A new quest for the Moon

As a series of landers, rovers and orbiters arrive on the Moon[1] or are under planning by various international space agencies, here we outline some novel perspectives which will drive lunar exploration in the next few decades. Our views regarding the formation and evolution of the Moon had fundamentally changed after the Apollo and Luna sample-return missions. Before Apollo landed on the Moon, several theories were proposed regarding the origin of the latter: fission from the earth, co-accretion with the earth and capture by the earth[2]. Return samples from the Moon showed that the proportion of $^{18}O : ^{17}O : ^{16}O$ for it was identical to that of the earth, implying a common source material. It is now considered that the Moon had formed at around 4.5 billion years ago (Ga), as a result of a grazing collision of an impactor of the size of Mars with the early earth, and ejected material from the earth and impactor, which accreted to form the Moon[2,3]. Further the discovery of anorthosite, an igneous rock, in returned samples suggested that a large part of the Moon was likely to be molten, with the anorthositic crust being formed by flotation above the crystallizing magma[3]. This is the widely accepted 'magma ocean' model for early lunar differentiation.

The lunar surface also provides a record of bombardment; indeed, radiometric ages of lunar samples suggest a spike in impact activity and that a 'late heavy bombardment (LHB)' phase occurred around 3.9 Ga (refs 1, 4). It is also presumed that several large lunar basins on the nearside formed at this time due to a considerable increase in the influx rate of bombarding planetesimals. However, additional ages of lunar samples from new missions are necessary to determine whether the record of older impacts is reset by younger impacts, and whether LHB may signify the end of a diminishing rate of impact activity on the Moon. The ~2 billion year age reported for lunar basalts returned by Change-5 implies that the impact flux rate may have been lower than previous estimates based on youngest Apollo and Luna basalts, but requires confirmation from future studies[4,5].

The lunar volatiles are expected to be preserved in cold traps or buried beneath the surface layer near the poles. For several decades following the sample-return missions in the 1960s, the Moon was believed to be entirely dry. Infrared mapping by the Moon Mineralogy Mapper (M^3) on Chandrayaan-1 resulted in the detection of hydroxyl (OH) and water on the uppermost few millimetres of the lunar surface[6]. Ever since the discovery of lunar polar volatiles in the 1990s, their origin, distribution, depth and spatial extent remain open questions. Furthermore, this represented the first direct evidence of ballistic transport of water, where it was discovered that the strength of the 3 μm hydration band (OH/H_2O) showed strong temperature dependence, implying migration of water along temperature gradients. However, this interpretation has been questioned since it requires correction for thermal emission, and different methods have resulted in varying conclusions about temperature dependence. Novel approaches are necessary to provide conclusive evidence of mechanisms proposed for the transport of volatiles on the lunar surface. Additionally, measurements of water abundances in returned samples suggest a range between 0.3 and 200 $\mu g\ g^{-1}$ for the mantle source region. However, a maximum mantle water abundance of 1–5 $\mu g\ g^{-1}$ has been derived from measurements of water abundances of apatite and ilmenite inclusions from Change-5 basalts[7], implying that the mantle source of these basalts had become dehydrated around 2 billion years ago. Further studies will indicate whether the derived water abundances of mantle source regions of lunar basalts imply a heterogeneous distribution of water in the interior of the Moon.

Radioisotope dating of basaltic samples returned by Apollo and Luna missions has revealed that basaltic magmatism occurred on the Moon between ~4.4 and ~2.9 Ga (ref. 6). However relative ages estimated using crater-counting chronology suggest that volcanism may have continued till 1.2 Ga (ref. 7). Recently, Pb–Pb ages of ~2 Ga have been reported for basalt fragments returned by the Change-5 mission[4,5], providing confirmation for the first time that lunar volcanism continued at least until 2 Ga. Additional radiometric ages are necessary from future missions to confirm this finding and to provide calibration points for ages determined using crater counting. Further, the μ value ($^{238}U/^{204}Pb$) of the source of the melt which formed the basalt was observed to be ~670–680 (refs 3, 4, 7) and is indicative of a KREEP-poor source. This suggests that the idea of KREEP-induced heating for producing young lunar magmas requires research or other novel mechanisms need to be proposed. Determination of new uranium, thorium and potassium in youngest basalts and KREEP-rich basalts from lander or rover platforms is necessary to determine whether these heat-producing elements are significantly higher in such young basalts in order to explain how a KREEP-poor source could result in extended volcanic activity on the Moon. Models for thermal evolution of the Moon may need revision, and inclusion of a non-KREEP origin for the youngest basalts of the Procellarum KREEP Terrane[8].

1. Voosen, P., *Science*, 2021, **373**, 1188–1192.
2. Bhandari, N., *Curr. Sci.*, 2002, **83**, 377–393.
3. Carlson, R. W., *Science*, 2019, **365**, 240–243.
4. Li, Qiu-Ll *et al.*, *Nature*, 2021, **600**, 54–58.
5. Che *et al.*, *Science*, 2021, **374**, 887–890.
6. Pieters *et al.*, *Science*, 2009, **326**, 568–572.
7. Hu Sen *et al.*, *Nature*, 2021, **600**, 49–53.
8. Tian, Heng-Ci *et al.*, *Nature*, 2021, **600**, 59–63.

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