REGIONAL AND LOCALIZED DEPOSITS ON THE MOON

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ABSTRACT

Earth-based telescopic remote sensing studies have provided important information concerning lunar pyroclastic deposits. Combined with the returned lunar sample studies and analyses of lunar photography, we have learned a great deal about the nature and origin of these explosive volcanic materials. Lunar pyroclastic deposits are more numerous, extensive, and widely distributed than previously thought. Two generic classes of lunar pyroclastics have been identified, regional and localized. From the former, two separate spectral compositional groups have been identified; one is dominated by Fe^{2+}-bearing glasses, the other is composed of ilmenite-rich black spheres. Comparatively, three separate spectral groups have been identified among the localized deposits: highlands-rich, olivine-rich, and mare-rich. Returned sample studies and the recently collected Galileo and Clementine data also corroborate these findings. Albedo data and multispectral imagery suggest that the thicker core deposits of the regional dark mantle deposits (RDMD) are surrounded by pyroclastic debris and subjacent highlands material. The presence of a major component of pyroclastic debris in the regolith surrounding the core regional deposits has important implications for the resource potential of these materials. Both telescopic and orbital spectra indicate that the regional pyroclastic deposits are rich in iron, titanium and oxygen-bearing minerals. Particle shapes vary from simple glass spheres to compound droplets with quench crystallized textures Their small grain size and friability make them ideal indigenous feedstock. Compared to other resource feedstock sources on the Moon, these pyroclastic materials may be the best oxygen resource on the Moon.

INTRODUCTION

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. As impact craters can be used as windows to the lunar interior, volcanic deposits can be used as windows to the deep lunar interior. Craters excavate and uplift materials from depths ranging from the near-surface to as much as 1/10 the crater diameter (Pieters et al., 1994). Pyroclastic glasses, among the most chemically "primitive" of lunar rocks, directly sample depths as great as 400 km (Delano, 1986) and thus can help address two major science theme strategies put forth by the Lunar Exploration Science Working Group, LExSWG: to better understand the formation of the Earth-Moon system and the thermal and magmatic evolution of the Moon (LExSWG, 1992), while helping us to plan better for upcoming lunar missions.

Earth-based telescopic studies have provided most of our information concerning lunar pyroclastic deposits. Combined with the returned lunar sample studies and analyses of spacecraft photography, we continue to gain insight into the nature and origin of these explosive volcanic materials. Two generic classes of lunar pyroclastics are recognized: regional and local. Our previous work has shown that the larger regional deposits are more numerous, extensive, and widely distributed than previously thought (e.g., Coombs, 1988; Hawke et al., 1989; Coombs & Hawke, 1995), leading us to suggest that they may exhibit distinct compositional variations. Returned sample studies and the recently collected Galileo and Clementine spacecraft data also corroborate these findings (e.g., Greeley et al., 1993; McEwen et al., 1994).

Whole and broken green glass beads were first found in abundance at the Apollo 15 site. On the Apollo 17 mission, orange glass beads and their quench-crystallized black equivalent were found in high concentration at Shorty Crater Station 4 (Figure 1). Various interpretations for the origin of these glass beads were proffered: (1) impact melt ejecta from large impacts which had penetrated to more mafic material at depth (Carr and Meyer, 1972; Hussain, 1972), (2) vapor condensates (Cavaretta et al., 1972; Quaide, 1973), (3) splash droplets from impacts into lava lakes (Roedder and Weiblen, 1973), or (4) pyroclastic material (McKay and Heiken, 1973; McKay et al., 1973; Huneke, 1973; Carter et al., 1973; Reid et al., 1973; Heiken and McKay, 1974). The explosive volcanic, or pyroclastic origin is now commonly accepted for the Apollo 17 orange and black glass spheres and Apollo 15 green glass. Similarly, it is now commonly accepted that the widely spread dark mantle deposits present elsewhere on the Moon also formed in similar explosive eruptions.

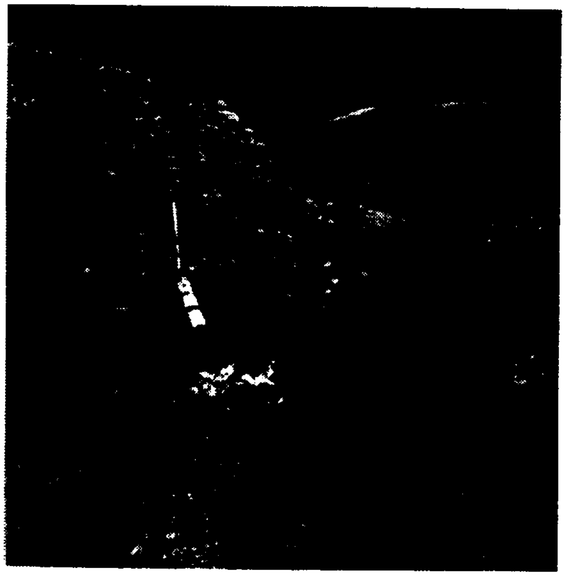

Figure 1: Trench at Apollo 17 revealing orange soil. Samples collected from this area also collected black glass spheres.

Since their initial identification and classification, many more dark mantle deposits have been identified. Among the largest of these are the Aristarchus Plateau, Mare Humorum, South Mare Vaporum, and Sulpicius Gallus deposits. Characteristically, the lunar pyroclastic deposits are very smooth, low albedo (0.079 - 0.096; Pohn and Wildey, 1970) units that cover and subdue underlying terrain.he regional pyroclastic deposits occur as thick accumulations in topographic lows and are thin or absent on adjacent hilltops (e.g., Lucchitta and Schmitt, 1974). Visual observations by Apollo astronauts and 2m-resolution Orbiter photographs indicate that the surface of these deposits is relatively fine textured with a velvety smooth appearance (Lucchitta, 1973; Schmitt, 1974; Lucchitta and Schmitt, 1974; Gaddis et al., 1985) Color varies among the deposits from a bluish-gray to a reddish-brown and locally may have a strong red, orange or blue hue (e.g., Schmitt, 1974).

