BBC

APOLLO 17: THE FINAL LUNAR LANDING & ITS LEGACY

#211 DECEMBER 2022

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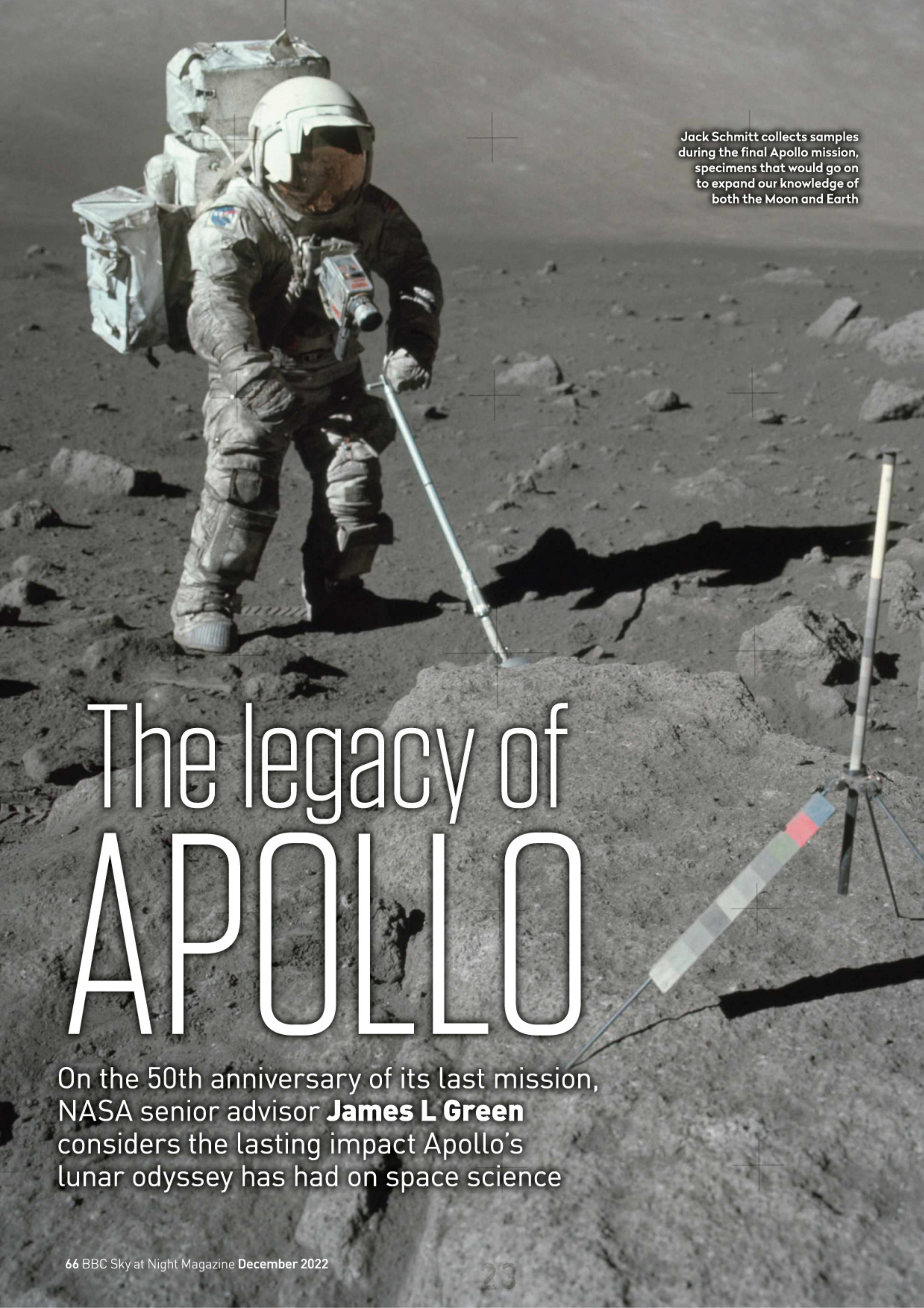


Jack Schmitt collects samples during the final Apollo mission, specimens that would go on to expand our knowledge of both the Moon and Earth

