumination map of the south polar region of the Moon. Areas in black receive no sunlight, and areas in warmer colors are illuminated a greater fraction of the time. Many polar craters have permanently shadowed floors, making them cold enough to retain water ice, and the rims of some of these craters are illuminated at least 70 percent of the time (from the Lunar Reconnaissance Orbiter Camera; data available in the Lunar QuickMap and method to calculate illumination conditions from Speyerer and Robinson, 2013).

Base image mosaic from National Aeronautics and Space Administration, Arizona State University, and Applied Coherent Technology Corp. Lunar QuickMap, 0.5 and 100 meter resolution

Helium-3

Another lunar energy resource that has been discussed in the past is the heavy isotope of helium (^3He), which could fuel clean fusion reactors in the future (Schmitt, 2020). Found in small quantities in the solar wind, ^3He is implanted into the lunar regolith in concentrations of 2.4–26 parts per billion by mass, as measured in samples from the Apollo 11 mission (Schmitt, 2006). This indicates that a kilogram of ^3He would require processing approximately 100,000–1,000,000 metric tons of regolith (Schmitt, 2020). The solar wind bathes the entire Moon whenever it is outside of the Earth's protective magnetosphere but the concentration of implanted ^3He may not be homogenous. There is evidence that helium (He) is preferentially retained in regolith rich in the mineral ilmenite, which is scarce in the polar regions of the Moon (Fa and Jin, 2007). At the same time, it is plausible that solar wind volatiles, including ^3He, are preferentially retained in the colder parts of the Moon. This makes extrapolating our knowledge of ^3He from the Apollo samples to where the Artemis program plans to build a base at the south pole very uncertain. However, since fusion reactors are in the research stage, and it is unclear if ones that use ^3He will be producing power on an industrial scale in the next 30 years (Waldrop, 2020), there is little urgency in completing a formal assessment of ^3He as a lunar resource. For now, ^3He can be classified as an inferred unrecoverable resource (table 1).

Mineral Resources on the Moon

The Moon is almost entirely covered in a layer of pulverized rock called regolith. The only exceptions are bedrock exposures on steeper slopes such as crater rims. The regolith has many potential uses, but the ones that have garnered the most attention are (1) aggregate for construction and (2) feedstock for oxygen production. There are stated needs for both commodities to support the development of a lunar base in the second phase of the Artemis program (NASA, 2019).

Regolith for Construction

With the lunar surface covered with crushed rock, it is extremely inefficient to bring such material from Earth to construct a lunar base and the associated infrastructure such as landing pads and roads. In considering regolith for construction, we work through the steps required for a quantitative resource assessment (fig. 6). A thorough descriptive model for lunar regolith can be compiled thanks to the combination of returned samples, including multiple drive tubes and drill cores from the Apollo missions (fig. 8), and comprehensive remote sensing observations (Heiken and others, 1991). The constant bombardment of the Moon's surface by particles ranging from large meteorites to cosmic rays has pulverized the rocks at the lunar surface, with 90 percent of the particles less than 1 millimeter (0.04 inch) in size (Carrier, 2003). Owing to the absence of transport by wind or water, lunar particles are sharp, angular fragments (Heiken and others, 1991). Impacts are capable of melting and vaporizing some of the surface materials, resulting in frozen droplets of rock and coatings that cement particles together into clumps called agglutinates (Basu, 1977).

Over billions of years, the regolith layer is laterally and vertically mixed by impacts and the repeated shaking of distant impacts has fully compacted the regolith below about 30 centimeters (about 12 inches) in depth (Heiken and others, 1991). However, where the regolith has had less time to mature,