During the past decade an enlightened attitude developed toward man's exploration and colonization of space. As part of this reawakening, the possibility of establishing a manned lunar base needs to be revisited. When established, such an endeavor should provide sound economic benefits as well as being a solid base from which to conduct scientific experiments. In the immediate post-Apollo era it was suggested by a number of workers that titanium production might be a profitable economic activity for a permanent needs to be revisited. When established, such an endeavor should provide sound economic benefits as well as being a solid base from which to conduct scientific experiments. In the immediate post-Apollo era it was suggested by a number of workers that titanium production might be a profitable economic activity for a permanent manned lunar base. Following that, it was suggested that fine-grained lunar regolith material would be useful for shielding orbiting space stations or military facilities. In the past few years, attention has focused on the production of oxygen propellant and helium-3 as nuclear fusion fuel both for use at the base and to transport materials back to Earth (e.g., Simon, 1985; Gibson and Knudson, 1985; Kulcinski et al., 1986; Kulcinski, 1988). From these early studies, ilmenite-rich material became the preferred source for the production of these resources (see Mendell, 1985; Hawke et al., 1989a,b). Hawke et al. (1990) discussed the resource potential of lunar pyroclastic deposits and suggested that they would make an excellent site for locating a lunar base. Most recently, Allen et al. (1995) extracted 6% O_2 from Apollo 17 glass spheres, the highest amount collected yet. In this paper we summarize some of what is known about these deposits, discuss models for their emplacement, and further explore their scientific, engineering and resource-related advantages as lunar base sites.

LUNAR PYROCLASTIC MATERIALS

REGIONAL VS LOCAL

Based on recent geologic and remote sensing data, the lunar pyroclastic deposits have been divided into two genetic classes: regional and localized (e.g., Lucey et al., 1984; Gaddis et al., 1985; Coombs, 1989; Hawke et al., 1989). These subdivisions are based upon their compositions as well as overall size and distribution. The regional dark mantle deposits cover a relatively large area of the lunar surface with respect to the smaller, localized deposits. Indeed, the regional deposits vary in size from 4,000 to 30,000 km^2. These large deposits are located in highlands areas adjacent to (and in some cases are superposed on) many of the major maria. The explosive fire-fountaining that formed these regional deposits may have been associated with some of the early mare-filling volcanic episodes (McGetchin and Head, 1973; Head, 1974). Endogenic craters and other irregular depressions are thought to be the source vents for these deposits (e.g., Zisk et al., 1973; Head, 1974; Gaddis et al., 1985; Coombs and Hawke, 1988).

The localized pyroclastic deposits are more widely spread across the lunar nearside than are the regional pyroclastics. These deposits too were emplaced via volcanic fire-fountaining. On average, the localized deposits cover 250-550 km^2 although some may be as small as 80 km^2, and some as large as 700 km^2 (Coombs et al., 1987; Coombs, 1988; Hawke et al., 1989). They are concentrated around the perimeters of the major lunar maria and are commonly found in the floors of large Imbrian and pre-Imbrian aged impact structures (e.g., Head and Wilson, 1979; Coombs and Hawke, 1988). The localized deposits are generally associated with small endogenic source craters (<3 km) and are aligned along crater floor-fractures and/or regional faults. Typically, these source craters are irregular in shape and lack obvious crater rays.

The explosive eruptions that formed the lunar dark mantle deposits have been likened to some types of terrestrial volcanic activity. The regional deposits most likely formed in a manner similar to terrestrial strombolian fire-fountaining, while the smaller, more localized deposits most likely formed by "vulcanian-type" explosions (Wilson and Head, 1979; Head and Wilson, 1981; Coombs, 1988; Hawke et al., 1989). A strombolian, or continuous eruption cycle is consistent with the volatile coated spheres returned from the Apollo 17 landing site, which chemical studies have shown to have originated deep in the lunar interior (<300 km).

In a strombolian eruption relatively small time-transient explosions occur at intervals ranging from less than 0.1 second to hours. Gas and pressure build up as the magma rises to the surface. The rising magma eventually reaches the surface through propagating cracks and or faults in the overlying rock. Explosive decompression occurs as the pressure is released and the magma and gas rise in an expanding column of erupting material. Environmental conditions on the Moon cause the particles to spread out over an area roughly six times larger on the Moon than they would for a similar eruption on Earth. With the 1/6 gravity and lack of atmosphere on the Moon, no pyroclastic flows will occur, rather, the pyroclasts will be spread over a broad area, with a size-grading of the clasts. Larger fragments will be deposited closest to the vent while finer grained particles may travel 100's km before settling out (Wilson and Head, 1979).

In the vulcanian-type eruptions that formed the localized pyroclastic deposits, magma, gas and pressure build up beneath a cap-rock in the conduit. Eventually, when enough pressure builds up, explosive decompression occurs and the cap-rock is blown away, along with the rising magma and gas. These eruption columns too will spread out more evenly on the Moon and cause the settling pyroclasts to cover a larger area than they would on Earth (Coombs, 1988; Coombs et al., 1989).

Due to their small areal extents and relative thinness, however, it is thought that the smaller, localized deposits would be less efficient for use in extracting lunar resources, and thus will be left out of the current discussion and evaluation as a potential lunar resource.

Pyroclastic Soil Evolution

Sample work done on the returned Apollo 17 orange and black glasses indicates that they are chemically indistinguishable from each other; the only difference being that the black spheres are partially quench-crystallized. Collectively, the glass beads are fine grained and have a mean grain size of ~40 µm and their shapes vary from subequant spheres to angular fragments. Many of them are coated with sublimates and or micromounds. Fig. 2 illustrates the breakdown of the mean grain size versus standard deviation for the A17 soils. From this figure, it is clear that the orange and black glasses are finer grained than most mature lunar soils.

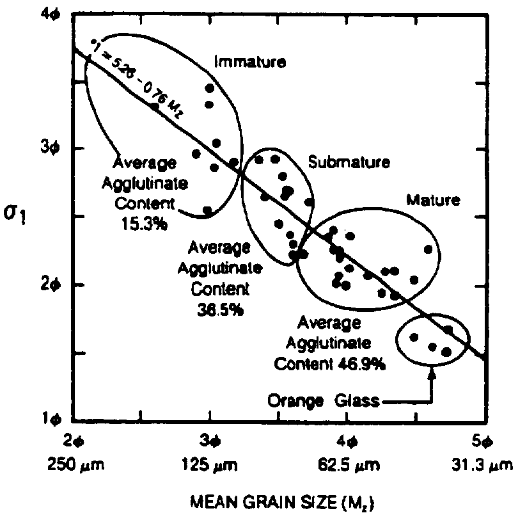

Figure 2: Mean grain size versus standard deviation for lunar soils. Note where the Apollo 17 orange glass lies in relation to other lunar soils. It is much finer grained than even mature lunar soils.

