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Planetary science

Robotic sample return reveals lunar secrets

Richard W. Carlson

A mission to unexplored lunar territory has returned the youngest volcanic samples collected so far. The rocks highlight the need to make revisions to models of the thermal evolution of the Moon. **See p.49, p.54 & p.59**

The wait is over for more news from the Moon[1]. Three studies in this issue, by Tian *et al.* (page 59)[2], Hu *et al.* (page 49)[3] and Li *et al.*[4] (page 54), together with one in *Science* by Che *et al.*[5], report data on the lunar samples brought back by China's robotic Chang'e-5 mission – the first to return samples since the Soviet Union's Luna 24 mission in 1976. These data shed light on volcanic eruptions that occurred more than one billion years more recently than those known about previously, and provide information on the cause of the volcanism that cannot be obtained from orbit. The results raise questions about the structure and thermal evolution of the lunar interior, and could help to improve methods for estimating the age of planetary surfaces throughout the inner Solar System.

In December 2020, the Chang'e-5 lander set down in the Rümker region near the northwest corner of Oceanus Procellarum on the side of the Moon closest to Earth (Fig. 1). Like the sites visited by Luna and by NASA's Apollo missions, the Rümker region consists predominantly of a magnesium-rich volcanic rock known as basalt, but the difference from previous missions is that the Rümker basalts are potentially as young as 1.2 billion to 2.3 billion years old, which makes the Chang'e-5 samples the youngest taken from the Moon so far[6].

The Chang'e-5 landing site is in an area known as the Procellarum KREEP Terrane[7], where KREEP is an acronym for a rock that is rich in potassium (chemical symbol K), the rare-earth elements and phosphorus (chemical symbol P), together with a number of other elements, including the radioactive elements uranium and thorium. All of these elements are called 'incompatible' because they do not readily fit into the group of minerals that crystallize from a magma of composition similar to that of the interior of the Moon.

KREEP features prominently in models of lunar evolution that suggest the Moon was initially mostly molten, existing as a lunar magma ocean[8]. In this scenario, KREEP is thought to have been the last liquid left during the final stages of crystallization of this ocean. Radioisotope studies show that its chemical characteristics formed around 4.4 billion years ago, at roughly the same time that the oldest rocks in the Moon's crust were produced, as well as the source regions for younger lunar basalt magma[9]. That implies that this age might date the formation and crystallization of the magma ocean.

The high abundance of radioactive elements in KREEP also suggests that radioactive decay in KREEP is a key source of heat in the lunar interior. Orbital data for thorium concentrations (Fig. 1) show that KREEP is found mainly on the Moon's Earth-facing side. This high concentration of radioactive heating might explain several differences between the lunar near and far sides. The younger age of volcanoes, different crater shapes[10] and thinner crust[11] on the near side all reflect the role of high temperatures in prolonging melting in the lunar interior and weakening of the overlying crust.

The Chang'e-5 mission brought back 1.731 kilograms of the lunar surface, consisting of basalt fragments and other surface material welded together by impacts into a rock type known as a breccia. Using a technique called secondary ion mass spectrometry, Li *et al.* found that the uranium-rich mineral phases in the basalt fragments came from eruptions that occurred between 2,026 million and 2,034 million years ago. Che *et al.* found that the samples were between 1,906 million and 2,020 million years old. Tian *et al.* and Che *et al.* determined that these basalt fragments have titanium concentrations that lie in the middle of the concentration range for the fragments sampled by Apollo. Hu *et al.* calculated that the concentration of water in the source of the Chang'e-5 basalts is 30 to 140 times lower than for the mantle sources of Earth's driest lavas[12]. These low water concentrations are consistent with

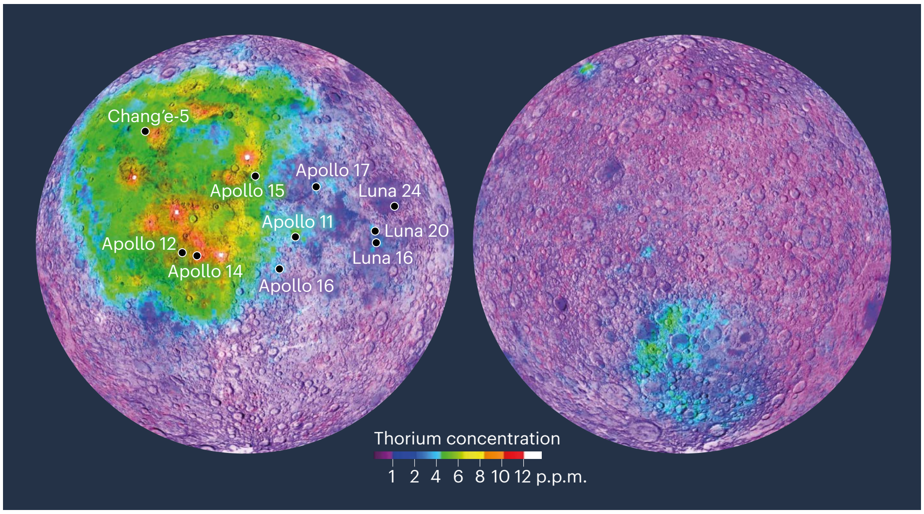

Figure 1 | Mission sites on the Moon. Tian *et al.*[2], Hu *et al.*[3], Li *et al.*[4] and Che *et al.*[5] report analyses of samples returned from the Chang'e-5 mission, which landed in the Rümker region of the Moon, away from the landing sites of NASA's Apollo missions and the former Soviet Union's Luna missions. Data taken from orbit are shown here for thorium, a radioactive element that is often used as an indicator of a type of rock known as KREEP. The concentration of thorium is high in a region on the near side of the Moon (left) called the Procellarum KREEP Terrane, and low on the far side of the Moon (right). Although these orbital data imply that the Rümker region is rich in KREEP, samples from Chang'e-5 suggest otherwise. p.p.m., parts per million.

