CONCEPT OF OPERATIONS STRATEGIES FOR A LUNAR PIT MISSION.

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Introduction: Collapse pits in the lunar mare lava deposits expose rare sequences of bedrock and may also lead to large subsurface lava tubes [1-3]. These pits are of interest for scientific exploration and have also inspired architectures for longer-term human bases because of protection they provide from radiation, micrometeorites, and large temperature swings [4-8]. Many architectures have been considered for lunar pit exploration, including flying spheres, hopping robots, tethered rappelers, and cranes [6, 9-13]. The Moon Diver architecture consists of a stationary lander and a two-wheeled, tethered, extreme-terrain rover called Axel. The lander (equipped with solar panels and direct-to-Earth antenna) lands close to the pit [14] and then deploys Axel, which unspools its tether as it rappels down into the pit to study the exposed stratigraphy in the pit walls and explore the sublunarean void below over the course of one lunar day (**Fig. 1**). Moon Diver's payload includes a set of stereo cameras, a multispectral microimager [15], and an X-ray fluorescence spectrometer [16].

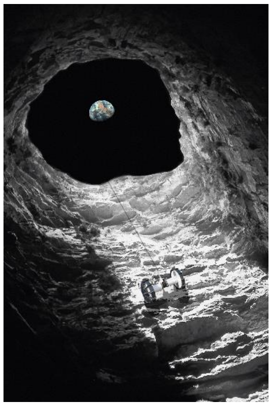

Fig. 1 Moon Diver pit exploration architecture.

The goal of the project described here is to explore science concept-of-operations challenges germane to lunar pit exploration using the Moon Diver architecture and instrument payload as a baseline. Some of the concept-of-operations challenges facing a mission like Moon Diver are shared with the many other lunar missions currently being formulated for the lunar surface, while others are specific to operations on a pit wall. Key challenges include: **(1)** A two-week mission length (one lunar day). **(2)** Near real-time operations, meaning that only a limited time is available to analyze collected data on the ground before moving on to the next data collection point. **(3)** Extreme and potentially unstable terrain. Volcanic pit walls range from mild to vertical to overhanging [17], and they can be jagged and prone to falling rocks and debris. As a result, the rover is not guaranteed up-close access to the wall at every point along its transect. **(4)** "Hot corners": places on the pit wall where the heat load on the rover is maximized due to the obscuration of cold sky by hot rock walls. **(5)** Moving shadows that introduce time-dependency into both imaging strategies and thermal management. **(6)** Unknown diversity of target stratigraphy. In the interest of time, a pit mission should strive to collect the minimum number of data points necessary to capture the diversity of the target rock layers. However, the distribution of compositional diversity in the rocks is not known *a priori*. Therefore it is vital to develop an effective strategy for distributing rover stops that can be efficiently implemented and responsive to what is found in-situ (e.g., upon first looking into the pit and seeing the opposite wall).

Methods: This project approaches these challenges in five steps: **(1)** Collect a dense grid of data analogous to Moon Diver's data at a several terrestrial analog pit sites with distinct lava morphologies. **(2)** Develop data processing pipelines to create useful data products from the raw data and determine how they can be produced in real-time and used to aid in decision-making. **(3)** Benchmark the derived data against traditional laboratory approaches to ensure that Moon Diver's payload is sufficient. **(4)** Use the collected data and derived products to create a "Design Simulation" for the Moon Diver science team simulating real mission operations. **(5)** Run the Design Simulation and assess the performance of the team against pre-defined metrics.

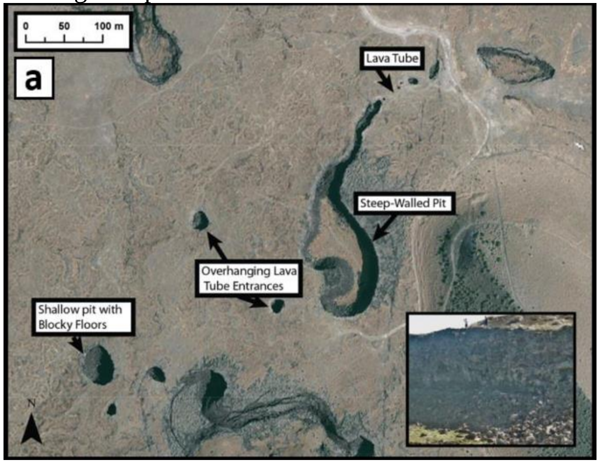

Fig. 2 Planview image of one of the two analog field sites and target vertical wall (inset).

Data was collected over two field seasons (2022 and 2023; **Figs 2** and **3**). Camera images were combined to produce rover-scale DEMs of the working area to determine how much of it is accessible with the current instrument placement devices. Multispectral images are currently being compared with hyperspectral images to determine the ability of Moon Diver's chosen spectral bands to capture the spectral variability of the rocks in the field. Likewise, laboratory XRF data is being compared with surficial spatial XRF mapping that is resampled to APXS's spatial resolution. Results are being combined into a "dashboard" (**Fig. 4**) for use in the design simulation, scheduled for the end of the summer.