A size equilibrium is reached within lunar soils as a result of meteorite reworking. Basically, the grain size of any soil is determined by the amount of fresh ejecta present. For example, if there is a lot of fresh ejecta present, the soil will be fairly coarse grained. Or, if not much fresh material is introduced, the grains will become smaller and smaller over time as the mature soil is continuously being reworked by micrometeorites and impacts. Eventually, the soil or regolith is made into agglutinates that in turn, are reworked and mixed together with extraneous exotic materials. These materials then continue to be reworked. In time, it appears that with thicker soils, such as the 30 - 50 m thick dark mantle deposits, the steady addition of ejecta from fresh bedrock will go away and the continuous reworking of the already present regolith is continued.

If the supply of fresh material diminishes, the grain sizes will reduce to approximately 20 µm. Earlier studies by McKay et al., (1974), indicate that this 20 µm size is the smallest fraction that the glass beads to which will break down. The grain size is determined by the ratio of large to small particles. If there is no longer a significant input of larger particles, then the grain size will continue to decrease and reach an equilibrium floor of ~20 µm.

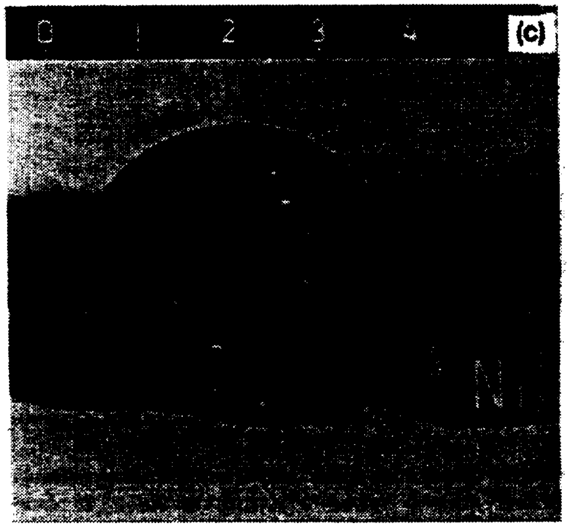

Figure 3: Vesicles within glass sphere 60095 from retuned Apollo 17 sample suite. Clast size is approximately 1 cm. Vesicles due to presence of internal gas during formation and cooling phase.

The maximum estimated thickness for a regional pyroclastic deposit is ~50 m. Based on early work by McKay and Heiken (1974) and Carrier (1974) the mean grain size within this deposit will be 5.35 ø or 25 µm. For an average thickness of 30 m, the mean grain size expected for a mature deposit would be 29 µm or 5.11ø. Analyses of the entire orange and black glass collection have yielded no single particle size greater than 1 mm, although some fragile clods of agglutinate material were larger than 1mm.

Morphology of Pyroclasts

Looking a little more closely at these glasses, the particle shapes vary from simple glass spheres to compound droplets with quench crystallized textures that vary from fine-grained dendrites to subequant skeletons. The bulk of the returned glass samples is comprised of fine grained fragments and shards, which raises a question about their origin and emplacement. These fragments are now interpretted to be the esult of anexplosive eruption, as mentioned above, whereby the material erupted, landed, bounced and more material was deposited on top. As a result, a process of self collision and breakdown occurs. These fragments are beneficial to the resource potential of these glasses. That is, the more surface area exposed, the more solar wind that can be adsorbed by the glasses. Quick calculations indicate that the surface area of a small bucket full of lunar pyroclastic materials is the equivalent surface area of an American football field (K. Joosten, pers. communication).

Vesicles are seen in less than 6% of the returned samples. Vesicles form in pyroclastic material by trapping gases in the magma during the fire-fountaining phase. The gases become isolated and trapped as the magma blebs cool and solidify during flight. These gases may represent volatiles released during the volcanic activity, and thus may be representative of the interior composition of the Moon. Possible vesicle gases include flourine compounds, sulfur, solar-wind gases and carbon monoxide (Goldberg et al., 1976). Carbon monoxide remains among the favorite of the vesicle-forming gases. Laboratory studies performed by Gibson et al. (1975) found that most of the C in mare basalts is released as CO and CO_2 as trapped magmatic gases. This, in addition to atmospheric and sputtering losses and recycling into subsequent lava flows, may account for the low C content currently detected in lunar soils.

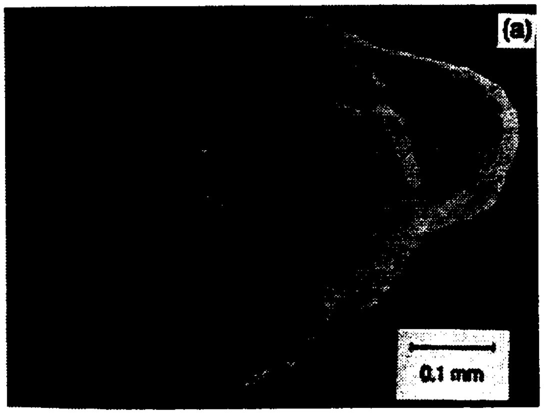

Figure 4: Compound droplet collected from the 74001/2 core tube sampled at Apollo 17.

Many of the glass beads form compound droplets (Figure 4), whereby one bead cooled and another hot droplet hit the bigger one while it was still soft and "squished" around it. Some of these secondary or parasitic droplets have been shown to be partly crystallized just beneath the surface. It is thought that the film, composed of Zn, Ga, Pb, Cu,Ti, S, F, Cl and other elements condensed on the surfaces during lava fountaining. Meyer et al. (1975) propose an anhydrous sulfide, chloride, and flouride rich vapor, originating from a pyroxenite layer deep inside the Moon. In addition, many of the glass beads are coated with a thin film of micromounds (Figure 5). The micromounds range in size from 20 - 500 Å in diameter (McKay et al., 1973). These are interpretted to be vapor condensate features that formed by venting gases, similar to the condensate deposits found around terrestrial volcanic/fumarolic centers. The micromounds found on the lunar glasses are enriched in sulfur, with some Zn, K, and Na also present (Clanton et al., 1978).

