**MOON DIVER: JOURNEY INTO THE ANCIENT LAVAS OF THE MOON.** L. Kerber[1] and the Moon Diver Team [1]Jet Propulsion Laboratory, California Institute of Technology, 4800 Oak Grove Dr., Pasadena, CA (kerber@jpl.nasa.gov)

**Introduction:** In 2009, the Japanese spacecraft Kaguya discovered several holes in the surface of the Moon [1]. Some of these holes are more than 100 m deep, and open into large caverns extending an unknown distance beneath the lunar surface [2–3]. Hypothetical lunar lava tubes may provide beneficial locations for future habitation: the caves offer protection from radiation, a shield from micrometeorites, and, with a predicted constant temperature of ~20°C, they provide refuge from the extreme temperature swings of the lunar surface [4–5]. Scientifically, the treasure is found within the walls of the pits: the exposure of near-vertical cross-sections through the Moon's uppermost crust, extending from the top of the regolith, through the regolith/bedrock transition, and through up to 70 m of intact lunar mare bedrock layers [2–3].

The *Moon Diver* mission concept proposes to use the extreme terrain Axel rover [6] to descend into the lunar mare (**Figure 1**), using a pit in Mare Tranquillitatis as a natural drill hole with which to access an unprecedented exposure through the regolith and bedrock of the Moon's secondary crust. At the bottom of the pit wall, *Moon Diver* will peer into a lunar cavern, and become the first mission ever to venture beneath the surface of another world.

**Science Goals:** *Moon Diver's* science goals are to understand the formation and evolution of the Moon's secondary crust. The Moon provides an especially useful example of secondary crust formation since (unlike the Earth and Venus) it is one of the few places where resurfacing stopped before the primary crust was completely obscured—meaning that we can determine both the composition of the secondary crust as well as the composition of the original crust through which it was emplaced. The relative geological simplicity of the Moon means that the evidence of these processes can be exquisitely preserved for billions of years. *Moon Diver*'s science objectives, derived directly from community documents [7–8], are to: **(1)** Determine the extent to which the regolith is representative of the underlying bedrock. **(2)** Determine whether the mare basalts were emplaced massively in turbulent flows, or if they were emplaced incrementally in smaller, but more numerous complex or inflated flows. **(3)** Determine the composition(s) of the parental magmas of the exposed basalts and what they tells us about the magma source regions in the lunar interior.

**Figure 1. Representation of the Axel rover rappelling into a lunar pit (left) and exploring the cavity below (right) as part of the *Moon Diver* mission.**

These objectives will be met by scaling the cross-section exposed in the wall of a mare pit, where both the process of regolith formation and the sequence of mare lava formation can be understood in their full contexts. Required measurements include:

**(1)** Elemental and mineralogical assessment of the regolith and the underlying basalts.

**(2)** Macro- and microscale physical characterization of the regolith up to and including the transition to the first bedrock layers.

**(3)** Assessment of macroscale lava flow morphology and microscale flow textures, lava layer thicknesses, and lava composition in order to determine lava flow rates.

**(4)** Chemical, mineralogical, and textural characterization of lava layers to constrain their petrologic origins.

**Science Implementation:** *Moon Diver* combines classic measurement techniques with a novel mobility system to achieve its ambitious science objectives. To make the measurements described above, the rover carries a suite of three simple instruments: (a) a trio of high-resolution cameras (Mars 2020 EECAM heritage [9]) to capture the macroscale morphology of the regolith and near and far pit walls with 20 megapixel color stereo images, (b) an Alpha-particle X-ray Spectrometer (APXS; MSL heritage [10]) to measure the elemental composition of both regolith and lavas, and (c) a multi-spectral microscopic imager (MMI) that uses controlled LED lighting to characterize grain, vesicle, and crystal size as well as capturing spatially resolved mineralogy [11]. The rover also carries a surface preparation tool, which creates a fresh, flat surface for the instruments to examine when needed.

**Mission Implementation:** Access to the record exposed in the wall of the target pit is provided by two key technologies: pinpoint landing (allowing the delivery of the payload close to the pit) and extreme terrain mobility (allowing the delivery of the instruments to the cliff wall to make their measurements).

Pinpoint landing uses Terrain Relative Navigation, similar to Mars 2020, which allows the spacecraft to recognize landmarks on the surface and adjust its trajectory to land extremely accurately [12]. It is expected to be even more accurate on the Moon in the absence of an atmosphere.

The extreme terrain mobility is provided by the Axel rover, which descends from the lander, rolls across the surface, and rappels down into the pit [6]. The lander provides mechanical support, power, and communication with the rover through its tether. The rover houses a winch on board, which pays out the tether as Axel moves. The instruments are housed inside Axel’s wheel wells, where they are protected from the environment. The wheel wells rotate independently from the rover’s wheels, allowing the surface preparation tool, the MMI, and the APXS to be placed on the same target with a high degree of accuracy [6]. Axel's simple design protects its instruments and makes it robust to the challenges of navigating a steep wall of lava layers.

**Field Preparations:** To test the mission concept and develop procedures for operating the rover and instruments in a lunar pit environment, a prototype of the Axel rover was outfitted with a suite of representative instruments: commercial equivalents of the EECAMs and APXS and a brassboard version of the MMI. This integrated suite was deployed to a terrestrial analogue site: a steep-sided basaltic collapse pit in Arizona called "Devolites Pit" (**Figure 2**). The rover was driven from a remote “mission” control, navigating the flat, funnel, and wall portions of the pit and taking representative science measurements along the way. Another field test was conducted in September 2019, where Axel rappelled down a near-vertical basaltic cliff (**Figure 3**).

**Implications:** The terrestrial planets are dominated by secondary crust. Understanding the process of secondary crust formation on the Moon, where there are fewer unknown or confounding variables, can provide a keystone for understanding crustal formation on other bodies [13]. In particular, planetary flood basalt flow rates currently have an uncertainty of many orders of magnitude, ranging from slow, laminar flows to fully turbulent flows. The measurements taken by *Moon Diver*, such as accurate flow thicknesses, could reduce this uncertainty for lunar basalts by up to seven orders of magnitude.

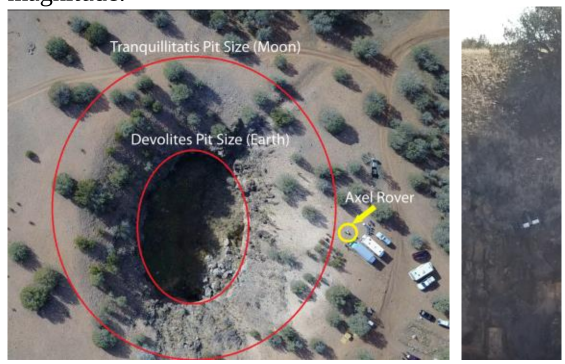


**Figure 2. Left: Field test site. Red circles show size of terrestrial versus lunar pits compared to the Axel rover (yellow). Right: The Axel rover on a vertical basalt wall.**

**Figure 3. Field test site at Fossil Falls, California. The Axel rover on a vertical basalt wall.**

Similarly, an examination of regolith formation and evolution from the surface to bedrock on the Moon, in concert with accumulated knowledge from *Apollo* and *Luna* samples, lunar meteorites, and remote sensing datasets, would help us interpret this process on other airless bodies where only remote datasets are available or where samples are available without contextual information.

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**Acknowledgments:** This work was carried out at the Jet Propulsion Laboratory California Institute of Technology under a contract with NASA. This abstract has been updated from a similar version presented at LPSC 2019 in Houston, TX.