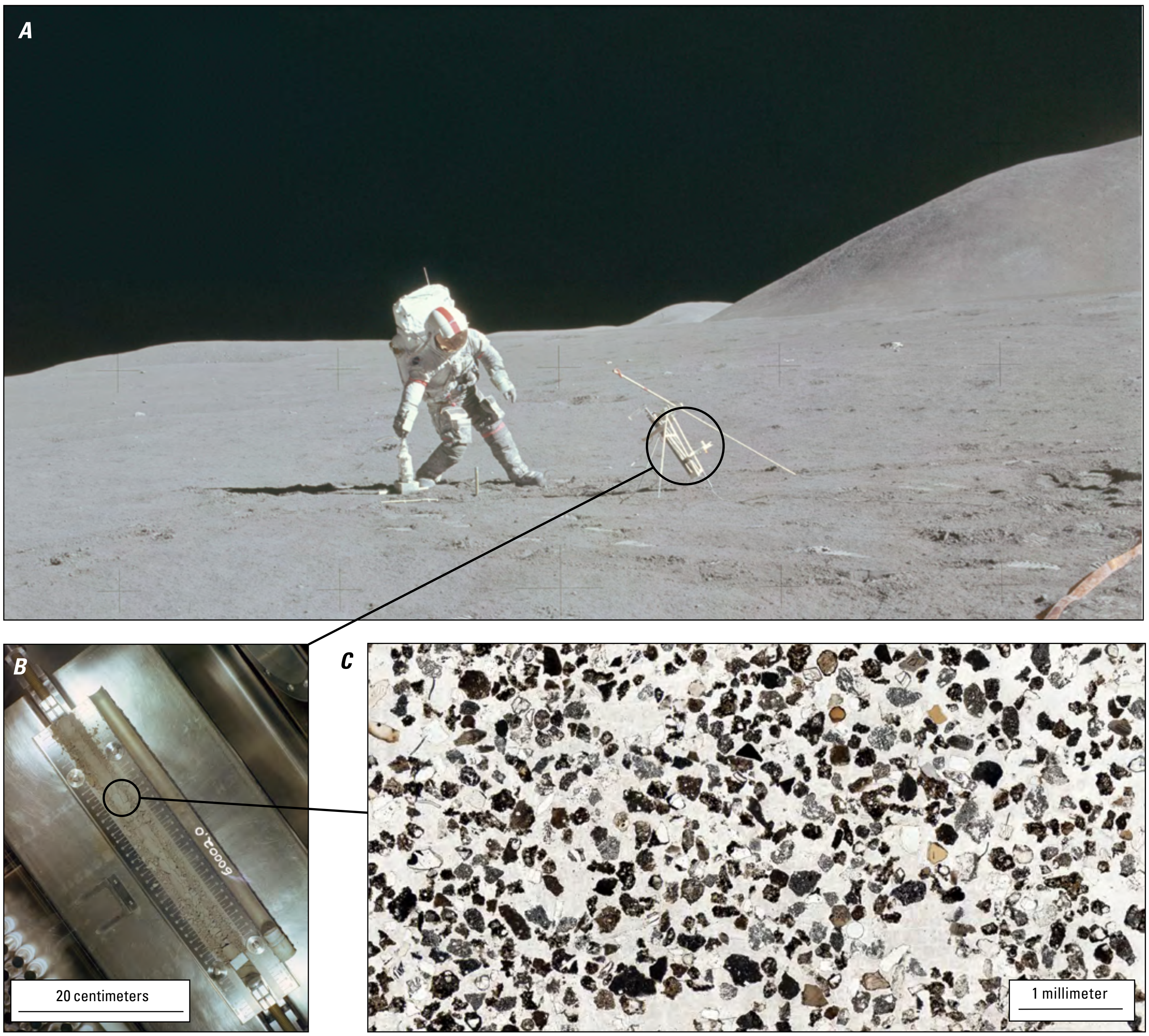


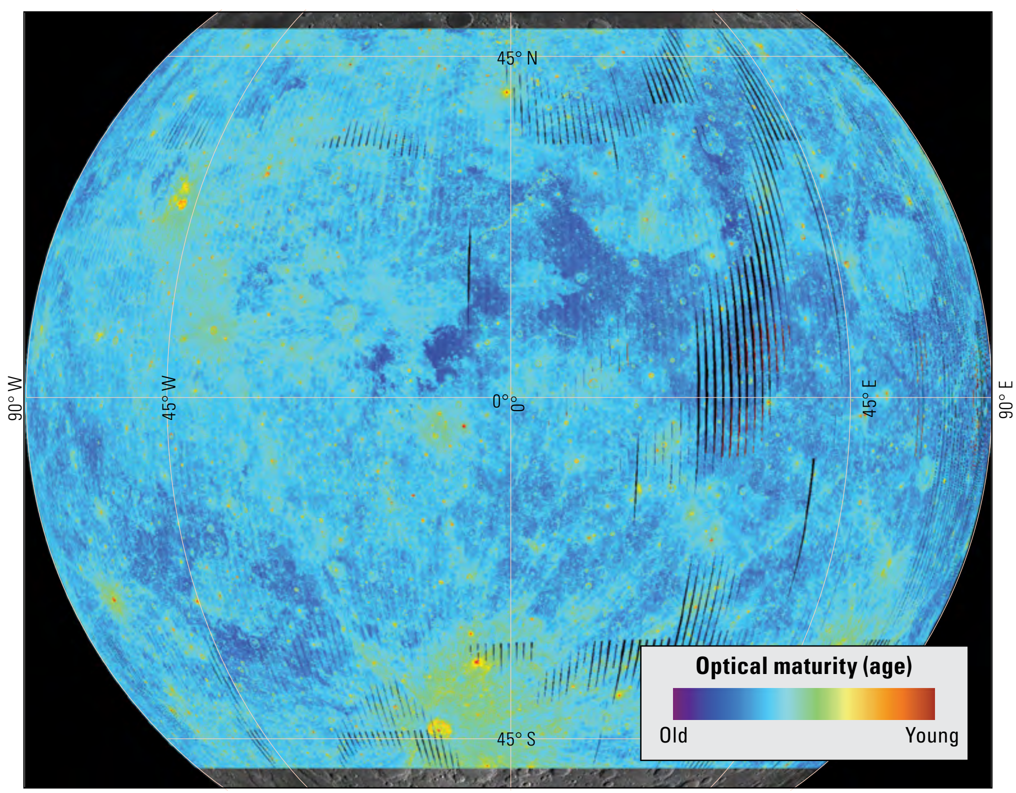
Figure 8. Images showing lunar regolith sampling during the Apollo missions. *A*, Photograph showing Apollo 15 Commander David Scott setting up a deep drill. National Aeronautics and Space Administration (NASA) photograph AS15-87-11847 taken by James Irwin. *B*, Photograph of a regolith core from the Apollo 16 mission opened at the Johnson Space Center in Houston, Texas. NASA photograph S74-21082. *C*, Microscope image of regolith sample 68501 from the Apollo 16 mission. Photograph from the NASA Apollo Virtual Microscope Collection.

it is thinner and contains more large rocks. Younger regolith has also been subjected to less irradiation by the solar wind and cosmic rays. The extent of the radiation damage to the minerals can be detected by spectrometers on Earth-based telescopes and lunar orbiters, which provides a method to determine the relative age of the regolith termed "optical maturity" (Lucey and others, 2000; Lemelin and others, 2016). A map of optical maturity shows that the Moon is almost completely covered in mature regolith with only small spots and streaks of younger regolith (fig. 9). Visible and thermal images show that these areas are associated with recent impact craters that exhume fresh boulders from the bedrock under the regolith, creating local areas with younger and coarser regolith.

The idea that lunar regolith is effectively one global deposit with only modest variations is supported by global mapping with radar, infrared-ultraviolet spectroscopy, high-resolution imaging, and gamma-ray spectrometry. This means a deposit density model is not needed for a lunar regolith assessment. However, it is important to quantify the variability in regolith particle sizes and the thickness since these would affect the quality and quantity of the regolith for construction. Based on the Apollo seismic experiments and the size of craters that contain exhumed bedrock, the regolith is on average about 5–20 meters (20–70 feet) deep (Nakamura and others, 1975; Elder and others, 2019). It is significantly thinner only on steep slopes (about 30 degrees) where loose material slides downhill under the influence of gravity. The variations in regolith depth, particle size, and surface slope have not been fully mapped and quantified, but there are sufficient data to produce the quality and quantity models necessary for a quantitative assessment of regolith as a lunar resource (fig. 6).