Morphologic textural features present within the Apollo 17 glass sample suite include the predominance of olivine and ilmenite crystals. These are thought to be due to devitrification of the glass bead. Parasitic crystals have also been found on the surfaces of some beads. The exact composition of these crystals is unknown, however, the larger ones are predominately of two compositions, potassium-chloride and sodium-chloride. The surfaces of some orange glass beads were also found to contain ameoboid blebs of iron.

Figure 5: SEM photomicrograph of sublimate micromounds on the surface of a glass sphere.

Table 1: Pristine Lunar Glass Varieties Arranged According to wt % TiO_2 Abundance

CLASS/VARIETY	SiO_2	TiO_2	Al_2O_3	Cr_2O_3	FeO	MnO	MgO	CaO	Na_2O	K_2O
1) Apollo 15 Green C	48.0	0.26	7.74	0.57	16.5	0.19	18.2	8.57	n.d.	n.d.
2) Apollo 15 Green A	45.5	0.38	7.75	0.56	19.7	0.22	17.2	8.65	n.d.	n.d.
3) Apollo 16 Green	43.9	0.39	7.83	0.39	21.9	0.24	16.9	8.44	n.d.	n.d.
4) Apollo 15 Green	46.0	0.40	7.92	0.55	19.1	n.a.	17.2	8.75	n.d.	n.d.
5) Apollo 15 Green D	45.1	0.41	7.43	0.55	20.3	0.22	17.6	8.43	n.d.	n.d.
6) Apollo 15 Green E	45.2	0.43	7.44	0.54	19.8	0.22	18.3	8.15	n.d.	n.d.
7) Apollo 14 Green B	44.8	0.45	7.14	0.54	19.8	0.24	19.1	8.03	0.06	0.03
8) Apollo 14 VLT	56.0	0.55	9.30	0.58	18.2	0.21	15.9	9.24	0.11	0.07
9) Apollo 11 Green	43.7	0.57	7.96	0.46	21.5	n.a.	17.0	8.44	n.d.	n.d.
10) Apollo 17 VLT	45.3	0.66	9.60	0.40	19.6	0.26	15.0	9.40	0.27	0.04
11) Apollo 17 Green	44.3	0.91	6.89	n.a.	20.2	0.23	19.5	7.40	0.10	n.d.
12) Apollo 14 Green A	44.1	0.97	6.71	0.56	23.1	0.28	16.6	7.94	n.d.	n.d.
13) Apollo 15 Yellow	42.9	3.48	8.30	0.59	22.1	0.27	13.5	8.50	0.45	n.d.
14) Apollo 14 Yellow	40.8	4.58	6.16	0.41	24.7	0.30	14.8	7.74	0.42	0.10
15) Apollo 17 Yellow	40.5	6.90	8.05	0.63	22.3	0.25	12.6	8.64	0.39	n.d.
16) Apollo 17 Orange	39.4	8.63	6.21	0.67	22.2	0.28	14.7	7.53	0.41	0.04
17) Apollo 17 Orange	38.5	9.12	5.79	0.69	22.9	n.a.	14.9	7.40	0.38	n.d.
18) Apollo 15 Orange	37.9	9.12	5.63	0.65	23.7	n.a.	14.9	7.41	0.36	n.d.
19) Apollo 17 Orange	38.8	9.30	7.62	0.66	22.9	0.29	11.6	8.55	0.39	n.d.
20) Apollo 11 Orange	37.3	10.0	5.68	0.63	23.7	n.a.	14.3	7.62	0.31	n.d.
21) Apollo 14 Orange	37.2	12.5	5.69	0.86	22.2	0.31	14.5	7.04	0.28	0.29
22) Apollo 15 Red	35.6	13.8	7.15	0.77	21.9	0.25	12.1	7.89	0.49	0.12
23) Apollo 14 Red	35.6	15.3	4.81	n.a.	23.7	n.a.	13.0	6.49	0.50	n.d.
24) Apollo 14 Black	34.0	16.4	4.6	0.92	24.5	0.31	13.3	6.90	0.23	0.16
25) Apollo 12 Red	33.4	16.4	4.6	0.84	23.9	0.30	13.0	6.27	0.05	0.12

n.a.: not yet analyzed

n.d.: not detected

Modified from Delano (1986).

GEOCHEMISTRY OF THE LUNAR PYROCLASTIC DEPOSITS

Geochemistry Of Returned Samples

Since their return, many microprobe, SEM, TEM, and petrographic analyses have been done on the lunar glass droplets (e.g., Chao et al., 1970; Reid et al., 1972, 1973; Ringwood, 1973; Heiken and McKay, 1974; Green et al., 1975; Glass, 1976; Marvin and Walker, 1978; Warner et al., 1979; Green and Delano, 1980; Delano and Livi, 1981; Chen et al., 1982; Delano, 1986). As a result of these many detailed studies Delano (1986) identified and confirmed the existence of twenty-five varieties of pristine, or volcanic, glass. These classes are based on their individual compositions and include: Apollo 11 green and orange; Apollo 12 red; Apollo 14 green (A & B), VLT, yellow, orange, black, and red; Apollo 15 green (A, B, C, D, E), orange, yellow, and red; Apollo 16 green; and Apollo 17 orange, yellow, VLT, and green (see Table 1). To accomplish this, Delano synthesized all of the previously published data and removed any interlaboratory bias by consistently using the Apollo 17 pristine orange glass composition as a working standard throughout his investigations of the high-Ti glasses. Likewise, the Apollo 15 pristine yellow glasses and Apollo 15 pristine green A glasses, respectively, were used as standards for other glass droplets containing medium- and low-Ti abundances (Delano, 1986).

The laboratory data indicate a composition rich in SiO_2, FeO and MgO for the various pyroclastic classes. These values are consistent with remote sensing data collected over the various regional pyroclastic deposits and discussed below.

