TAURUS LITTROW PYROCLASTIC DEPOSIT: HIGH-YIELD FEEDSTOCK FOR LUNAR OXYGEN.

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Introduction: Future human habitation of the Moon will likely require the use of locally derived materials because of the high cost of transportation from Earth. Oxygen, extracted from oxides and silicates, is a potentially abundant lunar resource vital for life support and spacecraft propulsion. The anticipated costs of supplying all oxygen needs for a lunar base from Earth are high enough to warrant serious study of oxygen production from local resources.

Lunar Oxygen Production: Over 20 different processes have been proposed for oxygen production on the Moon [1]. Among the simplest and best studied of these processes is the reduction of oxides in lunar minerals and glass using hydrogen gas.

Oxygen can be extracted from lunar soils and pyroclastic glass beads by exposing the samples to flowing hydrogen at subsolidus temperatures (~1050°C). Total oxygen yield (wt. %) from 16 lunar soils is directly correlated to each sample's abundance of Fe^{2+} (wt. %) but is not correlated to the abundance of any other cation [2].

$$\textbf{Oxygen Yield} = \mathbf{0.19 \times Fe^{2+} + 0.55} \qquad \mathbf{r^2 = 0.87}$$

Oxygen is extracted predominantly from FeO, with lesser contributions from TiO_2 and SiO_2. Oxygen yield is independent of soil maturity. All major FeO-bearing phases contribute oxygen, with extraction from ilmenite and glass significantly more efficient than from olivine and pyroxene.

Lunar Pyroclastic Deposits: Pyroclastic glass may be an optimum feedstock for lunar oxygen production using the hydrogen reduction process, based on oxygen yield. Telescopic observations and orbital images of the Moon reveal at least 75 lunar pyroclastic deposits, interpreted as the products of explosive volcanic eruptions [3]. The deposits are understood to be composed primarily of sub-millimeter beads of basaltic composition, ranging from glassy to partially-crystallized [4]. Delano [5] documented 25 distinct pyroclastic bead compositions in lunar soil samples, with a range of FeO abundances from 16.5 - 24.7 wt%. The FeO-rich species, represented by the isochemical orange and black glasses collected by the Apollo 17 astronauts, promise particularly high yields. In hydrogen reduction experiments, samples of this material yielded 3.7 wt. % oxygen, the highest percentage of oxygen of any Apollo rock or soil [2]. These samples are uniformly fine grained, offering a feedstock that reacts rapidly and can be used with little or no processing prior to oxygen extraction.

Taurus Littrow: The Taurus Littrow regional pyroclastic deposit, located in eastern Mare Serenitatis (Fig. 1), extends across the Apollo 17 landing site. The Shorty crater orange and black glass beads, with an average diameter of 44 µm [6], are understood to be samples of this deposit. The orange and black glasses are identical in major element abundances, with the color indicating the degree of ilmenite and olivine crystallization following eruption [7]. These glasses have FeO abundances of 22.7 wt% (17.6 wt. % Fe^{2+}), among the highest abundances of any pyroclastic glass.

A future mission to demonstrate oxygen production on the lunar surface could produce high yields if targeted to a FeO-rich pyroclastic deposit. Analyses by the Diviner Lunar Radiometer Experiment (Diviner) on the Lunar Reconnaissance Orbiter (LRO) spacecraft, coupled with high-resolution images of the Taurus Littrow deposit from the Apollo Metric Mapping Camera and the Lunar Reconnaissance Orbiter Narrow Angle Camera (LROC NAC), provide new information to support landing site optimization.

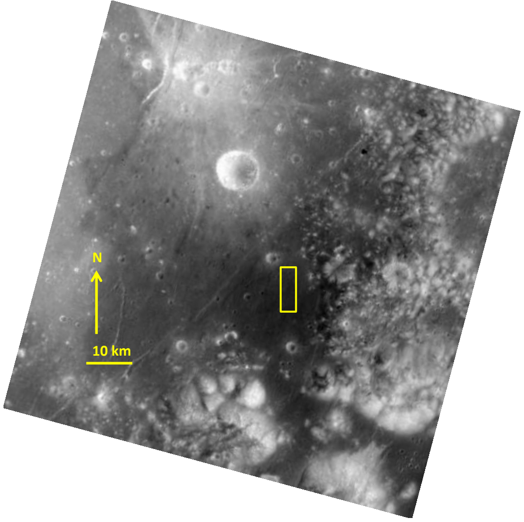

Figure 1. Taurus Littrow regional pyroclastic deposit (dark area), with the region of interest outlined (Apollo metric mapping camera image AS15-M-0972)

Diviner Lunar Radiometer Experiment: Diviner is a near- and thermal-infrared mapping radiometer on LRO, with a 320 m (in track) by 160 m (cross track) detector field of view at an altitude of 50 km [8]. Three channels centered near 8 µm are used to calculate the emissivity maximum known as the Christiansen feature

(CF) [9]. Diviner CF wavelength values, taken from data obtained near local noon, were reduced using the corrections of Greenhagen *et al*. [10]. These corrected CF values are particularly sensitive to silica polymerization in minerals including plagioclase, pyroxene and olivine. Given the restricted mineralogy of most lunar samples, CF values are closely correlated to major element oxide abundances, particularly FeO. The CF and FeO values correlate across the full range of Apollo soil and pyroclastic glass compositions. The published correlation [11] between FeO abundance (wt. %) and CF (μm) is:

$$\mathbf{FeO = 74.24 \times CF - 599.9 \qquad r^2 = 0.90}$$

Region of Interest: A region of interest with an area of ~ 20 km^2 (Fig. 1), bounded by 20.93 to 21.15° N and 30.02 to 30.10° E, was selected for detailed examination, based on consistently high Diviner CF values. This area, in the eastern portion of Taurus Littrow, is within the darkest area of the deposit. The combination of albedo and CF data indicates that the region of interest encompasses one of the least-contaminated sections of the deposit, and that the material is uniform in composition.