For the technical and economic models (fig. 6), it is important to consider the likely uses for the regolith. Here, we focus on construction of basic infrastructure like landing pads and roads. Landing at unprepared sites on the Moon blasts regolith at high speed out from under the landing rockets, which would potentially damage not only nearby structures but also infrastructure in lunar orbit (Metzger and Mantovani, 2021; Metzger and Autry, 2022). Apollo 12's lunar lander, *Intrepid*, sandblasted the *Surveyor 3* robotic lander when it landed within 200 meters (700 feet) of it. Damaging existing infrastructure was not an issue for the Apollo missions since each landing was at a completely new site. However, the Artemis program aims to develop a sustained base camp, which would be the site of repeated landings (and departures). Landing pads are explicitly noted as critical pieces of early infrastructure, and therefore, the development of the ability to build durable pads out of lunar regolith is a high priority for NASA (NASA, 2019). The pads may need to be augmented with circumferential protective berms to deflect the rocket exhaust. Regolith can also be used in the construction of paved roads to mitigate the hazards posed by mobilized lunar dust as well as protecting habitats from micrometeorite bombardment and radiation, all essential for establishment of a long-duration lunar base (Farries and others, 2021).

A wide range of technologies are under active development to construct this essential infrastructure. These range from cages filled with coarse regolith for landing pad berms to



Base image mosaic from National Aeronautics and Space Administration, Arizona State University, and Applied Coherent Technology Corp. Lunar QuickMap, 0.5 and 100 meter resolution

Figure 9. Map of the relative age of the regolith (from the Multispectral Imager of the Japanese Kaguya lunar orbiter; data available in the Lunar QuickMap and method to calculate optical maturity parameter from Lemelin and others, 2016). Red and orange colors represent ejecta from recent craters where the regolith is young and unusually thin and rocky.

three-dimensional printing using a regolith-based cement to build habitat exteriors (for example, Metzger and Autry, 2022). There are efforts in many countries to develop the technology to cement regolith by partially melting it (a process called sintering) using microwaves, lasers, or even focused sunlight (Meurisse and others, 2018; Xu and others, 2019; Farries and others, 2021; Kim and others, 2021). All of these use fine, powdered rock. This makes the particle size distribution a key metric for the quality of the regolith for this use case.

The amount of regolith that can be considered technically recoverable in a 30-year timeframe may not be limited by geology but by extraction technology. The most mature excavating rover designed for the Moon has demonstrated an ability to extract regolith from a depth of about 2 meters (7 feet) on reasonably flat terrain in a laboratory setting (fig. 10). Assuming this capability, roughly 2 cubic meters (70 cubic feet), or more than 3 metric tons, of usable regolith can be extracted from every square meter of the lunar surface that excavators can access (that is, away from rare steep slopes and rocky terrain). Because the area of the Moon is close to 40 million square kilometers (about 15 million square miles), more than 100 million megatons of regolith can be considered a technically recoverable resource using technology expected to be developed in the next 30 years. For comparison, the United States produced close to 90 megatons of cement in 2019 (U.S. Geological Survey, 2020). There are other technologies for producing landing pads that do not require excavation but rather require grading (smoothing) an area and then cementing or sintering the flat surface. Therefore, it can be important to specify the use case when assessing regolith as a resource. However, the existing data show that bulk lunar regolith is an abundant and readily accessible resource for many potential uses. While currently regolith should be classified as a measured unrecoverable resource, it can be expected to be a technically recoverable within 30 years (table 1).

Regolith for Oxygen

Oxygen is primarily needed as a component of rocket propellant but can also be used to replenish life- support systems. NASA's analysis assumes that the Artemis program will need about 10 metric tons of oxygen per year (Kleinhenz and Paz, 2020). Most rocks contain large amounts of oxygen. This oxygen is tightly bound to other elements so, on Earth, rock is not used as a source of oxygen. However, with the application of sufficient energy, these molecular bonds can be broken and oxygen extracted from rock.

The information needed for the essential parts of a quantitative resource assessment for regolith as a source of oxygen exists. The descriptive model is the same as for regolith as a resource for construction. The ample data from samples and remote sensing exist for the quality and quantity models. The oxygen content of the lunar regolith varies by only a few percent from location to location, meaning we have samples of the same type of regolith we expect at the Artemis site. More specifically, at the Apollo 16 landing site in the Descartes region of the lunar highlands, where the regolith composition is most like that expected around the lunar poles, the material is slightly more than 40 percent oxygen by mass. This means that, for a 5- to 20-meter-thick (20- to 70-foot-thick) layer of regolith with a density close to 2,000 kilograms per cubic meter, there are 4 to 16 metric tons of oxygen per square meter of surface area. Currently, oxygen in regolith can be considered a measured unrecoverable resource (table 1).

However, the amount of oxygen that is technically recoverable in the 30-year timeframe is somewhat uncertain. Oxygen production requires not just excavating the regolith but also a process to extract the oxygen. At this time, three basic approaches are being extensively studied: hydrogen reduction, carbothermal reduction, and electrolysis (Schwandt and others,

Figure 10. Image of the Regolith Advanced Surface Systems Operations Robot (RASSOR) undergoing testing at National Aeronautics and Space Administration (NASA) Kennedy Space Center in Florida. In this photograph, RASSOR is demonstrating the capability to excavate to a depth approaching 2 meters (7 feet) and transport materials to a processing facility. The vehicle is capable of driving over steep slopes (35 degrees) and large boulders but significant excavations in such terrain are not achievable. NASA photograph by Drew Smith, used with permission.

