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ABUNDANCES OF SODIUM, SULFUR, AND POTASSIUM IN LUNAR VOLCANIC GLASSES: EVIDENCE FOR VOLATILE LOSS DURING ERUPTION. J. W. Delano¹ and J. McGuire², ¹Department of Geological Sciences, State University of New York, Albany NY 12222, USA, ²Department of Earth and Space Sciences, State University of New York, Stony Brook NY 11794, USA.

Introduction: Six varieties of lunar volcanic glass are known to occur within the Apollo 17 sample collection [1]. Investigations have shown that 25 volatile elements (B, C, N, F, Na, S, Cl, K, Cu, Zn, Ga, Ge, Se, Br, Ag, Cd, In, Sb, Te, I, Au, Hg, Tl, Pb, Bi) are known to be concentrated on the exterior surfaces of individual volcanic glass spheres [e.g., 2-10]. Since bulk analyses (e.g., INAA, XRF) of volcanic glass provide an integrated abundance of an element on and within the glass spherules, other methods must be relied on to determine the interior abundance of an element. The interior abundance of an element within a volcanic glass sphere establishes the abundance of that element in the melt at the time of quench. The current study is part of a comprehensive attempt to measure the abundance of three volatile elements (Na, S, and K) within representative spheres of the 25 varieties of lunar volcanic glass currently known to exist at the Apollo landing sites. Comparison of the measured abundances of these elements within the interiors of individual glasses with (1) bulk analyses and (2) crystalline mare basalts will furnish new constraints on the geochemical behavior of volatile elements during lunar mare volcanism. **F. NO**

Analytical Procedures: Polished thin sections of lunar regolith and regolith breccias that expose the interiors of volcanic glass spheres were analyzed by electron microprobe (JEOL 733 Superprobe). The acceleration potential was 15 kV and the cup current was 50.0 nanoamps. A spot size of 20 μm was typically used. Counting times per analysis consisted of 300 s on the peak position of each element, as well as 150 s on each of the two background positions. Under most circumstances, each lunar glass was analyzed two or three times in order to check for chemical homogeneity and to improve analytical precision. The nominal detection limits for Na, S, and K for these operating conditions were 50 ppm, 32 ppm, and 37 ppm respectively. Reproducibility of multiple analyses on individual volcanic glass spherules were observed to be within a factor of 2 of those values. In order to check for the possible mobility of these elements within the glass during the analysis, which is commonly observed in terrestrial glasses, a natural lunar glass from Apollo 17 containing 3410 ppm Na, 900 ppm S, and 1220 ppm K was repeatedly analyzed at 60-s intervals, at the same spot location, for a total integrated beam exposure time of 1380 s using a cup current of 50 nanoamps. Within the counting statistics, no mobility of Na, S, or K was observed. This convinced us that mobility of these elements is not a problem in these dry, picritic lunar glasses during electron microprobe analyses. This study also attempted to measure the abundances of F and Cl within lunar volcanic glasses. Although the nominal detection limits for F and Cl were 200 ppm and 70 ppm respectively, neither of these two elements were detected. The higher detection limit for F is due to interferences on both sides of the F K-alpha peak from Fe L-alpha and a second-order Mg K-beta.

Results: Twenty-one volcanic glass spheres from 74220,128 have been analyzed for S. Eighteen of those same glasses were also analyzed for Na and K. Although these spheres have been previously reported to be chemically homogeneous [11-14] among the major elements (Si, Ti, Al, Cr, Fe, Mg, Ca), the abundances of Na, S, and K have been observed in this study to display ranges among spherules

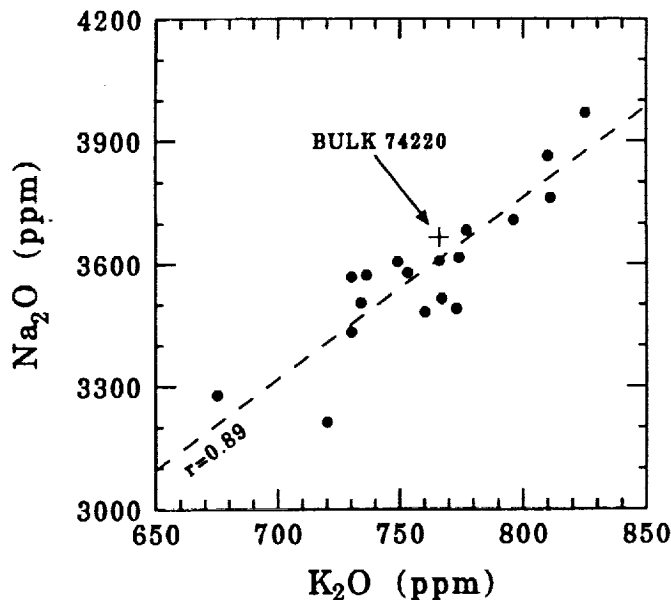


Fig. 1. Abundances of Na and K in 18 glass spherules (solid circles) from 74220,128. A 20–25% variation is observed among these glasses, whereas individual spherules appear to be homogeneous within analytical uncertainty. The bulk composition [15–20] of 74220 is shown by the + symbol. The linear least-squares fit to the data has a correlation coefficient of 0.89.