The legacy of APOLLO

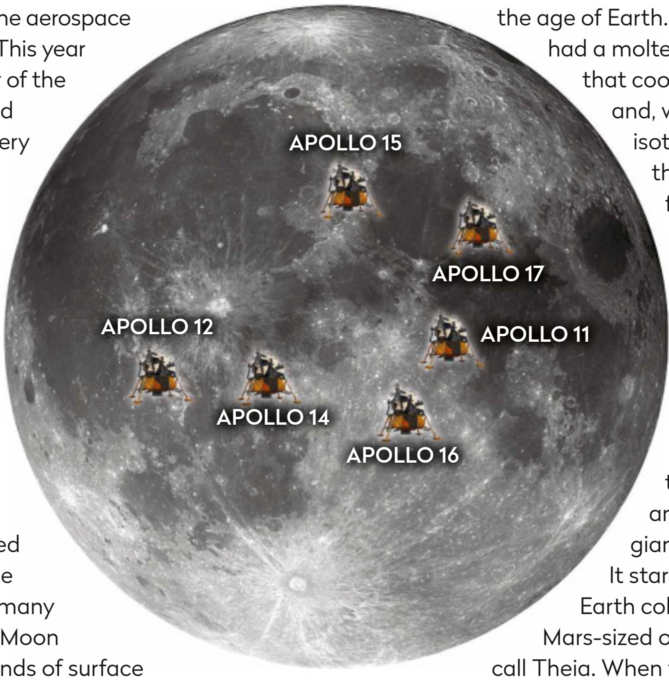
On the 50th anniversary of its last mission, NASA senior advisor **James L Green** considers the lasting impact Apollo's lunar odyssey has had on space science

A Mars-sized object colliding with the proto-Earth is widely considered to be the most likely origin of the Moon

ILLUSTRATION

When we first landed on the Moon in 1969, fulfilling President Kennedy's 1962 declaration to put humans there by the end of the decade, I was in high school and over the next several years I followed each mission closely. Although I was already sure I wanted to be involved in space before the Apollo missions, so many of my fellow students were also inspired in that era to get involved in the aerospace industry in some way. This year is the 50th anniversary of the landing of Apollo 17 and although it seems so very long ago, the legacy of Apollo has made a significant difference in the exploration of space that followed.

When we look at where the Apollo landing sites are located (see right) we see that they are in the mid to low latitudes on the lunar near side and separated by great distances. The astronauts examined many different areas on the Moon and deployed many kinds of surface experiments, bringing back 382kg of lunar material. What we learned from all these efforts was truly astounding and took many decades for scientists to really appreciate and understand. In fact, even today we are still actively analysing lunar samples.