2012; ISECG, 2021). All three work best with powdered rock, which means that coarse regolith particles need to be removed from the process. Hydrogen reduction flows hydrogen gas over regolith heated to about 1,000 degrees Celsius (°C) (1,800 degrees Fahrenheit [°F]), which causes a reaction that forms water vapor that is then condensed and split by electrolysis into oxygen and hydrogen. The hydrogen is recovered and sent back into the gas flow over the regolith to extract more oxygen. This process is only efficient in the presence of the mineral ilmenite, a titanium-iron oxide that is found in small quantities in lunar lava flows. It can operate at lower efficiency if the regolith contains glass-rich agglutinates. Laboratory demonstrations of hydrogen reduction have been successfully completed using lunar simulants (Sargeant and others, 2021).

The second process, carbothermal reduction, is similar to hydrogen reduction but uses a carbon-bearing gas, such as methane (CH_4). The reactions are more complex but are not dependent on the presence of ilmenite. The carbothermal reduction process starts with breaking down methane into hydrogen (H) and carbon (C). Then the carbon reacts with oxygen (O) in molten regolith to produce carbon monoxide (CO), which is then split into oxygen and carbon. The carbon can be recombined with the hydrogen to create methane that can be recycled to extract more oxygen. Initial laboratory testing with lunar highlands simulants indicate that the process can produce oxygen, but substantial technical challenges remain, such as efficiently mixing the gas and molten regolith and the high temperature (greater than 1,200 °C [2,200 °F]) required to melt the regolith (Balasubramaniam and others, 2010; Linne and others, 2021).

The third process, electrolysis, is the conceptually simplest process, where molten rock is subjected to a voltage difference across two electrodes. Negatively charged ions, mostly oxygen, will accumulate at one electrode and positively charged ions, mostly metals, will accumulate at the other electrode (Schreiner and others, 2016). Electrolysis can operate at around 900 °C (1,600 °F) with powdered rock mixed into a molten salt such as calcium chloride. This process has successfully been demonstrated in the laboratory and the residue is a metal alloy that may have other uses (Lomax and others, 2020).

At this point, no process to generate oxygen from regolith is sufficiently mature to make confident estimates of the efficiency that can be expected from a production plant. The electrolysis process has removed 96 percent of the oxygen in a lunar simulant under laboratory conditions (Lomax and others, 2020), whereas hydrogen reduction has extracted only 1–4 percent from ilmenite-bearing regolith and less than 0.1 percent from ilmenite-poor regolith (Sargeant and others, 2021). If we assume, for illustrative purposes, that in 30 years about 10 percent of the oxygen can be converted to a useful commodity, and that the regolith can be excavated to a depth of about 2 meters (7 feet), the technically recoverable oxygen would be about 120 kilograms per square meter of the surface. Across the entire Moon, this translates into a technically recoverable resource of nearly 5 million megatons of oxygen, or approximately one-twentieth of the amount contained in the Earth's atmosphere. In more practical terms, it means that NASA's estimated need for 10 metric tons of oxygen per year could be supplied by processing just over 160 cubic meters (5,600 cubic feet) of regolith per year, which can be provided by digging to a depth of 2 meters (7 feet) across an area of 8×10 meters (25×32 feet). For comparison, this is about the size of a large backyard swimming pool. However, if the efficiency is only around 0.1 percent, an area slightly larger than a football field would need to be processed each year.

Water and Hydrogen Resources on the Moon

We note that hydrogen and water are often conflated when discussing lunar resources. This is because water can be produced on the Moon if hydrogen is obtained, but hydrogen is rare on the Moon whereas oxygen is abundant. Water is an especially desirable resource because it has many different uses, the most prominent of which are for life-support systems and propellant for rocket engines However, the system selected by NASA in 2021 to land humans on the Moon burns oxygen and methane, not oxygen and hydrogen. Hydrogen is also particularly good at absorbing neutrons, and thus water is useful for radiation shielding. A sustained base on the Moon is also likely to use plants as part of the life-support cycle, necessitating additional water.

Water and Hydrogen from Regolith

Small quantities of hydrogen bound to oxygen in different ways can be found in the lunar regolith (Jolliff and others, 2018). As already discussed, there is adequate information on the regolith itself to conduct an assessment—the key questions revolve around the amount and form of water or hydrogen in the regolith. This means building the descriptive, spatial, quality, and quantity models for a quantitative assessment (fig. 6) is not simple. Volcanic eruptions are one source of hydrogen, bringing hydrogen from the deep interior of the Moon to the surface. Our current understanding of lunar volcanism is imperfect but should suffice to create a descriptive model that has an emphasis on deposits from gas-rich lava fountains. These types of volcanic deposits can be reliably identified and mapped globally from orbit (for example, Gaddis and others, 1985; Gustafson and others 2012), which can provide a good spatial model for this resource. Laboratory analyses of the small volcanic glass beads found in the deposits from lunar lava fountains have discovered microscopic sections that contain as much as 270–1,200 parts per million water (Hauri and others, 2011). On average, the beads contain 15–30 parts per million of trapped water (Saal and others, 2008). Additionally, orbital spectral data have indicated that some volcanic deposits may locally have 150–400 parts per million of water (Milliken and Li, 2017). Taken together, these types of data provide the basis for constructing models of the deposit density, quantity, and quality. Because this water is tightly bound to the lava rocks, little has been lost even after billions of years but this water could also require heating to near the 1,200 °C (2,200 °F) melting temperature for efficient extraction. There are multiple technologies under development (such as regolith sintering and oxygen extraction) that would heat regolith close to these temperatures (Meurisse and others, 2018; Xu and others, 2019; Farries and others, 2021; Kim and others, 2021), so it is plausible that a meaningful fraction of this water may be technically recoverable. However, there are no volcanic deposits near the south pole of the Moon, so this resource is not immediately relevant to current plans for the Artemis program.