REMOTE SENSING OF LUNAR PYROCLASTIC DEPOSITS

Orbital Geochemistry

The Apollo15 and 16 spacecrafts each flew a flourescent X-ray experiment package from which intensity ratios for the elements Mg, Al and Si were measured. In a procedure outlined by Bielefeld (1977), the various intensity ratios were converted to geochemical concentration ratios by weight. From these data, a positive correlation was noticed between high Mg/Al ratios and the presence of dark mantle material (Schonfeld and Bielefeld, 1978). Of the four large, regional pyroclastic deposits mentioned thus far, Sulpicius Gallus has the highest overall average Mg/Al values. Studies by Butler et al. (1978) show that the green, orange and brown pyroclastic glasses have extremely high Mg/Al concentration ratios (2.7, 2.6 and 1.7, respectively) compared to ordinary mare soils (ave. 0.61). When these glasses are mixed with the mare soils, an overall increase in Mg and decrease in Al concentration occurs. Mixing models performed by Schonfeld and Bielefeld (1978) estimate that approximately 32-37% of the Sulpicius Gallus formation is composed of orange and black glass. Similarly, they estimate that the two glasses compose 28% of the Taurus-Littrow deposit. Returned samples, however, indicate that only about 10-25% of the Apollo 17 soil was composed of orange and black glass, with the exception of Shorty Crater where pure concentrations of orange and black glass were found (AFGIT, 1973). This discrepancy may be due to the 50 km distance between the Apollo 17 landing site and the Taurus-Littrow deposit.

Other similar correlations between high Mg/Al ratios and the presence of dark mantle pyroclastic material were found at the craters Picard (Olson and Wilhelms, 1974) and Pierce (Casella and Binder, 1972) in Mare Crisium as well as in Mare Fecunditatis.

Andre et al. (1975) also analyzed the orbital geochemistry data collected over the Apollo 17-Taurus Littrow site. They looked at the Al/Si concentration and found that a decrease in intensity of the Al/Si ratio correlates with a distinct chemical boundary between the highland and dark mantle units. Less pronounced, however, was the distinction between the dark mantle unit and the floor of Mare Serenitatis. Here, the X-ray flourescence data indicated only a slight variation in Al/Si between the two materials (Andre et al. 1975). Nine Taurus-Littrow basalt samples studied by Nava (1974), Rhodes et al. (1974), and Rose et al. (1974) have an Al/Si concentration ranging from 0.22 to 0.28, or an intensity ratio between ~0.50 to ~0.66. The average concentration ratio yields an Al/Si intensity ratio of ~0.59, which corresponds to the average value for four orbital data points in the mare proper (Andre et al., 1975). The calculated concentration and intesity ratios for the orange and black glass are 0.19 and 0.48 respectively. These data correspond nicely with the visible albedo data of Pohn and Wildey (1970), the color-difference photograph of Whitaker (1972), and the relative spectral reflectivity curves of McCord et al. (1972), Gaddis et al. (1985), Coombs (1988), and Hawke et al. (1989).

Earth-Based Radar

As discussed briefly above, 3.8- and 70-cm radar backscatter images show that the surfaces of the regional pyroclastic deposits lack signal-scatterers, or rocks and boulders in the 1-50 cm size range. Rather, the data indicate that the surfaces of these deposits are smooth and block-free, and, that the nearsurface zones of these deposits are also block-free (Zisk et al., 1974; Thompson, 1979). With the low angle of incidence in the 3.8-cm radar images, the polarized signals returned are largely a function of the local slope. The unpolarized signals, on the other hand, are almost entirely dependent upon the inherrent properties of the surface materials, and exhibit little or no slope effects. These data support the field observations made by Apollo 17 astronauts, Cernan and Schmitt, during their EVA at Shorty Crater (Bailey and Ulrich, 1975), where they cored into a dark mantle deposit. In general, within any particular dark mantle deposit, areas of high radar return, or where a small impact penetrateted the pyroclastic mantle and exposed higher albedo material, are rare.

Earth-Based Telescopic Spectra

Earth-based telescopic spectral reflectance studies have provided important information concerning the composition of regional pyroclastic deposits (e.g., Adams et al., 1973; Pieters, 1973, 1974; Gaddis, 1985; Lucey et al., 1986). Figure 6 shows a number of near-infrared spectra that were collected from regional pyroclastic deposits on the lunar nearside (e.g., Sinus Aestuum, Rima Bode, Mare Vaporum, Taurus Littrow, Aristarchus Plateau). These spectra were collected from the University of Hawaii 2.2 meter telescope on Mauna Kea and processed according to the methods outlined by McCord et al., 1981.

The spectra indicate that the regional pyroclastic deposits are rich in iron, titanium and oxygen-bearing minerals. Some minor compositional variations do exist between the deposits. For example, the top three spectra in Figure 6 from Taurus Littrow, Sinus Aestuum, and Rima Bode, indicate a composition rich in iron, titanium and oxygen. The absorption bands in the continuum removed spectra are shallow and broad, with somewhat irregular base curves. The bottom two spectra from, Mare Humorum and the Aristarchus Plateau, on the other hand indicate that these deposits are rich in Fe^{2+}-bearing glass (Gaddis et al., 1985; Lucey et al., 1986; Coombs, 1988; Hawke et al., 1989). Here the absorption bands exhibit broader, deeper and more smooth or uniform signatures and extend to longer wavelengths.

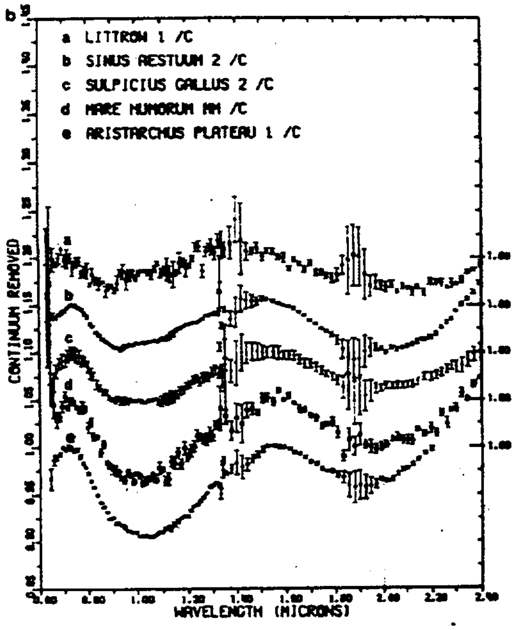

Figure 6: Continuum removed spectra collected from the U.H. 2.2 m teslescope on Mauna Kea of some regional pyroclastic deposits.