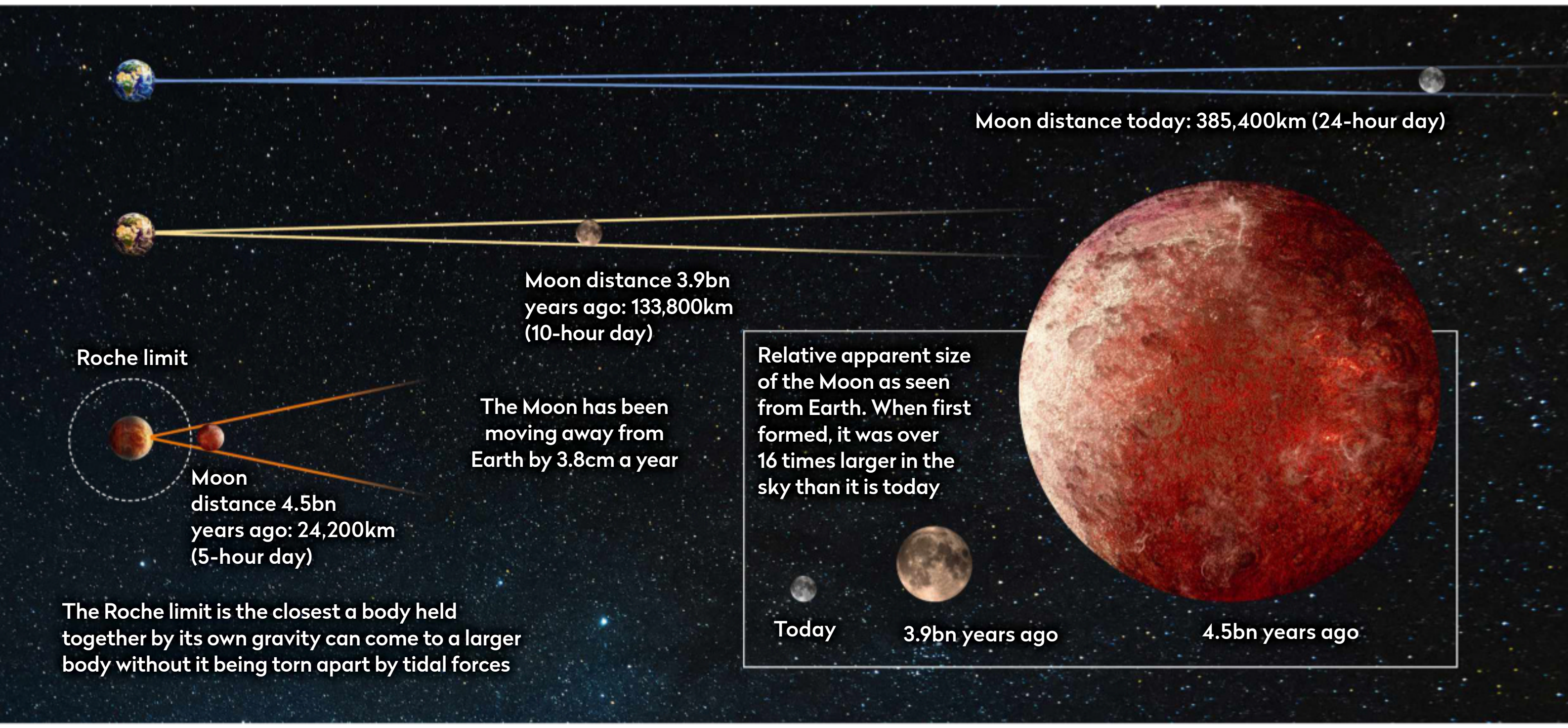
▲ The six Apollo landing sites took in a wide variety of the Moon's landscapes

Determining the Moon's age

The Moon is old, around 4.5 billion years old in fact; much older than any rocks found on Earth today. We now know that, due to plate tectonics and erosion, Earth's early crust has completely disappeared. In other words, we had to go to the Moon to find the age of Earth. The young Moon had a molten magma ocean that cooled to form its crust and, when combined with isotopic analyses of the lunar rocks, these facts tell us that the Moon and Earth are virtually identical in composition. They were made at the same time and the same place in our Solar System.

The top theory for the creation of Earth and the Moon is the giant impact hypothesis. It starts out with the proto-Earth colliding with another Mars-sized object, which scientists call Theia. When the dust settled on this planetary-scale collision, Theia was destroyed and the proto-Earth was reformed into a larger body, while ►

NASA, PETE LAWRENCE, STOCKTREK IMAGES/ISTOCK/GETTY IMAGES



▲ **The Moon's proximity to Earth early in its history would have had some interesting effects: there would have been larger tides, key perhaps to life's evolution, more lunar eclipses, and materials from large impacts on one body potentially landing on the other**

▸ the ejected material formed a much smaller body. At that time the Moon was so close to Earth that it had a huge presence in the sky, being more than 16 times larger than we see it from Earth today.

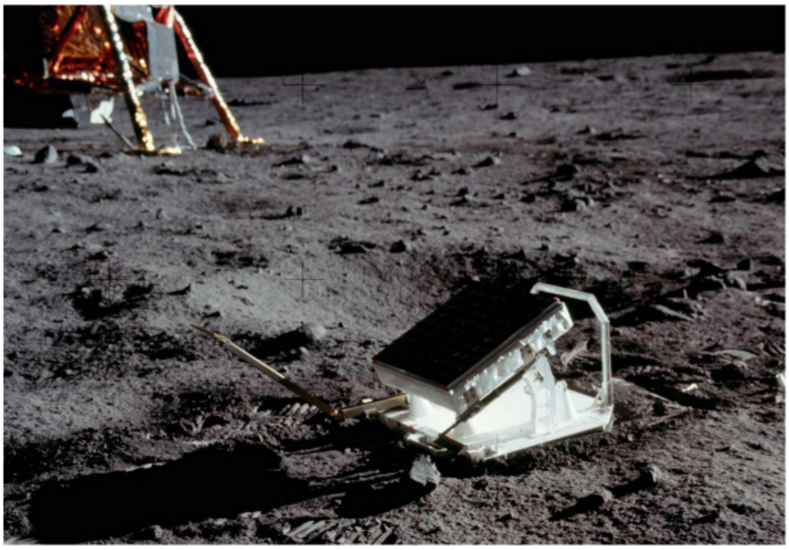
The Apollo astronauts left retroreflectors on the Moon, which scientists have targeted with lasers each year since 1969. From accurately measuring the light travel time from Earth to the Moon and back again, we find that the Moon is moving away from Earth by around 3.8cm each year. Over the last 4.5 billion years the Moon has moved from 24,200km to now lie 385,400km from Earth (see diagram above).