Another source of hydrogen in the regolith is solar wind, which contains a stream of protons, which become hydrogen atoms with the addition of an electron. These solar wind protons impact the surface and can penetrate a few nanometers where some will interact with oxygen to form hydroxyl and water molecules (Housley and others, 1974). These hydrogen-bearing molecules have been detected by various spectrometers (for example, Pieters and others, 2009; Sunshine and others, 2009; Clark, 2009), a finding that is confirmed by laboratory measurements of the Apollo samples. The analyses of the samples indicate most of this hydrogen is trapped (as hydroxyl) in agglutinate particles containing between 30 and 500 parts per million of water. Agglutinates accumulate as regolith matures, so the water concentration in mature regolith may be around 70 parts per million water (Liu and others, 2012). However, how these molecules are bound to the regolith is still not well-understood and is a subject of active research. Some studies indicate that the hydrogen-bearing molecules are migrating to the poles (for example, Crider and Vondrak, 2002; Sunshine and others, 2009), potentially reaching a concentration of 500–750 ppm in the upper few micrometers of the surface (Li and Milliken, 2017). Others indicate hydrogen-bearing molecules are relatively uniformly distributed across the Moon (Bandfield and others, 2018). It is also possible that the bound water is mobilized by meteorite showers (Benna and others, 2019). Taking the value of 70 parts per million that appears typical near the equator of the Moon, the 5- to 20-meter-thick (20- to 70-foot-thick) global regolith layer could contain 30–100 billion tons of water-equivalent solar-wind hydrogen.

Extraction of the implanted hydrogen, hydroxyl, and (or) water from the lunar regolith may be possible by heating the material to 100–300 °C. How much hydrogen and water can be obtained by heating to different temperatures is under investigation (Hibbitts and others, 2011; Reiss, 2018; Reiss and others, 2019), and therefore, it is difficult to predict how effective this process will be. However, the studies to date indicate that obtaining 10 parts per million of useful water-equivalent hydrogen seems plausible in most locations on the Moon and, optimistically, extracting 100 parts per million might be possible in the most favorable locations near the poles. This indicates that solar-wind-implanted hydrogen could form a global technically recoverable resource greater than 1.5 billion metric tons of water-equivalent hydrogen. As a more practical measure, at a concentration of 10 parts per million of water, 100 metric tons of regolith would need to be processed to generate 1 liter of water. If 100 parts per million can be extracted near the Artemis site, perhaps 10 metric tons of regolith will be needed to obtain 1 liter of water. This is equivalent to processing between 10 and 100 pickup truckloads of regolith for a liter of water (fig. 11).

In summary, more studies are required to understand the temporal and spatial variability of hydrogen implanted into the regolith in polar areas before a quantitative assessment can be completed. However, even in the absence of a formal quantitative assessment, it is clear that hydrogen is a widely distributed, highly accessible, but low-concentration resource. Recovering useful amounts of hydrogen from regolith appears technically feasible but will require processing large quantities of regolith. For now, hydrogen from regolith can be classified as an inferred unrecoverable resource (table 1).

Water and Hydrogen from Polar Ice

The idea that ice could be trapped in permanently shadowed craters near the lunar poles was first published in 1961 by Watson and others. Radar experiments using antennas on Earth and the *Clementine* spacecraft flown by the U.S. Department of Defense were inconclusive but indicative of ice (Nozette and others, 1996). Hydrogen was definitively detected in 1998 by the neutron spectrometer onboard the NASA Lunar Prospector orbiter, with the data allowing as much as 6 billion tons of ice in the upper two meters of the Moon, (Feldman and others, 1998). New instruments, such as the Lunar Exploration Neutron Detector on the Lunar Reconnaissance Orbiter (LRO), and advances in data processing continue to strongly indicate the presence of water ice, but this method cannot pinpoint the location of the ice from orbit (Mitrofanov and others, 2010; Teodoro and others, 2010; Sanin and others, 2017). The LRO Diviner Lunar Radiometer Experiment thermal mapper showed that the temperatures in many of the permanently shadowed regions were consistently below 110 Kelvin (−260 °F), which has allowed ice to be stable for billions of years (Paige and others, 2010). Mapping by the Miniature Radio Frequency (mini-RF) radars onboard both Lunar Reconnaissance Orbiter and the Indian Chaandrayaan-1 orbiter found signals consistent with ice in many of the polar craters and in some surrounding areas (Spudis and others, 2013). Although the permanently shadowed craters do not receive direct sunlight, their floors have been sensed using Lunar Reconnaissance Orbiter's laser altimeter (LOLA) and the Lyman Alpha Mapping Project (LAMP) camera which obtains images using reflected starlight. These detectors showed that some areas were unusually bright, consistent with some frost at the surface (Lucey and others, 2014; Hayne and others, 2015; Qiao and others, 2019). Spectral data from the U.S. Moon Mineral Mapper (M3) instrument on the Indian Chaandrayan-1 orbiter support the interpretation that this brightening is indeed caused by numerous patches of surface water frost (Li and others, 2018). However, the different remote sensing instruments do not entirely agree on where the ice is located and do not provide consistent constraints on the quantity of ice. Some permanently shadowed areas appear to have less ice than others and some ice is indicated in regions where it can only be stable in the subsurface (Sanin and others, 2017, Brown and others, 2022).

The most definitive detection of water on the Moon came in 2009 from the Lunar Crater Observation and Sensing Satellite (LCROSS) mission which observed the plume of material that was excavated during an impact into the coldest

