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NAG9-846

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FINAL
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December 10, 1997

TO: Ms. Cynthia Barnes

FROM: Dr. Cassandra Coombs CK

RE: FINAL REPORT: NAG9-846

As required, I am submitting a final report of my efforts for the grant, NAG9-846, Evaluation of Lunar Dark Mantle Deposits as a Key to Future Lunar Lunar Habitats.

Objective:
To better understand the nature, origin and use of lunar pyroclastic materials as potential resource materials for future human missions to the Moon.

Project summary:
I proposed to continue detailed mapping, analysis and assessment of the lunar pyroclastic dark mantle deposits in support of the Human Exploration and Development of Space (HEDS) inititative. Specifically, I (1) continued gathering data via the Internet and mailable media, and a variety of other digital lunar images including; high resolution digital images of the new Apollo masters from JSC, images from Clementine and Galileo, and recent telescopic images from Hawai'i. (2) continued analyses on these images using sophisticated hardware and software at JSC and the College of Charleston to determine and map composition using returned sample data for calibration. (3) worked closely with Dr. David McKay and others at JSC to relate sample data to image data using laboratory spectra from JSC and Brown University. (4) mapped the extent, thickness, and composition of important dark mantle deposits in selected study areas. And (5) began composing a geographically referenced database of lunar pyroclastic materials in the Apollo 17 area. The results have been used to identify and evaluate several candidate landing sites in dark mantle terrains. Additional work spawned from this effort includes the development of an educational CD-Rom on exploring the Moon: *Contact Light*. Throughout the whole process I have been in contact with the JSC HEDS personnel.

Student Involvement:
This research effort also involved two undergraduate students.

Follow-on Work:
This initial effort has led to the very recent award of a grant from NASA's Planetary Geology and Geochemistry Branch to complete the GIS CD-Rom and lunar pyroclastic database.

Publications and Presentations:

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Coombs C.R., C.C. Allen, B.R. Hawke, D.S. McKay (1997) A geologic evaluation of the Aristarchus Plateau as a potential landing site for Human Lunar Return. *In progress.*

Hawke B.R. C.R. Coombs, L.R. Gaddis, P.G. Lucey, C.A. Peterson, M.S. Robinson, G.A. Smith, and P.D. Spudis (1997) Remote sensing studies of geologic units in the eastern Nectaris Region of the Moon. In *Lunar and Planetary Science XXVIII,* pp. 529-530.

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ARISTARCHUS PLATEAU: A FUTURE ISRU SITE? C.R. Coombs[1], C.C. Allen[2], B.K. Joosten[3], M.F. Johnson[4]. [1]College of Charleston, 58 Coming Street, Charleston, SC 29424, cass@loki.cofc.edu, [2]Lockheed-Martin Engineering and Sciences. NASA/JSC, Houston, TX, 77058, allen@snmail.jsc.nasa.gov; [3]NASA JSC, Code SN2, Houston, TX 77058. joosten@snmail.jsc.nasa.gov; [4]Bridgewater State College, Bridgewater, CT, m6johnson@bridgew.edu.

INTRODUCTION

The NASA Strategic Plan calls for opening the space frontier by exploring, using, and enabling the development of space [1]. Within this plan a key goal of the Human Exploration and Development of Space (HEDS) Enterprise is to "Explore and settle the Solar System" [2]. As part the exploration strategy, NASA has been studying the feasibility of a low cost human return to the Moon. The currently planned mission has a dual focus on the advancement of lunar science and the use of *in situ* resources. To date, humans venturing into space have relied almost exclusively on equipment and supplies carried from Earth. This strategy is certainly appropriate for operations in Earth orbit, or for stays of a few days on the surface of the Moon. However, the ability to effectively utilize local resources, to "live off the land," will prove vital for long term habitation of the Moon and planets. This study synthesizes a wide range of data to characterize the Aristarchus Plateau, one of the primary candidate sites for human lunar exploration. Based on this synthesis study, we recommend two sites on the Aristarchus Plateau that will maximize science return and provide a convincing demonstration of the use of *in situ* resources and which may be a viable future lunar base site.

BACKGROUND

The Aristarchus Plateau is located in central northeastern Oceanus Procellarum on the lunar nearside (25°N 52°W). For years the Aristarchus Plateau has been a subject of interest to planetary scientists. It is one of the most geologically diverse regions for its size on the lunar surface. Recognized early in the Apollo days as being unique, it became an early candidate for an Apollo landing when site selection discussions stressed the need for geologic diversity and traverse distance [3]. Its surface is riddled with impact craters and secondary crater chains, volcanic constructs and pyroclastic deposits as well as many sinuous rilles and scarps (Figure 1). Among the geologic features are a blanket of dark mantling material; the densest concentration of sinuous rilles as well as the Moon's largest lava channel, Schröter's Valley; volcanic vents, sinks or depressions, and domes; mare materials of various ages and colors; one of the freshest large craters; and other large craters in different states of flooding and degradation [4].