Multispectral ratios of these deposits exibit very high 0.40/0.56 µm values and the deposits appear "blue" in 0.40/0.56 µm images presented by Pieters et al. (1974) and McCord et al. (1976).

RESOURCE POTENTIAL OF LUNAR PYROCLASTIC MATERIALS

The surfaces of the lunar dark mantle deposits are uniform and exhibit a low amount of contamination (Pieters et al., 1974; McCord et al., 1976, 1979; Gaddis et al., 1981, 1985; Coombs, 1988; Hawke et al., 1989). The deposits are widespread and cover large areal extents. They are relatively deep, varying from 10-50 m thick. The deposits are homogeneous with uniform sizes and compositions and are relatively unconsolidated.

The mechanical properties of the pyroclastic deposits are predictable as compared to typical mare or highland regoliths, where there is much more variation in heterogeneity. Thus, it would be much easier to design a rover and other such necessary mining equipment to traverse the pyroclastic deposits. Mining and excavation will be straightforward in this material due to its fine-grained nature. These deposits have an excellent resource potential as they are relatively high in solar wind contents and the bulk chemistry of the glass is enriched in Si, Fe, Mg, and Ti. Also, these deposits would provide an extremely useful source of shielding and construction material. The high density of the deposit materials makes these glass beads ideal for radiation protection. Also, the combination of high density and potentially thick, fine-grained deposits make tunnelling for habitats extremely attractive. A mere 10-20 m covering of this material will provide a year-round ambient temperature of zero degrees C and would almost eliminate radiation hazards.

Recent laboratory studies performed here at JSC by Allen et al. (1994) demonstrated that the Apollo 17 orange and black glasses release the most oxygen when exposed to hot hydrogen than any other lunar material. Compared to other resource feedstock sources on the Moon, these pyroclastic materials may just be the best oxygen resource on the Moon. Additionally, we now know that the orange and black glass spheres are rich in easily accessible sulfur and other sublimates as mentioned above. These samples have approximately 700 ppm by weight, sulfur in the bulk glass sample. Sulfur may be easily extracted from the lunar glass beads by heating them to relatively low temperatures compared to other samples. Gibson and Moore (1974) heated beads from sample 74220,84 and determined that sulfur is released at temperatures as low as 250°C to 650-700°C. The iron-rich pyroclastics may also be very good feedstocks for producing construction material such as sintered concrete-like blocks and for extracting metallic iron for a lunar base power system.

CONCLUSION

An evaluation of the remote sensing data confirm that lunar pyroclastic deposits are more prevalent and widespread than intially mapped. In addition, more material is thought to have erupted and been distributed than previously thought. Results of the geologic and remote sensing studies now lead us to believe that some pyroclastic deposits are exposed remnants of much larger regional deposits that are now largely buried by crater ejecta and/or subsequent lava flows.

Laboratory compositional evaluations and soil studies support the use of these materials as resource feedstock. Not only are they readily avaiable in the most useful form - friable, fine-grained spheres, they are full of needed resource elements which can be readily beneficiated and used to establish and maintain a lunar base.

As with so many topics, we now know enough about lunar pyroclastics to know taht we need to know much more before we can claim we understand them. Recently returned satellite data and future missions such as Questions we will address in the future with the help of the higher resolution Clementine and Galileo data include: What is the 'true' geographic extent of the pyroclastic deposits? Can we actually identify potential source vents and how do the volcanic deposits relate to them? How does the composition of a deposit vary? How does the Apollo 17/Taurus-Littrow deposit, a comparatively well studied site from which we have samples, relate to similar, remote sites like Sulpicius Gallus or Rima Bode? How well can we extrapolate our findings to other sites? How do the regional sites compare to the local sites? How do the glass samples in most lunar soils fit into the picture? We know that the Apollo 17/Taurus Littrow spectra and samples correlate, but how far can we extend this correlation and our comparative methods? Do Apollo 11, 12, 14, 15, and 16 samples correlate with Clementine/Galileo spectra, and if so, how? What do the fresh craters tell us about these deposits? Can we find fresh, pristine exposures on the crater rims/walls? Can we determine the relationship of regolith maturity to grain color? How do the spectral signatures of individual pyroclastic glass particles relate to the signatures of larger scale deposits? What is the relationship, if any, between the regional and local deposits?

REFERENCES

Adams, J.B., Pieters, C.M., and McCord, T.B. 1974. Orange glass: Evidence for regional deposits of pyroclastic origin on the Moon. Proc. Lunar and Planet. Sci. Conf. 5th, pp. 171-186.

AFGIT (Apollo Field Geology Investigation Team) 1973. Geologic exploration of Taurus-Littrow: Apolo 17 landing site. Science 182:672-680.

Allen C.C, G.G. Bond, D.S. McKay (1994) Lunar oxygen production - a maturing techonology, in Engineering, Construction and Operations in Space IV, pp. 1157-1166, Am. Soc. Civil Eng., New York, 1994.

Andre, C.G., Hallam, M.E., Weidner, J.R., Podwysocki, M.H., Philpotts, J.A., Clark, P.E., and Adler, I. 1975. Correlation of Al/Si X-ray flourexcence data with other remote sensing data from the Taurus-Littrow area. Proc. Lunar and Planet. Sci. Conf. 5th. pp. 2739-2748.

Bailey, N.G. and Ulrich, G.E. 1975. Apollo 17 voice transcript pertaining to the geology of the landing site. U.S.G.S. Rpt. 74-031, 361 pp.

Bielefeld, M.J. 1977. Lunar surface chemistry of regions common to the orbital X-ray and gamma-ray experiments. Proc. Lunar Sci. Conf. 8th, pp. 1131-1147.

Butler, P.Jr. 1978. Recognition of lunar glass droplets produced directly from endogenous melts: The evidence from S-Zn coatings (abstract). In Lunar and Planet. Sci. IX, (Lunar and Planetary Institute, Houston), pp. 143-145.

Carr, M.H. and Meyer, C.E. 1972 Chemical and petrographic characteristics of the regolith at the Apollo 15 landing site. In The Apollo 15 Lunar Samples. (The Lunar Science Institute, Houston), pp. 48-50.

Carter, J.L. , Padovani E., and Taylor, H.C. 1973. Morhology and chemistry of particles from Apollo 17 soils 74220, 74241 and 74081 (abstract). EOS. Trans. Amer. Geophys. Union 54:582-584.