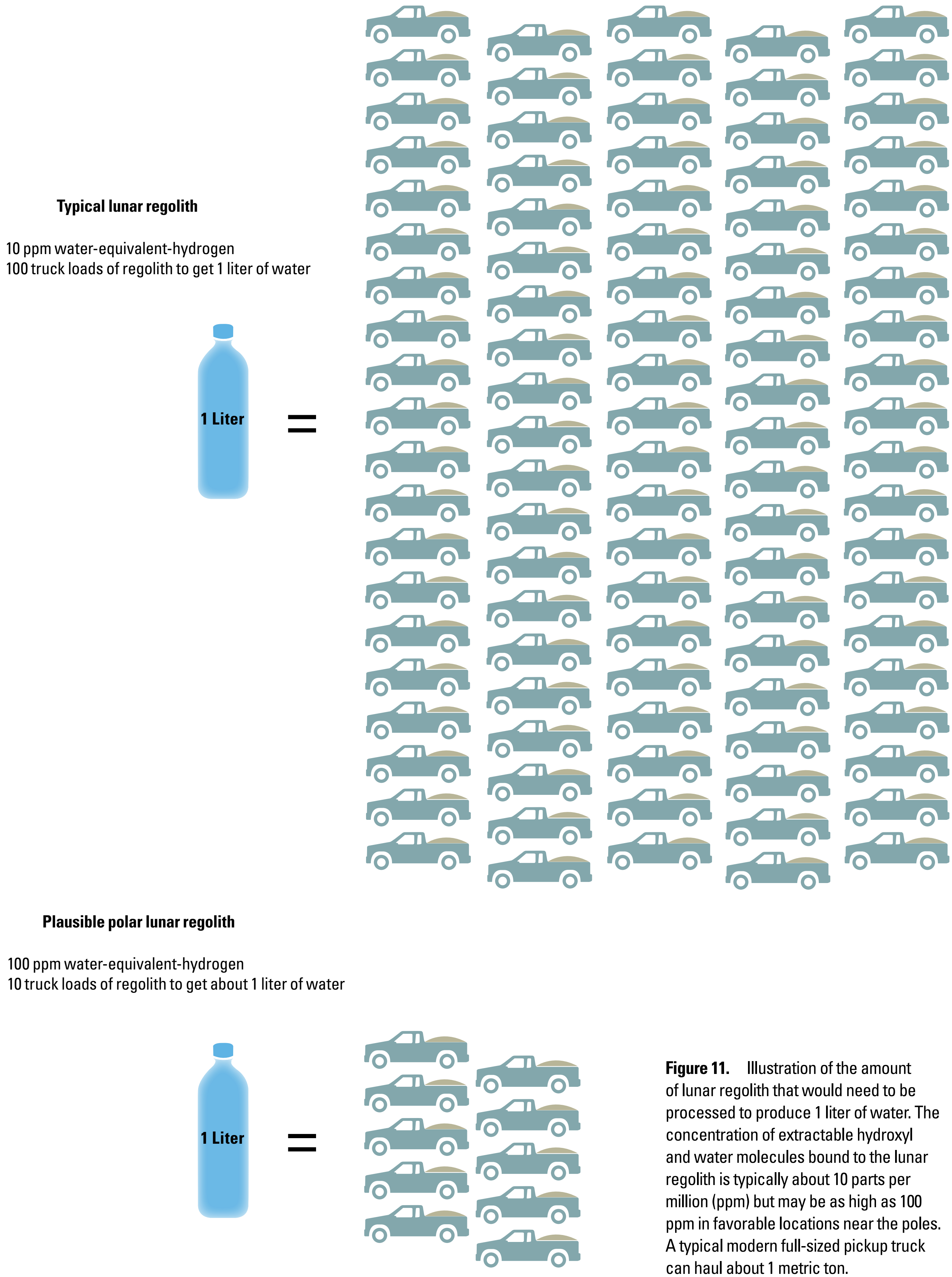


Figure 11. Illustration of the amount of lunar regolith that would need to be processed to produce 1 liter of water. The concentration of extractable hydroxyl and water molecules bound to the lunar regolith is typically about 10 parts per million (ppm) but may be as high as 100 ppm in favorable locations near the poles. A typical modern full-sized pickup truck can haul about 1 metric ton.

part of one of the coldest craters on the Moon, Cabeus, near the south pole (Colaprete and others, 2010). This was a particularly challenging observation, but analysis of the spectrum from the plume indicated that there was 5.6 percent water in the impacted surface. However, the uncertainties in this measurement were large, with a reported standard deviation of 2.9 percent. This means that at the 95 percent confidence level (that is, two standard deviations), the amount of ice in this location could be between 0 and 11 percent by mass. Along with water, the analysis indicated the presence of smaller amounts of other volatiles, such as hydrogen sulfide, ammonia, sulfur dioxide, carbon dioxide, and various organic compounds (Colaprete and others, 2010).

Although there are multiple lines of compelling evidence that substantial amounts of water ice exist in the lunar polar regions, determining exactly where the ice resides and how much of it exists is difficult. One of the key problems is that the hypotheses for when and how the ice deposits formed cannot be rigorously tested with the data in hand. One source of ice could be meteorites (that is, asteroids and comets), which primarily impacted the Moon prior to 3.7 billion years ago (Fassett and Minton, 2013). A second possible source is the volcanic gasses that accompanied the voluminous volcanic eruptions between 3.9 and 2.5 billion years ago (Schultz and Spudis, 1983). A third source could be the slow accumulation of solar wind protons, a process that continues to this day (Crider and Vondrak, 2002). It is entirely possible that all three processes have contributed, but because each was active during different chapters of the Moon's history, they could lead to different types and sizes of deposits. What this means for a quantitative lunar resource assessment for ice is that, not only do we not have a reliable descriptive model, but we do not even know how many different descriptive models will be needed.

Confounding the attempts to locate the ice and create a spatial model is the fact that the different measurements do not clearly agree on where ice exists. This is most likely because the different methods sense to different depths, but the vastly different spatial resolutions of the different measurements also complicate analyses (Kleinhenz and others, 2020). In terms of a quantitative lunar resource assessment rubric, this means that not only do we lack the information for any descriptive model(s), but also do not have a reliable spatial or deposit density model and have only a single measurement for a quality-quantity model. Therefore, using the terminology in figure 4, lunar ice is a speculative unrecoverable resource that we cannot reliably quantify at this time (table 1). This shortage of basic understanding means that, no matter what methodology is used, an assessment of lunar ice as a resource would be highly speculative. Two recent studies show a plausible range of the amount of ice on the Moon. Cannon and others (2020) considered 10,000 possible scenarios and suggested that as much as 1 billion metric tons of ice might be deeply buried within some polar craters. However, deeply buried ice is beyond our ability to detect so the presence of such deposits is purely hypothetical. Brown and others (2022) considered shallower detectable ice and suggested that several craters contain several million tons of ice. It is interesting that these numbers are consistent with the estimate provided by the late lunar science expert Paul Spudis. When asked by Air and Space Magazine in 2018, he speculated that there could be between 100 million and 1 billion metric tons. To put this number in perspective, it is the equivalent of between 0.1 and 1.0 cubic kilometers (0.02 and 0.2 cubic miles) of water—the volume of a modest lake or reservoir (fig. 12). If this educated guess proves correct, lunar ice would be a limited resource. Coupled with the currently favored hypothesis that most of the ice was deposited billions of years ago from impacts (Cannon and others, 2020), lunar ice would also be non-renewable. These are conditions that provide impetus for decisionmakers to carefully manage a natural resource.