Within the region of interest, LROC NAC images show the surface to be extremely smooth, with uniform albedo. Very few craters or other landing hazards are visible at the sub-10 m scale (Figs. 2,3).

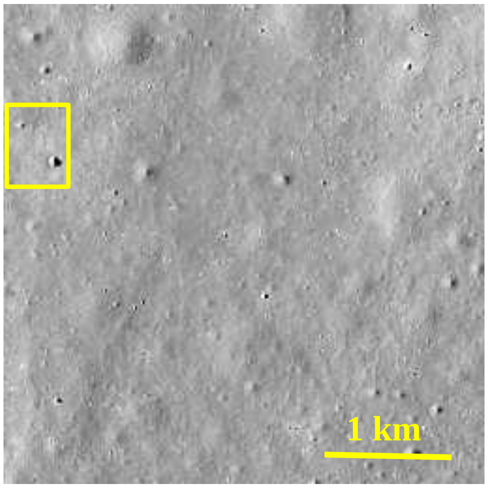

Figure 2. 15 km^2 area of the eastern Taurus Littrow pyroclastic deposit, within the region of interest (LROC NAC image; area of Figure 3 outlined)

Figure 3 also provides an estimate of the thickness of the pyroclastic deposit. The ~100 m diameter crater ejected distinct rays of dark material, indicating that the crater did not penetrate to higher-albedo material beneath the deposit. This observation indicates that the deposit has a minimum thickness of ~10 m at this location, in accord with the estimated thicknesses of pyroclastic deposits in Mare Orientale [12].

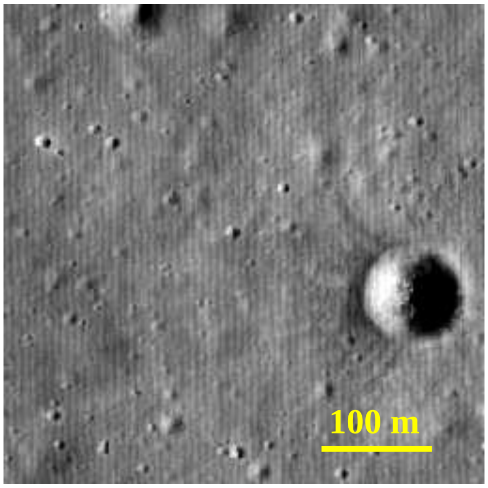

Figure 3. Inset in Figure 2 (LROC NAC image)

The average CF value in the region of interest is 8.37 μm, corresponding to a FeO abundance of 21.5 wt. % (16.7 wt. % Fe^{2+}). The standard deviation of these values is 0.03 μm, corresponding to an uncertainty in FeO abundance of 2.2 wt. % (1.7 wt. % Fe^{2+}) [13]. These values predict an oxygen yield from hydrogen reduction of 3.7 +/- 0.3 wt. %.

Implications for Lunar Oxygen Production: This study demonstrates that optimum landing sites for a lunar resources demonstration mission can be identified, and that the oxygen yield can be predicted, using a combination of high-resolution imaging and thermal-infrared data. A mission to Taurus Littrow would encounter a deposit at least 10 m in depth with few landing hazards, a near-uniform composition, and a predicted oxygen yield of approximately 3.7 wt. %, among the highest values to be expected on the Moon.

References: [1] Taylor L. A. and Carrier W. D. III (1992) *Engineering, Construction and Operations in Space III,* Am. Soc. Of Civ. Eng., 752-762. [2] Allen, C. C. et al. (1996) *JGR*, 101, 26,085. [3] Gaddis, L. R. et al. (2003) *Icarus*, *161*, 262. [4] Pieters, C. M. et al. (1974) *Science*, *183*, 1191. [5] Delano, J. (1986), *Proc. LPSC, 16th,* D201-D213. [6] Heiken, G. et al. (1974) *GCA*, *38*, 1703. [7] Weitz, C. M. et al. (1999) *Meteorit. Planet. Sci.*, *34*, 527. [8] Paige, D. A. *et al*. (2009) *Space Sci. Revs.*, DOI 10.1007/s11214-009-9529-2. [9] Greenhagen, B. T. et al. (2010) *Science*, *329*, 1507-1509. [10] Greenhagen, B. T. et al. (2011) *LPS XLII*, Abstract # 2679. [11] Allen C. C. *et al.* (2012) *JGR*, *117*, E00H28, doi:10.1029/2011JE003982. [12] Gaither T. A. et al. (2014) *LPS XLV,* Abstract # 1933. [13] Allen C. C. et al. (2014) *LPS XLV,* Abstract # 2447.