IN SITU DATING OF LUNAR BASALT SAMPLES AT INA.

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Introduction: The Dating an Irregular Mare Patch with a Lunar Explorer (DIMPLE) payload is designed to establish the age and lithology of the Ina lunar irregular mare patch (Fig. 1), a 3×2 km wide, ~50 m deep summit pit crater atop a ~3.5 Ga old [1] shield volcano. Ina consists of smooth mounds amid lower-lying rough terrain [2]. The central mystery of Ina is its scarcity of visible impact craters, suggesting that it could be exceptionally young (33 ± 2 Ma [3]), in contrast to the ancient shield volcano. For comparison, most volcanic rocks on the Moon have ages of 3800-3000 Ma (e.g. [4]), and the youngest dated basalts on the Moon are ~2000 Ma old [5, 6]. The potential for Ina to be much younger than other lunar volcanic rocks has been recognized by the Origins, Worlds, and Life Decadal Survey [7] to pose a challenge to our understanding of lunar thermal and geochemical evolution, since it requires unexpectedly long-lived heat sources in the lunar interior. However, an alternative possibility is that Ina is ancient (~3.5 Ga), and that its paucity of recognizable impact craters is an indication of very high-porosity target rocks [4]. If the volcanic activity at Ina turns out to be geologically recent, then the lunar mantle was warmer for longer than previously thought, perhaps aided by decay of long-lived radioactive elements. However, if the eruptions that formed Ina are much older, it would require re-evaluation of impact crater-scaling laws for a range of target material types, with implications for interpreting other impact crater-derived surface ages on the Moon and potentially other planetary surfaces.

Payload Overview: DIMPLE has been selected for flight as part of NASA's Commercial Lunar Payload Services (CLPS) initiative. The payload [8] will use a lander-mounted arm as well as a rake carried by a CLPS-provided rover to collect rock samples from Ina's surface. The rover will scoop and carry rocks back to the CLPS lander. The lander arm will grip rocks and present smoothed faces of them for analysis by the Chemistry, Organics, and Dating EXperiment (CODEX) [9]. In this lunar context, the organics capability of CODEX will not be exploited. CODEX operates as a laser-ablation mass spectrometer for measuring elemental abundances, and as a laser-ablation resonance-ionization mass spectrometer for measuring isotopic abundances of Rb and Sr. The mass spectrometer is designed and built by Southwest Research Institute, the Aerospace Corporation, and Universität Bern.

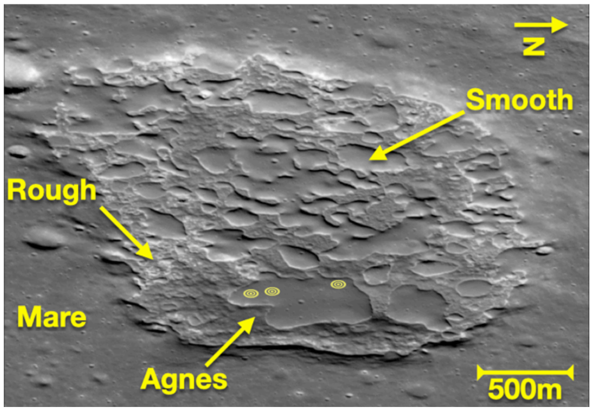

Fig 1. DIMPLE will make measurements to explain Ina's extraordinarily young (33 ± 2 Ma) impact crater retention age. The yellow circles on Mons Agnes show candidate landing sites. Image: LROC NAC M1108203502LR [NASA/GSFC/ASU]

Science Measurement Objectives and Questions: *Measure the age of rock samples at Ina.* DIMPLE will use CODEX to measure ^{87}Rb/^{87}Sr ratios at hundreds of spots within each rock sample. The data will then be used to produce isochrons, which will determine whether Ina had an exceptionally recent origin (e.g., ~33 ± 2 Ma [3]) or whether it is as old as other mare basalts (>2000 Ma). This information will help in understanding the duration of the Moon's magmatic and thermal history.

Identify the major lithology of rocks from Ina. CODEX will measure the major elemental concentrations of rocks at Ina. We anticipate measuring SiO_2 concentration with ≤5% relative precision and alkalis with ≤10% relative precision, sufficient to situate compositions on the total alkali-silica diagram. This diagram will enable an assessment of whether Ina is composed of basalt, as with most other lunar volcanic rocks, or a more evolved geochemical composition.