When it comes to the technology to extract the ice, a wide array of innovative ideas has been suggested. These include carrying ice-bearing regolith to an auger dryer (Collins and Erickson, 2021) or putting a tent over the regolith and heating it with microwaves or sunlight bounced off mirrors (Sowers and Dreyer, 2019). However, none of these concepts can be demonstrated to be end-to-end effective, even in a laboratory setting because we do not know how the ice is mixed with the regolith on the Moon. Fundamentally different technologies would need to be used if the ice is in the form of (1) a thin surface frost, (2) a thick layer of ice deeply buried under dry regolith, or (3) an intimate mixture of ice and regolith that is meters thick. A widely favored model assumes the ice is distributed in low concentration spread evenly in locations that have been persistently cold for billions of years (Cannon and Britt, 2020). Higher concentrations of ancient ice could also exist tens or hundreds of meters beneath the floor of some polar craters (Cannon and others, 2020). However, these hypotheses are untestable with the available orbital remote sensing data.

This situation will change once ground-truth observations are obtained by landers and rovers. These types of data are essential to understand how and when the ice was deposited. Observations of where and how the ice is distributed laterally and vertically at the scale of an excavator will provide the essential information needed to develop the density, quality, and quantity models for ice deposits. If this kind of knowledge can be obtained for at least one region, it should be possible to link it to the existing global remote sensing observations—making rigorous assessments of the lunar ice possible. The NASA Volatile Investigating Polar Exploration Rover (VIPER) mission, currently scheduled to launch in late 2024, is designed to collect precisely the kind of ground-truth information required to start a quantitative lunar resource assessment (Colaprete and others, 2021).

When the quantitative assessment of lunar ice becomes possible, it is likely that contaminants will be a major concern, just as with water resource assessments on Earth. The quantitative lunar resource assessment methodology proposed here may need to be adjusted to incorporate experience that USGS and partner organizations have in considering water quality as part of their water resource assessments (for example, Yager and others, 2013; Wilson and others, 2014; Batt and others, 2017).