NASA; ADAPTED FROM EXTENDED DATA FIG. 1 OF REF. 3 AND PLATE 1B OF REF. 7

the fact that the Moon is generally depleted in volatile elements and compounds, which are chemical species that can readily vaporize. If the Moon formed from material ejected during a giant impact with Earth, such species would have been vaporized and lost at the high temperatures involved in this event[13].

The concentrations of incompatible elements in the Chang'e-5 basalt samples are comparable to those typically found in KREEP, which is consistent with data from orbiting spacecraft. Tian *et al.* obtained an unexpected result, however, when they looked at the isotopic composition of strontium and neodymium – the isotopic abundances of these two elements are affected by radioactive decay. Their analysis suggests that the Chang'e-5 basalts derive from the melting of ancient sources in the lunar interior that are depleted in incompatible elements. These elements became enriched in the basalts because the magmas from which they crystallized came from minimal melting of the lunar interior and underwent large amounts of cooling and crystallization during their transit from source to eruption. Both the partial melting and the crystallization enriched the remaining magma in incompatible elements, but neither process affected the isotopic composition of the magma's source, which is depleted in these elements.

The age and compositional characteristics of the Chang'e-5 samples have at least two implications for our understanding of lunar structure and evolution. First, even though regions that have high concentrations of incompatible elements are seen across most of Oceanus Procellarum (Fig. 1), the Chang'e-5 data show that not all of these are composed of KREEP. This means that KREEP might form a much smaller component of the lunar interior than was suspected from Apollo samples, and data taken from orbit. Second, the melting that led to lunar volcanic eruptions two billion years ago did not involve heating due to high concentrations of radioactive elements in the magma source regions. Nor did it occur as a result of high water concentrations that reduce the melting temperature of rock in the same way that salt reduces the melting temperature of ice. An alternative explanation must now be sought for how the lunar interior was hot enough to drive volcanic eruptions two billion years ago.

The Chang'e-5 results demonstrate that samples returned from previously unvisited regions of the lunar surface can prompt a revision of models of lunar evolution that were developed on the basis of the Apollo and Luna samples. This is not surprising, given that the combined Apollo and Luna missions sampled only a restricted portion of the Moon's Earth-facing side. Much like Earth's surface, the lunar surface is a mosaic of materials created over the past 4.5 billion years. Each piece of that mosaic provides different information about the history of the Moon. The Chang'e-5 results show that sample-return missions to previously unexplored portions of the lunar surface will help models of the evolution of our nearest planetary neighbour to eventually converge on reality.

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Coronavirus

A reconstruction of early cryptic COVID spread

Simon Cauchemez & Paolo Bosetti

To respond better to future pandemics, we must understand how the SARS-CoV-2 virus dispersed so rapidly. A model of COVID-19 spread sheds light on cryptic transmission, undetected by surveillance efforts, in early 2020. **See p.127**

Over the past 20 months, the COVID-19 pandemic has caused more than 4.9 million reported deaths (https://coronavirus.jhu.edu), and measures to limit the spread of the SARS-CoV-2 virus have affected the lives of people around the world. Although modelling has helped to reconstruct the early dynamics of the epidemic in some countries, we still lack a coherent picture of how the pandemic unfolded globally. On page 127, Davis *et al.*[1] use a worldwide model to assess early, cryptic transmission of SARS-CoV-2 – the spread of the virus that was not detected by initial surveillance efforts – in the United States and Europe.

Looking back at the chronology of the first months of the pandemic, it is concerning how fast the virus spread around the world, leading to a massive shutdown of people's social and economic lives. On 10 January 2020, 41 cases of COVID-19 were reported in Wuhan, Hubei province, China. The first reports of infection outside China were made on 13 January (in Thailand) and 16 January (in Japan). Wuhan was locked down on 23 January, followed by lockdowns in Italy (11 March), Spain (14 March), Austria (16 March) and France (17 March). Many countries, caught off-guard by the rapidly changing situation, reported a large death toll. How can we do better next time? To answer this question and improve our preparedness in the face of future pandemics, it is crucial to build a clearer picture of the initial spread of the virus. This is difficult, because the limited capacity to test for virus infections at the time meant that, in many locations, SARS-CoV-2 transmission might have been undetected.

Davis *et al.* used the Global Epidemic and Mobility (GLEAM) model, which has both stochastic (incorporating elements of randomness) and mechanistic (including defined principles about the biological and social mechanisms associated with viral infection and transmission) components to simulate virus spread on a global scale[2]. The model relies on various types of data to capture the multifactorial nature of the epidemic process. This information includes data describing: the populations in which the virus spread, such as country-specific demographics; the movement of people on international and local scales (for example, airline transport networks and commuting flows); and behaviours, such as information documenting how individuals of different ages mingle with each other. The model also captures biological aspects of SARS-CoV-2 transmission, clinical features (such as lethality for each age group analysed) and the timing of non-pharmaceutical containment measures, such as lockdowns.

Using the model, the authors shed light on how the virus propagated around the world. For example, the model confirms that, at the