Compare sample composition with known lunar rock types. CODEX-measured major-element compositions will enable classification of rocks from Ina as mare basalt, KREEP basalt, or other. Though orbital remote sensing data [10] favors Ina being composed of mare basalt, with intermediate-to-high TiO_2 abundances (Fig. 2), DIMPLE will ground-truth that inference. DIMPLE compositional data for each of the major elements will enable comparisons between rocks from Ina and those from other lunar localities (Fig. 2).

Measure the abundances of heat-producing elements. CODEX will measure the concentration of U (as an oxide) and Th with <20% precision, and K with <10% precision. One possible way for the Moon to have produced magma very recently, as may have erupted at Ina, is by concentrating the elements K, U, and Th in the magma source region, with their long-lived radioisotopes producing heat as they decay. Global maps of heat-producing elements have been produced by gamma ray spectrometry experiments on board Lunar Prospector [15], Kaguya [16] and Chang'e 2 [17], yet the pixel size of these remote-sensing instruments is far greater than the 3 km diameter of the Ina formation. Therefore, only *in situ* measurements will be able to determine whether Ina rocks have an elevated concentration of these elements.

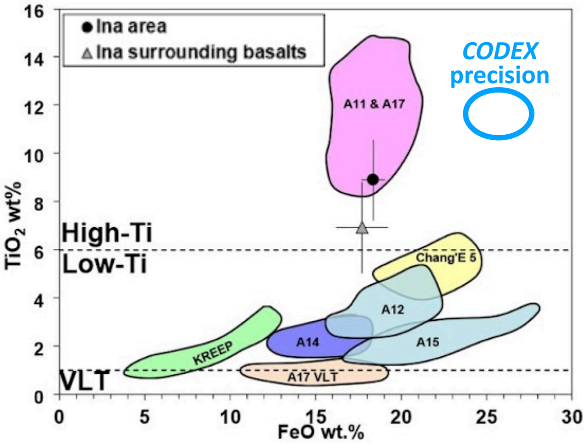

Fig 2. DIMPLE will determine *in situ* Ina's rock TiO_2, Al_2O_3, and K_2O, composition to compare with other lunar samples. Apollo data taken from [11] and Chang'e 5 data from [5, 12-14].

Assess KREEP involvement in melt origin by determining Rb and Sr isotope abundances. Rb and Sr concentrations, and especially $^{87}Sr/^{86}Sr$ ratios, are key fingerprints of KREEP assimilation. CODEX measurements of these quantities in rocks collected at Ina will be used to differentiate between KREEP-rich and mare-like, KREEP-poor magma sources.

Measure grain size and vesicularity of rocks at Ina. DIMPLE will use CLPS cameras mounted on the lander to image samples before and after sawing, as well as after laser ablation and analysis. These images, combined with CODEX analyses of elemental compositions on the ~80 µm scale, will enable the measurement of mineral grain size and rock vesicularity (Fig. 3). Vesicularity is important for understanding the young-looking surface at Ina because the material properties of target rocks affect the formation and retention of impact craters [e.g., 18, 19]. Laboratory experiments by Schultz et al. [20] showed that equivalent impactors excavate smaller craters upon striking more porous targets. Furthermore, impact-weakened, highly vesicular materials may not be able to retain crater forms over geologic time, which could explain the paucity of impact craters at Ina.

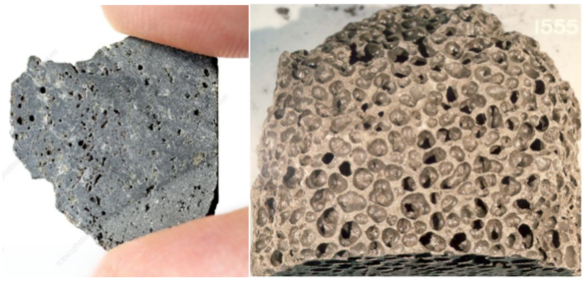

Fig 3. CLPS cameras will image rock samples, determining if the rock is massive (left) or vesicular (Apollo 15 basalt, right). Highly vesicular basalts may not produce impact crater-forms in the same way as stronger rocks, and therefore look erroneously young.

Acknowledgments: This work is supported through the NASA PRISM grant 80NSSC24M0001. The UK Co-Is are supported by UKRI STFC funding. RF and PW are supported by the Swiss National Science Foundation and Swiss Space Office.

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