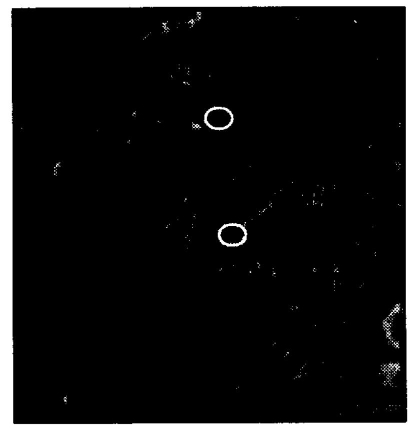

Figure 1: Lunar Orbiter IV photograph of the Aristarchus Plateau. The circles denote the suggested landing sites. Each is ~10 km in diameter. North is up.

The dark mantling deposits which cover much of the plateau are of particular interest. These deposits are very smooth, low units that mantle and subdue underlying terrain. The deposits are thought to be composed of microscopic glass spheres. First found as whole and broken green glass beads at Apollo 15, numerous classes of glass beads are now recognized in the returned Apollo sample collection. On the Apollo 17 mission orange glass beads and their quench-crystallized equivalents were identified at Station 4, Shorty Crater. Interpretations of their origin have swayed from vapor condensates to impact melt ejecta to pyroclastic material [e.g.,5,6,7,8,9]. The geologic diversity and large volume of Fe-rich pyroclastic material present at the Aristarchus site make it an ideal target for extracting O_2, H_2 and halogens. Extraction of lunar oxygen for rocket propulsion is a key example of in-situ resource utilization which will directly support a long-term human presence on the Moon. This is because one of the largest elements in any rocket is the oxygen required to burn the fuel. Nearly 90% of the propellant mass of a liquid hydrogen-liquid oxygen rocket is oxygen. Locally-produced oxygen for rocket propulsion promises by far the greatest cost and mass saving of any in-situ lunar resource [10]. As discussed below, the pyroclastic glass deposits which mantle much of the Aristarchus Plateau hold considerable promise as a source of such oxygen.

POTENTIAL IN-SITU RESOURCE UTILIZATION

Over twenty different processes have been proposed for oxygen production on the Moon [11]. One of the simplest and best-studied of these processes involves the subsolidus reduction of ferrous iron (Fe^{2+}) in lunar minerals and glass using hydrogen gas. This method of oxygen production is a two-step process. Ferrous iron (as FeO) is first reduced to metal, and oxygen is liberated to form water. The water is then electrolyzed as a second step, with hydrogen recycled to the reactor and oxygen liquefied and stored. Recent experiments on lunar materials and terrestrial analogs allow an assessment of the various proposed feedstocks for lunar oxygen production. Materials which have been proposed and/or tested include ilmenite, basalt, soil and volcanic glass. As the following discussion illustrates, some reacted better than others.

The first experiments to extract oxygen from lunar material utilized high-titanium basalt 70035. This sample, with an initial iron content of 14.35 wt%, produced from 3.2 to 4.6 wt% oxygen in hydrogen reduction experiments run at temperatures of 900-1050°C. Ilmenite occurs in abundances above 25 wt% in some lunar rocks. This mineral is easily reduced, and oxygen yields of 8-10 wt% may be achievable. However, experiments to date have invariably failed to completely segregate ilmenite from other mineral fragments, so that stoichiometric oxygen yield has not been realized.

Oxygen yields from soils are predictable, based solely on each sample's initial Fe abundance. Iron poor highland soils yield 1-2 wt % oxygen. Mare soils, especially those high in iron, yield as much as 3.6 wt % oxygen. The dominant Fe-bearing phases in lunar soil are the minerals ilmenite, olivine, pyroxene and impact glass. Each of these phases is a source of oxygen.

The greatest yield, 4.6 wt %, is derived from extremely iron-rich volcanic glass making it the optimum feedstock for production of lunar oxygen and other volatiles. At least 25 distinct glass compositions have been identified in the Apollo sample collection. The iron- and titanium-rich species, represented by the isochemical black and orange glasses from the Apollo 17 landing site, have demonstrated the highest oxygen yields of any lunar sample, approaching 4.5 wt% [12]. These samples are uniformly fine-grained, offering a feedstock which reacts rapidly and can be used with little or no processing prior to oxygen extraction.

Earth-based data, Apollo orbital photography and Clementine multispectral imagery was used to determine the precise extent and estimate the thickness of one widespread deposit covering the Aristarchus plateau [after 13]. We estimate the local pyroclastic resource reserve at 10-30 km depth with a volume of ~8000 km^3 over a 100 km area.