Telling the Solar System's story

The laboratory analysis of returned lunar rocks includes determining their mineralogy and age. The younger lunar rocks are from the darker mare regions and are basaltic or volcanic material from inside the Moon, filling large impact craters during a period from around 4.2 to 3.16 billion years ago, now referred to as the late heavy bombardment. For every one impact crater on the Moon, it is estimated that 20 meteorites hit Earth. Many will have burnt up in our atmosphere, but others would have made it to the ground. Over time, the dynamic climate and land motions of our planet have largely erased all traces of the initial impact craters, making the Moon the only witness to the early bombardment history of the inner Solar System.

Scientists now believe that the late heavy bombardment tells us of a dynamic early Solar System, where the giant planets changed their orbits due to gravitational resonances. Jupiter moved slightly inward, but Saturn, Uranus and Neptune all moved outward. Perhaps another giant planet was also ejected hundreds of astronomical units from the Sun, a distance so great that we can't see it with our modern telescopes. The motion of these giant planets changing their orbits around the Sun (a phenomenal concept I still have trouble picturing) gravitationally interacted with all the small-body debris of asteroids and comets, scattering them everywhere to produce this critical bombardment in the inner Solar System. The small bodies bombarding Earth had everything from organics to metals, reseeding the surface and perhaps bringing the right materials together for the spark of life to have started.

We now know that the Moon plays several critical roles in keeping the Earth uncommonly habitable. It causes lunar tides, stabilises Earth's spin axis and



▲ **The Lunar Laser Ranging Experiment left behind by Apollo 11 and still used to measure the Moon's increasing distance**

slows our planet's rotation rate, all believed to be important aspects for the development of complex life. This concept of giant planet migration has also informed our interpretation of other stellar planetary systems and exoplanets in many ways. Perhaps habitable exoplanets may also need an exomoon. It is thanks to the Apollo programme that we will never look at our Moon in the same way.

▲ **At 16 times larger than it appears today, the Moon would have been an incredible sight in the proto-Earth's night sky**

Driving spaceflight forward

Apollo's lunar samples and data have continued to raise significant interest from the world-wide science community. Indeed, it has helped establish a new scientific discipline by building a strong planetary science community, which at NASA is now driven to answer fundamental questions about the origin and evolution of our Solar System, and to determine if there is life beyond Earth. Human exploration of space is more politically driven.

Since NASA is an agency that falls under the Executive Branch in the United States, each new administration sets the strategic direction for human space exploration. After Apollo, the Nixon administration began to set the stage for NASA to develop the capability to explore how humans can live and work in low-Earth orbit. These activities included our first small space station called Skylab, the Space Shuttle, and then the International Space Station (ISS).