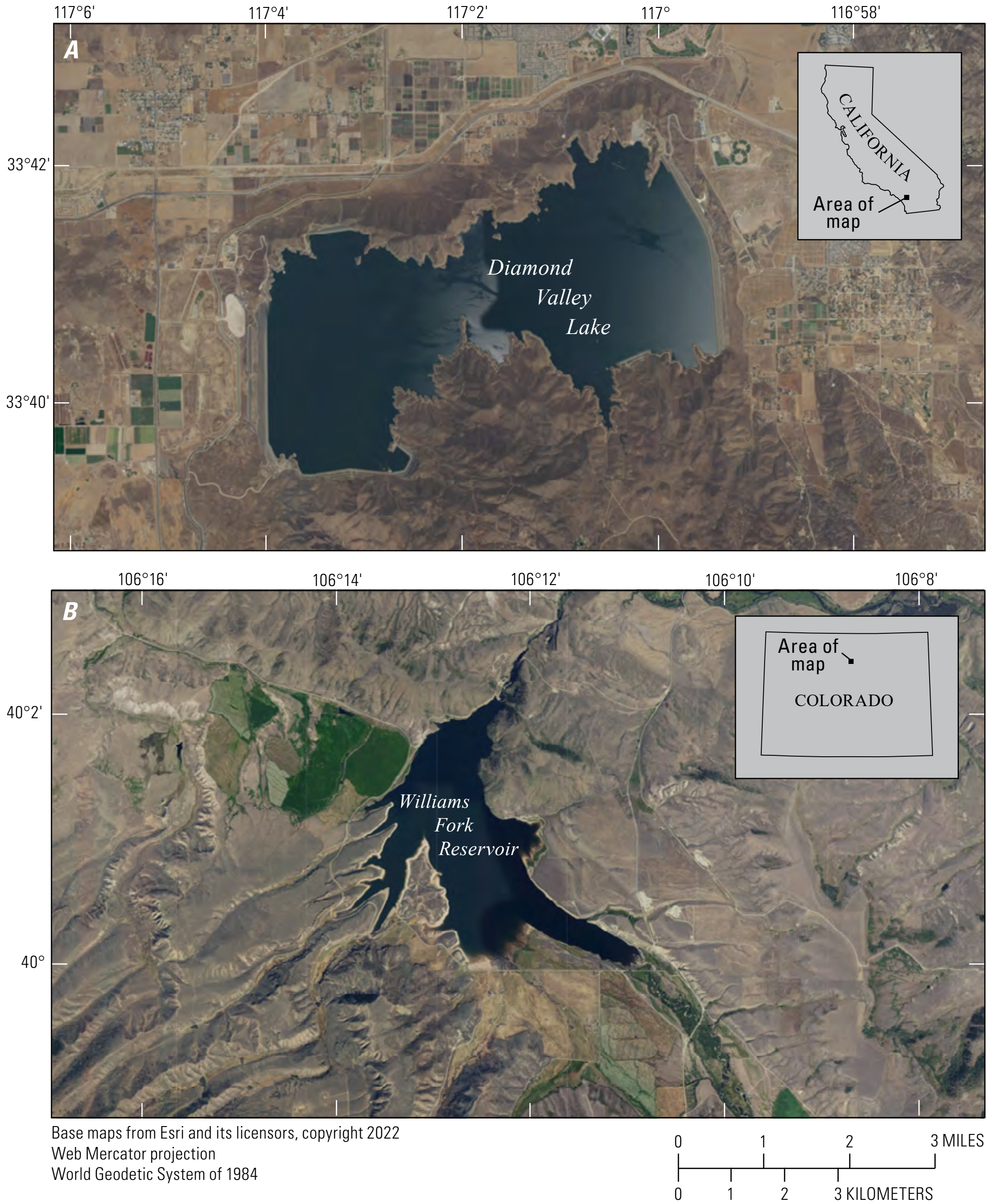


Figure 12. Maps showing examples of reservoirs in the United States that have volumes similar to the total amount of ice estimated to be on the Moon. *A*, Diamond Valley Lake, California, near San Diego has a volume of approximately 1 cubic kilometer (0.2 cubic miles), or 1 billion metric tons of water. *B*, Williams Fork Reservoir, Colorado, near Denver has a volume of approximately 0.1 cubic kilometer (0.02 cubic miles), or 100 million metric tons of water.

Summary

There are energy, mineral, and water resources on the Moon but their readiness to be assessed and used is not uniform (table 1). Solar power can be utilized in useful amounts with existing technology but there are technical challenges to installing arrays in optimal locations. The lunar regolith, the layer of pulverized rock found across the Moon, hosts multiple types of resources. Additionally, there are adequate data in hand to quantitatively assess most of these regolith resources. There are diverse maturing technologies to extract or use those resources for construction, oxygen, and even water, but not all are well-suited to the south polar region where the Artemis program plans to build a base camp. In terms of ice, however, there are fundamental gaps in knowledge that make it difficult to assess how much exists, let alone how much will be technically recoverable in a 30-year timeframe. Our understanding of lunar ice deposits is expected to greatly increase in the next few years as new landed missions explore the polar regions of the Moon. This will eventually permit an informed discussion about how to manage this valuable yet potentially scarce and non-renewable resource.

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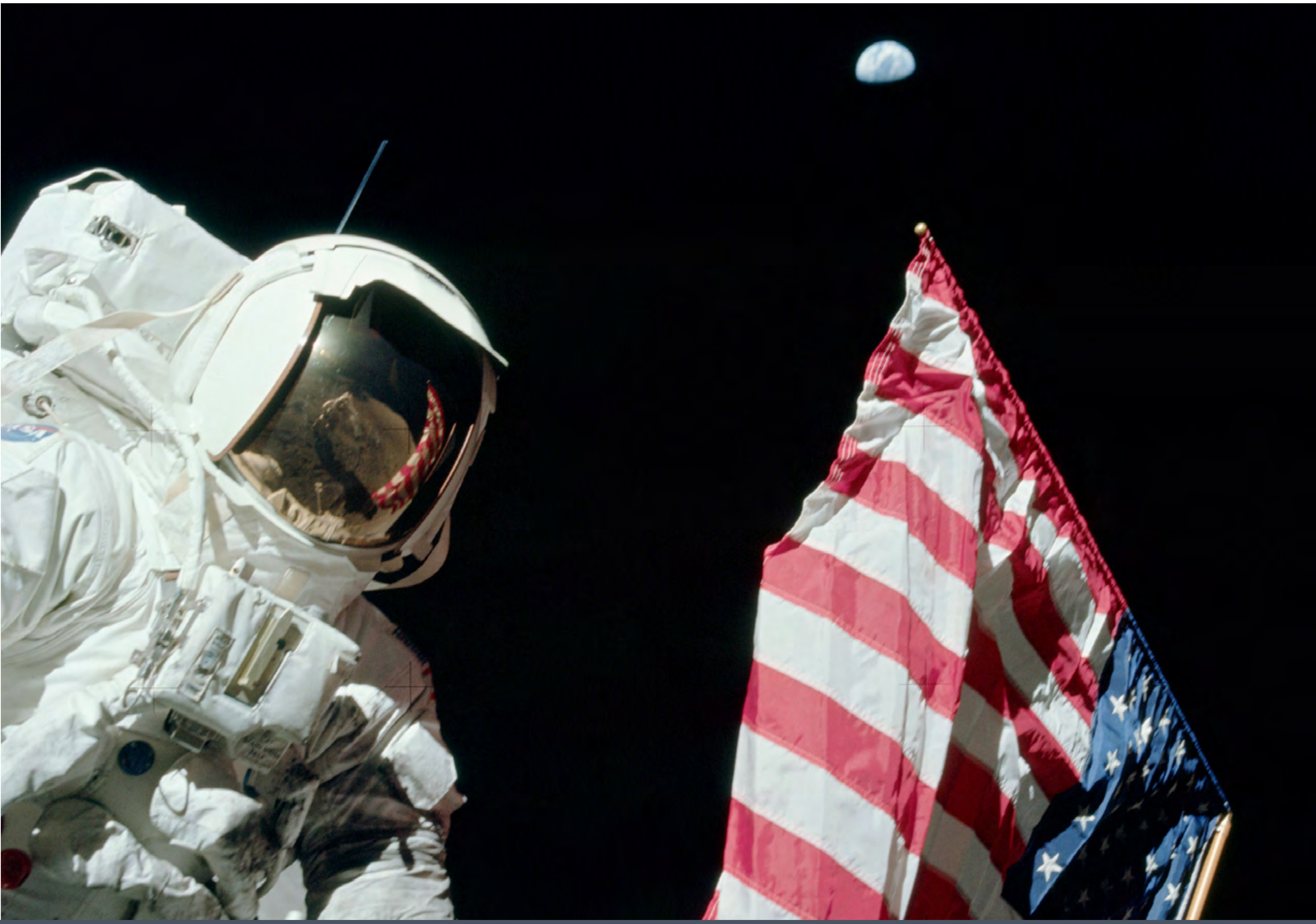
U.S. Geological Survey geologist and astronaut Harrison (Jack) Schmitt stands next to the U.S. flag with the Earth in the background during the first extravehicular activity of the Apollo 17 mission. National Aeronautics and Space Administration photograph.



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