of 24%, 97%, and 22% respectively. Intrasample variations appear to be within analytical precision (i.e., individual spherules are homogeneous). For Na and K, Fig. 1 shows that the mean abundance of these elements among the 18 glasses are close to that of the bulk 74220 soil [15–20]. Figure 1 also shows that a strong correlation exists between Na and K in the glass spherules from 74220,128. In contrast, the abundance of S within the 74220,128 glasses is markedly different from the bulk S abundance of 820 ppm [21]. The interior abundances of S measured in 21 glasses from 74220,128 range from 148 ppm to 292 ppm with a mean value of 218 ppm. This mean value is in good agreement with a predicted value of about 187 ppm S made by Butler and Meyer [8]. The fact that the abundances of S within the glass are 2.8–5.5 times less than the measured abundance of S in the bulk 74220 underscores the importance of surface-correlated S [e.g., 8,21] on these volcanic glasses. With the exception of two 74220 spherules among the 18 spherules analyzed in this study, there is a good correlation between Na and S abundances. At the present time, we have no reason to doubt the veracity of the two aberrant points.

Our analyses (Fig. 2) show that the interior abundances of S in 74220, and other varieties of volcanic glass from Apollo 17 and other Apollo sites, are markedly lower than the abundances measured in the crystalline mare basalts. Although it has been previously noted that the bulk 74220 soil is depleted in S compared to the other high-Ti mare volcanics at Apollo 17 [e.g., 21], this depletion is even more marked when the interior abundances within the glasses are compared with the mare basalts. For example, the correlation between Ti and S noted by [22,23] would predict an abundance of 1600 ppm S in the 74220 magma. In contrast, the bulk soil abundance (820 ppm [21]) is about a factor of 2 less than that value, whereas the individual spherules have interior abundances of S with depletion factors ranging from 5.5 to 10.8. While we have no reason to doubt the correlation between Ti and S among the crystalline mare basalts [22,23], it is apparent from Fig. 2 that little, if any, correlation exists between these

two elements among the varieties of lunar volcanic glass analyzed in the current investigation.

Discussion: The 20–25% range in Na abundances observed in the present study among the 74220,128 glasses is nearly identical to the range reported by Hughes et al. [15] in their INAA data on individual 74220 spherules. If one assumes that the 74220 magma was chemically homogeneous prior to eruption, then the range of Na, S, and K abundances observed among individual spherules is indicative of fractional volatile loss from the droplets during fire fountaining and prior to quench. Each spherule would have had its own temperature/time history during the eruption that would be reflected in the fraction of volatile loss. Specifically, those spherules having the lowest Na, S, and K abundances would have remained hotter longer than those having higher Na, S, and K abundances. If this view is correct, then diffusion profiles, especially for S, might be predicted to occur within individual glass spherules (i.e., decreasing abundances from center to edge of spherules). Although we have made several, high-precision profiles on lunar volcanic glasses, no unambiguous diffusion gradients have yet been observed. Instead, complex profiles, such as those reported by [24] for the Apollo 15 volcanic green glasses, appear to be common. Work continues.

The range and highly correlated nature of Na and K among the 74220 glasses implies that Na and K, like S, were being fractionally lost during the volcanic eruption that produced this mist of fine melt droplets. It is important to note that both Na and K have been observed to be significantly concentrated on the surfaces of these glasses [6,8]. Consequently, our analyses provide additional evidence that fractional volatilization of Na and K occurred during the lunar mare volcanism associated with the origin of the 74220 glasses. Volatiliza-

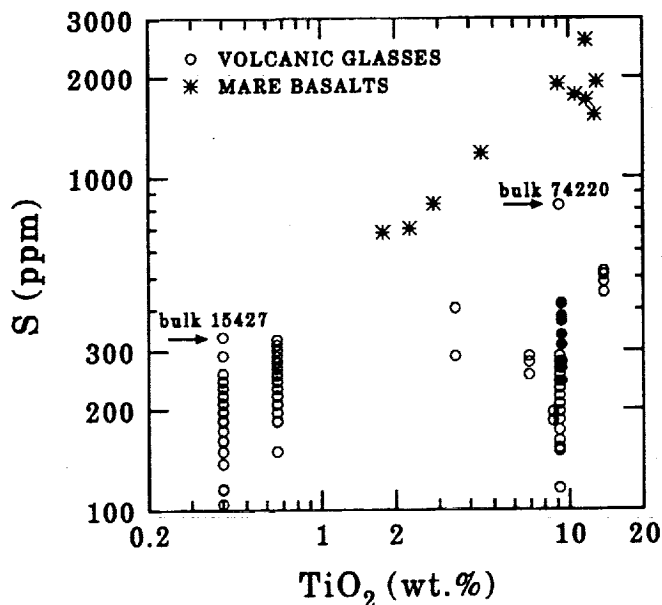


Fig. 2. Comparison of Ti and S abundances within lunar volcanic glasses (circles; this study) and crystalline mare basalts (stars). The abundances of S in bulk 15427 [21] and in bulk 74220 [21] are highlighted by arrows. The varieties of volcanic glass shown in this figure are the following (in sequence of increasing Ti abundance): Apollo 15 green, Apollo 17 VLT, Apollo 15 yellow, Apollo 17 yellow, Apollo 17 orange I, 74220 glasses, Apollo 17 orange II, and Apollo 15 red. Each circle represents an analysis of an individual glass spherule. Note that the volcanic glasses within a single magmatic suite display a large range in S abundances (see text for discussion).