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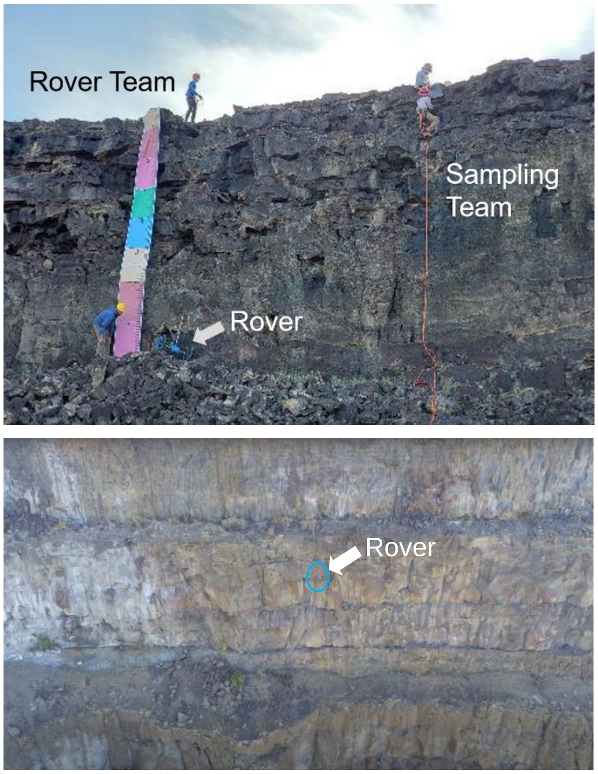

Fig. 3 (top) Field team using a "scarecrow" version of the Axel rover to collect imagery data on a 7 m wall, while human rappellers collected rocks that were used to generate a grid of SWIR microimages and XRF analysis. (bottom) Rover collecting data on 60 m wall.

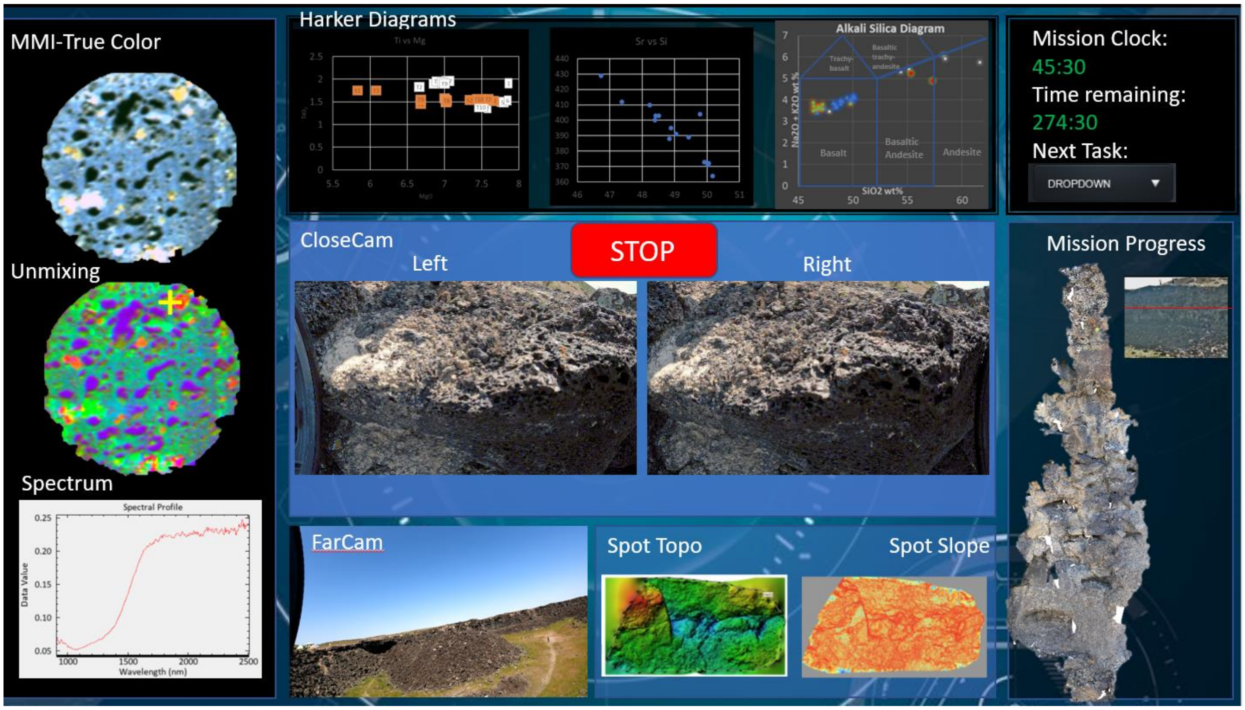

Fig. 4 Preliminary design of Moon Diver data "dashboard", populated with example field data.