Casella, J.C. and Binder, A.B. 1972. Geologic map of the Cleomedes Quadrangle of the Moon. U.S.G.S. Rpt. I-707, (LAC 44).

Cavaretta, G., Funiceileeo, R., Giles, H., Nicholls, G.D., Taddeucci, A., and Zussman, J. 1972. Geochemistry of green glass speres from Apollo 15. In The Apollo 15 Lunar Samples. (Lunar Science Institute, Houston), pp. 202-203.

Chao, E.C.T., Boreman, J.A., Minkin, J.A., James, O.B., and Desborough, G.A. 1970. Lunar glasses of impact origin: Physical and chemical characteristics and geologic implications. J. Geophys. Res. 75:7445-7479.

Chen, H.K., Delano, J.W., and Lindsley, D.H. 1982. Chemistry and phase relations of VLT volcanic glasses from Apollo 14 and Apollo 17. Proc. Lunar Planet. Sci. Conf. 13th, in, J. Geophys. Res. 87:A171-181.

Coombs, C.R. 1988. Explosive Volcanism on the Moon and the Development of Lunar Sinuous Rilles and Their Terrestrial Analogs. Ph.D. Dissertation, Univ. of Hawaii, 241 pp.

Coombs, C.R. and Hawke, B.R. 1988. Explosive volcanism on the Moon: A review. Proc. Kagoshima Int'l Conf. on Volcanoes. Kagoshima, Japan. pp. 416-419.

Coombs, C.R., Hawke, B.R., Lucey, P.G., Owensby, P.D., and Zisk, S.H. 1990. The Alphonsus region: A geologic and remote-sensing perspective. Proc. 20th Lunar and Planet. Sci. Conf., pp. 161-174.

Coombs, C.R., McKay, D.S., Heiken, G.H., and Hawke, B.R. 1991. Should the future lunar base be located on a pyroclastic deposit? (abstract) Conf. on Near Earth Space Resources, Tuscon, AZ.

Delano, J.D. 1986. Pristine lunar glasses: Criteria, data and implications. Proc. 16th Lunar and Planet. Sci. Conf., In J. Geophys. Res. 91:D201-D213.

Delano, J.D. and Livi, K. 1981. Lunar volcanic glasses and their constraints on mare petrogenesis. Geochim. Cosmochim. Acta. 45: 2137-2149.

Gaddis, L.R., Adams, J.B., Hawke, B.R., Head, J.W., McCord, T.B., Pieters, C.M., and Zisk, S.H. 1981. Characterization and distribution of pyroclastic units in the Rima Bode region of the Moon (abstract). In Lunar and Planet. Sci. Conf XII (Lunar and Planet. Institute, Houston), pp. 318-320.

Gaddis, L.R., Pieters, C.M., and Hawke, B.R. 1985. Remote sensing of lunar pyroclastic mantling deposits. Icarus 61:461-489.

Gibson E.K. and G. W. Moore (1974) Sulfur abundances and distributions in the vally Taurus-Littrow. *Proc. Lunar Sci. Conf. 5th,* p. 1823-1837.

Gibson, M.A. and Knudsen, C.W. 1985. Lunar oxygen production from ilmenite. In Lunar Bases and Space Activities of the 21st Century ,ed. W.W. Mendell, (Lunar and Planetary Institutes, Houston). pp. 543-550.

Glass, B.P. 1976. Major elemnet composition of glasses from Apollo 11, 16 and 17 soil samples. Proc. Lunar Sci. Conf. 7th. 679-693.

Green, D.H., Ringwood, A.E., Hibberson, W.O, and Ware, N.G. 1975. Experimental petrology of Apollo 17 mare basalts. Proc. Lunar Sci. Conf. 6th. 871-893.

Hawke, B.R., Coombs, C.R., and Clark B. 1989a. Pyroclastic deposits: An ideal lunar resource (abstract). In Lunar and Planetary Science XX, (Lunar and Planetary Institute, Houston). pp. 387-390.

Hawke, B.R., Coombs, C.R., and Clark B. 1989b. Ilmenite-rich pyroclastic deposits: An ideal lunar resource. Proc. Lunar and Planet. Sci. Conf. 20th, pp. 249-258.

Hawke, B.R., Coombs, C.R., Gaddis, L.R., Lucey,P.G., and Owensby, P.D. 1989c. Remote sensing and geologic studies of localized dark mantle deposits on the Moon. Proc. Lunar and Planet. Sci. Conf. 19th, pp. 255-268.

Hawke, B.R., Coombs, C.R., and Clark B. 1990. Pyroclastic deposits as sites for lunar bases. Proc. Space 90 Conf., pp. ??-??.

Head, J.W. 1974. Lunar dark mantle deposits: Possible clues to the distribution of early mare deposits. Proc. Lunar and Planet. Sci. Conf. 5th, pp. 207-222.

Head, J.W. and Wilson, L. 1979. Alphonsus-type dark halo craters: Morphology, morphometry and eruption conditions. Proc. Lunar and Planet. Sci. Conf. 10th, pp. 2861-2897.

Heiken, G.H, McKay, D.S. , and Brown, R.W. 1974. Lunar deposits of possible pyroclastic origin. Geochim. Cosmochim. Acta 38:1703-1718.

Huneke, J.C., Podesek, F.A., and Wasserburg, G.J. 1973. An argon bouillabaisse including ages from the Luna 20 site (abstract). In Lunar Science IV, (The Lunar Science Institute, Houston), pp. 403-405.

Hussein, L. 1972. The Ar- Ar and cosmic ray exposure ages of Apollo 15 crystalline rocks, breccias and glasses (abstract). In The Apollo 15 Lunar Samples, (The Lunar Science Institute, Houston), pp. 374-376.

Kulcinski, G.L. 1988. ed., Astrofuel for the 21st Century. (College of Engineering, University of Wisconsin, Madison). 20 pp.

Kulcinski, G.L., Santarius, J.F., and Wittenberg, L.J. 1986. Presentation at the 1st Lunar Development Symposium. September, 1986, Atlantic City, N.J.