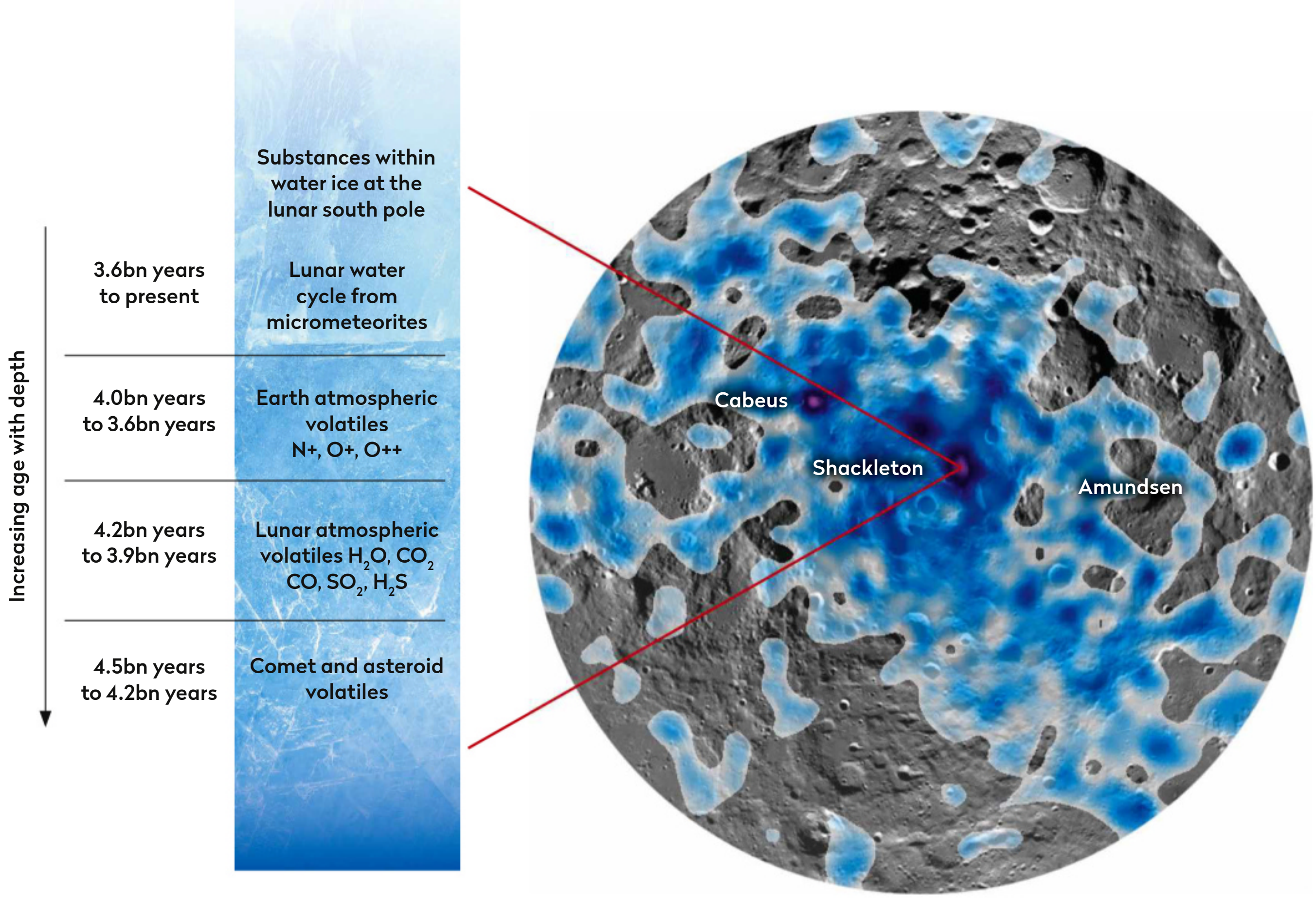
▲ **The ISS has become our place in space thanks to technology forged by the Apollo programme**

Although many have said NASA lost the momentum of humans exploring the Moon and beyond, in hindsight this diversion was perhaps a necessary step leading us to today, where we are realistically figuring out how to live and work on another planetary surface. Space is an extremely harsh environment for life and the challenges to overcome in the Apollo programme showed us how little we knew about it. This makes the achievements of the Apollo astronauts on the Moon even more amazing.

For the last 20 years, there has always been someone living aboard the ISS, which has evolved from an outpost on the edge of space into a highly capable international laboratory for research in its unique environment. We now know what space does to our bodies and how to utilise it to our advantage. By continually building on previous work in space, new results compound and new benefits materialise, aided by the continual revolution in computer and manufacturing technologies.

Pointing to hidden riches

While this half-century of research on humans living in space has produced amazing benefits, including for humanity on Earth, planetary scientists have also continued to explore the Moon. Over the last 15 years, several important lunar missions were conceived and executed that continued to ▸



▲ **Water ice in shadowed craters at the Moon's south pole, shown in blue on this diagram, has been building up for billions of years and contains volatile material from the Solar System's distant past**

▸ investigate the puzzles that arose from the analysis of Apollo data.