SUMMARY

In preparation for the Human Lunar Return (HLR) we have selected two potential landing sites on the Aristarchus Plateau (24°N 52°W) for an in-situ resource utilization (ISRU) demonstration (Figure 1). Recent planning for return to the Moon indicates that large cost savings can result from using locally produced oxygen, and recent JSC laboratory results indicate that iron-rich pyroclastic dark mantling deposits may be the richest oxygen resource on the Moon. Our earlier work demonstrated that instead of using regolith, bulk lunar pyroclastic deposits are better suited for beneficiation as they are thick (10's m's), unconsolidated, fine-grained deposits. In addition, the lack of rocks and boulders and the typically flat to gently rolling terrain will facilitate their mining and processing.

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USING GIS (GEOGRAPHIC INFORMATION SYSTEM) TECHNOLOGY TO ASSESS THE RESOURCE POTENTIAL OF LUNAR PYROCLASTIC DEPOSITS

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INTRODUCTION

Analyses of the lunar pyroclastic deposits can help address two major science theme strategies put forth by LExSWG: to better understand the formation of the Earth-Moon system, and the thermal and magmatic evolution of the Moon (LExSWG, 1992). To better visualize the interrelationships and assess the resource potential of the lunar pyroclastic sites, I have combined data collected from a variety of sources to generate a series of computer-based geographic information systems (GIS) for the major lunar pyroclastic sites; *Lunar Pyroclastic GIS*. An example of one data package is discussed here for the Taurus Littrow/Apollo 17 region of Mare Serenitatis.

What is a GIS?

A GIS is a computer system capable of capturing, storing, analyzing and displaying geographically referenced information in two or more dimensions (Fig. 1). A GIS package acts as both a data collator and spatial analyzing system, allowing one to easily query the entire set of spatially-registered data (e.g., local topography, sample sites, Apollo EVA 'roadmaps', photography at various resolutions and spectral ranges, telescopic spectra, sample chemistry, soil color and other available data). Each type of data is stored as a separate, 'transparent' data layer, allowing a wide variety of spatial analyses. This greatly enhances our ability to identify and further investigate underlying relationships and trends which may otherwise be difficult to recognize. Once completed, one can easily answer such queries as: How do the size and location(s) of the source vent(s) compare to the size of the deposit? How does the composition/spectra vary within a deposit? How does one deposit compare to another? Often, when all available data are included in a GIS, relationships that were never before envisioned become apparent. The potential of a GIS is only limited by the data available and one's imagination. Several computer programs were used to create and compile these GIS packages including ArcInfo, ArcView and Dimple.

Lunar Pyroclastic Deposits

Explosive volcanic, or pyroclastic, materials are unique phases in the lunar soils and are important as they hold clues to the history of lunar volcanism. Pyroclastic glasses, among the most primitive of lunar rocks, directly sample depths as great as 400 km (Delano, 1986). Earth-based telescopic studies have provided most of our information concerning lunar pyroclastic deposits. Combined with the returned lunar sample studies, recent telescopic data, and analyses of lunar photography, researchers continue to gather new information on the nature and origin of these explosive volcanic materials (Coombs, 1995; Coombs and Hawke, 1995). Based on their unique spectral signatures, two major classes and five subclasses of these deposits have been identified. Regional deposits are more numerous, extensive, thicker, and widely distributed than previously thought, leading us to suggest that they may exhibit distinct compositional variations and that they would provide ideal resource materials for a lunar base (e.g., Coombs, 1988; Hawke et al., 1989; Coombs and Hawke, 1995). Returned sample studies and the recently collected Galileo and Clementine data also corroborate these findings (e.g., Greeley et al., 1993; McEwen et al., 1994).

Example: Taurus-Littrow/Apollo 17

Located in the southeastern portion of Mare Serenitatis, the Taurus Littrow dark mantle deposit covers more than 4,000 sq. km. and varies in thickness from 10 to 30 m. This deposit is uniformly fine-grained and friable, offering a feedstock which reacts rapidly and can be used with little or no processing. Laboratory analyses of iron-rich samples represented by the orange glasses collected at this site yielded the highest percentage of oxygen of any lunar sample supporting its potential as an excellent resource material (e.g., Allen et al., 1994; Allen and McKay, 1995). Such a pyroclastic deposit could be a prime candidate for a future lunar oxygen plant, particularly with the high FeO abundance.

To further determine the potential of this resource deposit, a GIS was generated to facilitate data analysis and comparison. Data layers in this GIS package inlcude Apollo, Lunar Orbiter, and Ranger photographs and the more recent multispectral images, topographic, geologic and EVA maps, UV-VIS, near-IR and multispectral reflectance, 3.8- and 70-cm radar data and returned sample laboratory analyses as well as soil color and mophometric data. Although still in its infancy, the Taurus-Littrow GIS has permitted better visualization of the relationship(s) between deposit extent, sample locations and compositional variation. When completed, the Lunar Pyroclastic GIS will permit comparisons between the different pyroclastic deposits and expedite their evaluation as a potential resource.