Lucey, P.G., Hawke, B.R., Pieters, C.M., Head,J.W., and McCord, T.B. 1986. A compositional study of the Aristarchus region of the Moon using near-infrared reflectance spectroscopy. Proc. Lunar and Planet. Sci. Conf. 16th in, J. Geophys. Res. 91:D344-D354.

Lucchita, B.K. 1973. Photogeology of the dark material in the Taurus-Littrow region of the Moon. Proc. Lunar Planet. Sci. Conf. 4th, pp. 149-162.

Lucchita, B.K. and Schmitt, H.H. 1974. Orange material in the Sulpicius Gallus Formation at the soutwestern edge of Mare Serenitatis. Proc. Lunar and Planet. Sci. Conf. 5th, pp. 223-234.

Marvin, U.B. and Walker, D. 1978. Implications of a titanium-rich glass clod at Oceanic Procellarum. Am. Mineral. 63:924-929.

McCord, T.B., Pieters, C.M., and Feierberg, M.A. 1976. Multispectral mapping of the lunar surface using ground-based telescopes. Icarus 29:1-34.

McCord, T.B., Grabow, M.A., Feierberg, M.A., MacLaskey, D., and Pieters, C.M. 1979. Lunar multispectral maps: Part II of the lunar nearside. Icarus 37:1-28

McCord, T.B., Clark, R.N., Hawke, B.R., McFadden, L.A., Owensby,P.D., Pieters, C.M., and Adams, J.B. 1981. Moon: Near-infrared spectral reflectance, a first good look. J. Geophys. Res. 86:10,883-10,892.

McGetchin,T.R. and Head, J.W. 1972. Lunar cinder cones. Science 180:68-71.

McKay, D.S., Clanton, U.S., and Ladle, G. 1973. Scanning electron microscope study of Apollo 15 green glass. Proc. 4th Lunar Sci. Conf., pp. 225-238.

McKay, D.S. and G.H. Heiken 1973. Petrography and scanning electron microscope study of Apollo 17 orange and black glass (abstract). EOS. Trans. Amer. Geophys. Union 54:599-600.

Mendell, W.W. 1985. ed., Lunar Bases and Space Activities of the 21st Century. (Lunar and Planetary Institute, Houston), 866 pp.

Nava, D.F. 1974. Chemical compositions of some soils an drock types from the Apollo 15, 16, and 17 lunar sites. Proc. Lunar Sci. Conf. 5th, pp. 1087-1096.

Olson, A.B. and Wilhelms, D.E. 1974. Geologic map of Mare Undarum Quadrangle of the Moon. U.S.G.S. Rpt. I-837 (LAC 62).

Pieters, C.M. , McCord, T.B., Zisk, S.H., and Adams, J.B. 1973. Lunar black spots and the nature of the Apollo 17 landing area. J. Geophys. Res. 78:5867-5875.

Pieters, C.M., McCord, T.B., Charette, M.P., and Adams J.B. 1974. Lunar surface: Identification of the dark mantling material in the Apollo 17 soil samples. Science 183:1191-1194.

Pohn, H.A. and Wildey, R.L. 1970. A photoelectric-photgraphic study of the normal albedo of the Moon. U.S. G.S. Prof. Paper 559-E, 20 pp.

Quaide, W.L. 1973. Provenance of Apennine Front regolith materials (abstract). In Lunar Science IV, (The Lunar Science Institute, Houston), pp. 606-607.

Reid, A.M. , Warner, J., Ridley, W.I., Johnston, D.A., Harmon, R.S., Jakes, P. and Brown, R.W. 1972. The major element compositions of lunar rocks as inferred from glass compositions in the lunar soils. Proc. Lunar Sci. Conf. 3rd. 363-378.

Reid, A.M., Lofgren G.E., Heiken G.H., Brown, R.W., and Moreland, G. 1973a. Apollo 17 orange glass, Apollo 15 green glass and Hawaiian lava fountain glass (abstract). EOS. Trans. Amer. Geophys. Union, 54:606-607.

Reid, A.M., Warner, J.L., Ridley, W.I., and Brown, R.W. 1973b. Luna 0 soil: Abundance and composition of phases in the 45-125 µm fraction. Geochim. Cosmochim. Acta, 37:1011-1030.

Rhodes, J.M., Rogers, K.V., Shih, C., Bansal, B.M., Niquist, L.E., Wiesmann, H., and Hubbard, N.J. 1974. The relationships between geology and soil chemistry at the Apollo 17 landing site. Proc. Lunar Sci. Conf. 5th, pp. 1097-1117.

Ringwood, A.E. and Kesson, S.E. 1976. A dynamic model for mare basalt petrogenesis. Proc. Lunar Sci. Conf. 7th. 1697-1722.

Roedder, E. and Weiblen, P. 1973. Origin of orange glass spherules in Apollo 17 sample 74220 (abstract). EOS. Trans. Amer. Geophys. Union, 54:612-613.

Rose, H.J., Jr., Cuttita, F., Berman, S., Brown, F.W., Carron, M.K., Christian, R.P., Dwornick, E.J., and Greenland, L.P. 1974. Chemical composition of rocks and soils at Taurus-Littrow. Proc. Lunar Sci. Conf. 5th, pp. 1119-1133.

Schmitt, H.H. 1973. Apollo 17 report on the Valley of Taurus-Littrow. Science 182:681-690.

Schonfeld, E. and Bielefield, M.J. 1978. Correlation of dark mantle deposits with high Mg/Al ratios. Proc. Lunar Planet. Sci. Conf. 9th, pp. 3037-3048.

Simon, M.C. 1985. A parametric analysis of lunar oxygen production. In Lunar Bases and Space Activities of the 21st Century ,ed. W.W. Mendell, (Lunar and Planetary Institutes, Houston), pp. 531-541.

Thompson, T.W. 1979. A review of Earth-based radar mapping of the Moon. Moon and Planets 20:179-198.

Warner, R.D., Taylor, G.J., and Keil K. 1979. Composition of glasses in Apollo 17 samples and their relation to known lunra rock types. Proc. Lunar Planet. Sci. Conf. 10th. 1437-1456.

Whitaker, E.A. 1972. Lunar color boundaries and their relationship to topographic features: A preliminary survey. The Moon 4:348-355.

Zisk, S.H. , Pettengill, G.H., and Catuna G.W. 1974. High resolution radar map of the lunar surface at 3.8-cm wavelength. The Moon 10:17-50.