For instance, a remarkable discovery was made in the lunar north and south poles. Remote sensing data from missions like the Lunar Reconnaissance Orbiter has determined that the Moon holds a significant amount of frozen water and hydroxyl in its permanently shadowed regions (PSRs). Current estimates are that there may be as much as several hundred million tonnes of frozen water here.

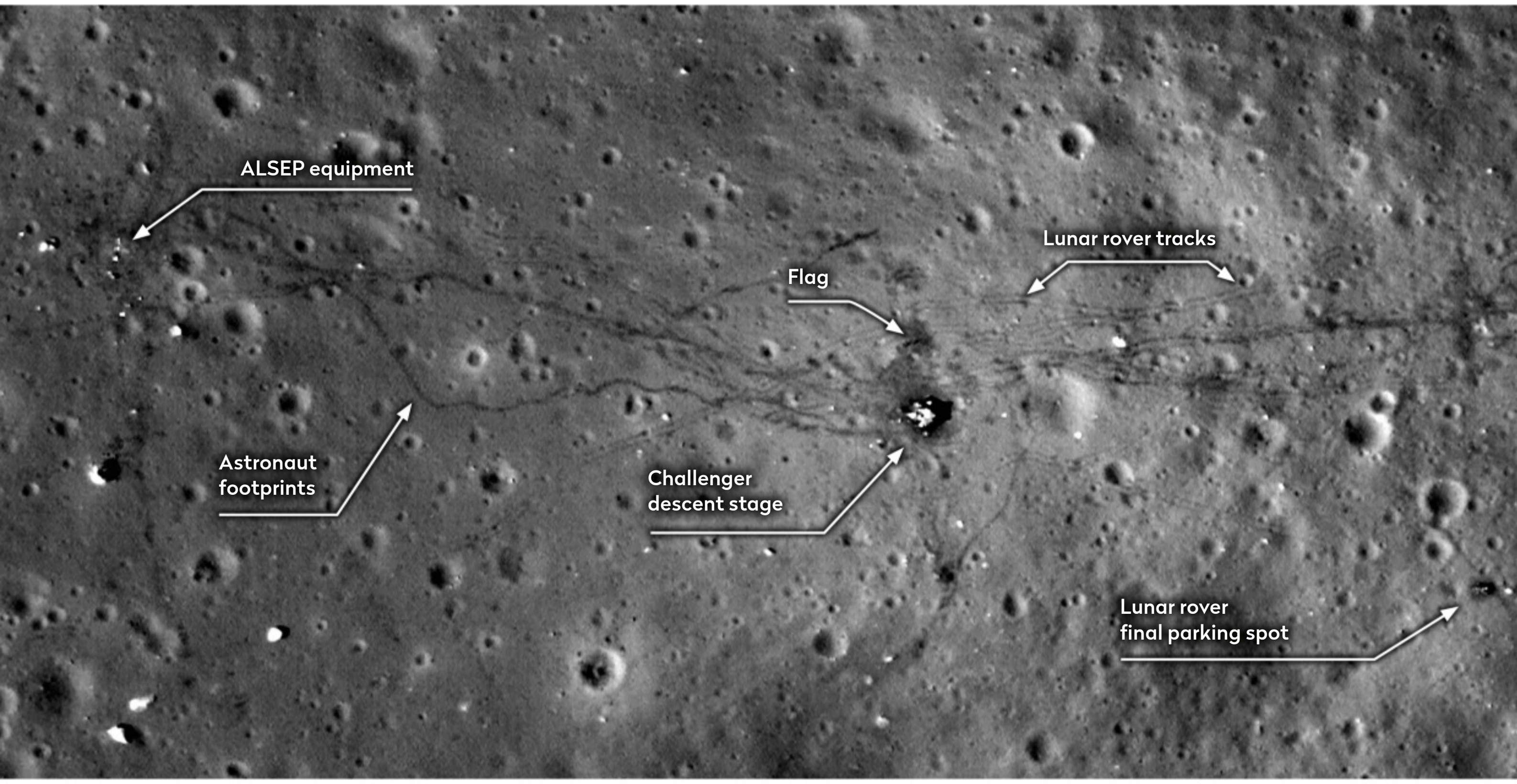
In addition to water, it now appears that in these regions there may also be volatiles like carbon dioxide, sulphur dioxide and nitrogen. Once these volatiles get into a PSR they will stay there, since there is no energy from sunlight to break the frozen volatiles into their components, causing them to drift away in the solar wind. We now believe that these volatiles were collected over time during important events in the evolution of Earth and the Moon.