References

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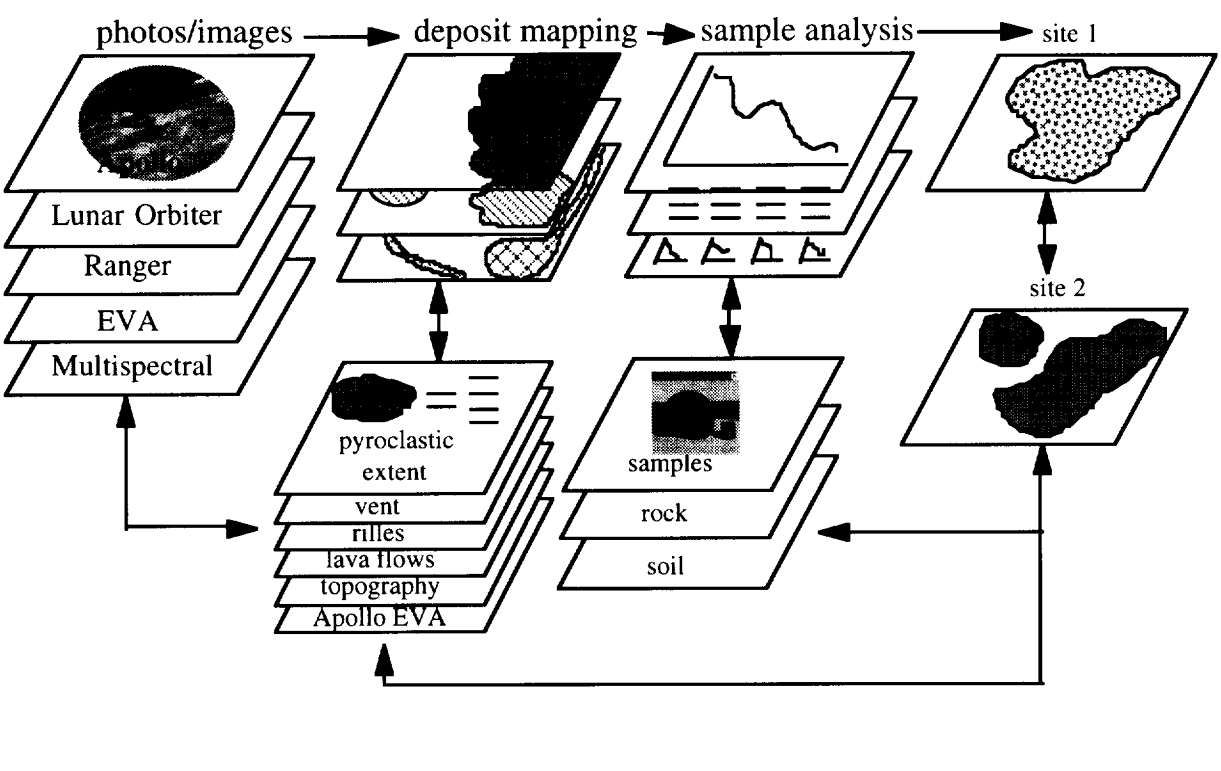

Figure 1: A schematic of a geographic information system (GIS) for a lunar pyroclastic deposit. Transparent data layers are user defined and may be combined in a variety of ways to provide the best assessment and visualization possibilities for a particular query.

Apollo 17 revisited: An interactive GIS database

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Submitted and presented to:
1997 Geological Society of America Annual Meeting: Salt Lake City, UT

When the Apollo 17 crew left the lunar surface they took with them the last geologic samples and photographs to be collected from the lunar surface in more than 25 years. In that time, much has been learned about the moon's dynamic geologic history. Currently, there is no coherent, readily accessible database or demonstration program that combines the lunar photography and imagery with geography and geology to illustrate the wealth of science generated by the Apollo program. We have generated a geographic information system, or GIS, package that acts as a collator and spatial analyzing system, allowing one to easily query the entire set of spatially-registered data. Data for this GIS includes local topography, sample sites, Apollo EVA 'roadmaps', photography at various resolutions and spectral ranges, telescopic spectra, sample chemistry, soil color, and other available data. Taurus Littrow and Apollo 17 were selected for this study because of the region's pyroclastic activity and resource potential as well as its other geologic characteristics. The GIS database matrix greatly enhances our ability to identify and use underlying trends and relationships which may otherwise be difficult to recognize. The data for this project were obtained from private data collections, the internet, the Lunar and Planetary Institute and NASA data centers. Following the completion of the Apollo 17 landing site, similar databases will be established for each of the Apollo and Luna landing sites and a CD-ROM will be made available for educational use.