After they formed, asteroids and comet bombardments brought water to the surface of the Moon. That process continues to this day but on a much-reduced level. Additionally, during the late heavy bombardment large amounts of molten, volcanic rock filled huge basins, creating the lunar mare and, in addition, lunar volcanos liberated huge amounts of trapped subsurface gases to create a thin, non-negatable lunar atmosphere. Over a short period of time, parts of the lunar atmosphere collapsed into the PSRs.

The Apollo lunar samples also tell us that the early Moon had a magnetic field for several hundred million years, protecting the early Earth's and early Moon's atmospheres from the harsh radiation from our young Sun. The magnetospheres of Earth and the Moon combined to provide a pathway for evaporation from early Earth's atmosphere to move to the polar regions of the Moon and become trapped in the PSRs.

Humans will need to extract resources from the ice to sustain the future Artemis Base Camp

NASA X 2, NASA'S GODDARD SPACE FLIGHT CENTER/ASU



▲ **Apollo 17's landing site, where geologist Jack Schmitt and commander Gene Cernan took humanity's last steps on the Moon in December 1972**

As shown in the diagram on the previous page, volatiles can tell us about the composition of the very early asteroids and comets, the atmosphere of the early Earth, and whether the young Moon had an atmosphere. It is hard to imagine, but we now think we have found in the PSRs a time capsule of the history of the volatiles in our Solar System. Scientists want to first enter these regions and core them to provide a proper assessment of what is there. Because of the continual micrometeorite impacts on the Moon mixing the soils and creating regolith, these cores are unlikely to capture an obvious, perfect record of that time in history, but they will reveal clues available in no other way about where these volatiles came from and how they were preserved.

A human return to the Moon

Why is it so important to find these volatiles for human exploration on the Moon? The simple answer is that they will allow humans to 'live off the land' as much as possible. Launching resources into space for humans to use is expensive and if we can use resources already on the Moon, our ability to stay and work on the lunar surface for long periods of time can become a reality. The water that can be extracted from a PSR can be used to drink and we can break up the water into its components and use the oxygen to breathe, along with creating hydrogen and oxygen reserves for rocket fuel.

Extracting these resources with new instruments is under rapid development at NASA and other space agencies. The yet-undetected but suspected other volatiles trapped in the PSRs will also be important. Indeed, extracting all of these volatiles for use is what we call a game-changer for the human exploration of space: if we can extract water and other volatiles for use on the Moon we can certainly do it on Mars, since it holds even greater reserves of these substances in its crust.

All of these results are feeding into NASA's plan for the next human lunar programme, Artemis. The first three missions are well laid out, with the Artemis I test flight using the new Space Launch System and the Orion capsule now targeted for the launch period of 12 November to 27 November. The uncrewed Artemis I is the first in a series of increasingly complex missions. Once it is completed, the results will be analysed before flying astronauts using the same trajectory on Artemis II. By 2025, Artemis III will land the first woman and first person of colour on the south pole of the Moon and establish long-term lunar science and exploration capabilities. NASA is planning the missions beyond Artemis III now, leading to what we call the Artemis Base Camp, a much more permanent place where we will learn to live and work on another planet.

So now, when we look at the image captured by the Lunar Reconnaissance Orbiter of the Apollo 17 landing site (see above), we can appreciate the enormous role that these early explorers played in getting us ready for the next step of human exploration into deep space. Just as it was with the Apollo programme, I have no doubt that the Artemis programme will inspire countless students to become scientists, engineers, inventors and mathematicians. They may walk on the Moon or be the explorers who venture onward to Mars and show humanity's limitless possibilities.

James L Green is a former NASA chief scientist and the longest-serving director of the Planetary Science Division in NASA. He coordinated NASA's involvement with the film *The Martian*