tion of Na, S, and K during lunar volcanism was a subject of some interest during the early days of lunar sample analysis [e.g., 25,26].

The marked depletion of S in lunar volcanic glasses compared to the crystalline mare basalts has been attributed [21] to either (1) strong degassing of magmas during the fire fountaining that produced the volcanic glasses compared to the quiescent fissure eruptions that produced the mare basalts or (2) major differences in the S abundance within the mantle source regions. While our data strongly indicate that the former mechanism certainly contributed to this difference between mare basalts and volcanic glasses, additional constraints [27] suggest that the picritic magmas that produced the volcanic glasses were generated from different source regions than most of the mare basalts.

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RESOURCE AVAILABILITY AT TAURUS-LITTROW. Larry A. Haskin and R. O. Colson, Department of Earth and Planetary Sciences and McDonnell Center for the Space Sciences, Washington University, St. Louis MO 63130, USA.

What constitutes a lunar resource? Presumably, anything available on or from the Moon (e.g., [1]) is a resource. Our knowledge of the Moon's resources stands to be enhanced markedly through further exploration. A resource is not necessarily an ore, i.e., an economical source of a desired product. For commercial lunar extraction or manufacture, we require a resource, a need for the product, and reason to believe a lunar source is economical, i.e., that for some time period costs of mining, processing, fabrication, and delivery can be done more cheaply than from Earth or another extraterrestrial source.

During the next few decades, a lunar source is likely to be economical only for materials used in large quantities on the Moon or in near-Earth space, where the Moon's low gravity may offer an edge over Earth in transportation cost (e.g., [2]). Even so, lunar soils are potential ores for key products (fuel, metal, construction materials). Also, there are two plausible exceptions. One is souvenirs; the other is ^3He , plentiful on the Moon but not on Earth, proposed as fuel for commercial fusion reactors [3].

Long-duration experience in reduced, but nonzero, gravity is a "product" that may be cheaper to obtain on the Moon than elsewhere. This product, research, includes experience with physiological ef-

fects of long-term exposure to low gravity, problems of living, means of exploring, and coping with another environment. It includes experience in mining, extraction, and manufacturing. The Moon, because it is nearby, is probably the most economical extraterrestrial site for this research, especially if astronauts as well as automated equipment are involved. It is not clear that the experience in mining, extraction, production, handling, and storage on a planetary surface can be adequately simulated on Earth or in orbit. Mining and manufacturing can probably be done more cheaply with astronauts to assist in set-up, adjustment, maintenance, and repair of equipment rather than in wholly automated mode.

The complexity of carrying out even simple tasks on the Moon is a taxing overhead on proposed mining and manufacturing processes. The Moon lacks abundant and cheap air, water, and fossil fuels. It has no known common ores and no developed infrastructure. Differences between lunar and terrestrial conditions are so great that simple transplantation of terrestrial technologies is unworkable [2]. Economical use of lunar materials requires invention, demonstration, and development of methods appropriate to the Moon. We contend that lunar technologies for the next few decades must be simple and highly automated or teleoperated, and require minimal tending by astronauts. Processes requiring astronaut attention during nominal operation or for frequent repairs and maintenance will be regarded as labor intensive, and lunar labor will be expensive. Full automation is not obviously an inexpensive substitute, however; the successful Viking landers were a costly means of doing simple laboratory tasks inflexibly.

Early lunar technologies [2] will probably use a common lunar material as ore. They will be robust to minor fluctuations in feedstock composition and will not require appreciable feedstock beneficiation (see Beneficiation in references) such as rock grinding or mineral concentration. Technologies using unprocessed soil and indifferent to its composition will have the advantage. Nevertheless, the size and grade of the ore body must be confirmed for even the most indiscriminate process. Simple uses such as heaping unprocessed lunar soil for thermal insulation or radiation shielding onto a habitat require that we know the depth of the regolith, the size distributions of its soils, the locations of large boulders, and the ease of excavation. Costs of detailed site surveys trade against restrictions on site selection and conservative engineering design to accommodate unknown conditions of a poorly explored site.

Given the above considerations, we consider briefly some abundant lunar materials, their proposed uses, and technologies for their preparation, with particular attention to the Taurus-Littrow site. Relatively few papers are referenced in this text; references to two bibliographies [4,5] and to numerous, mainly more recent papers grouped according to subject area are compiled at the end of this abstract.

The Taurus-Littrow site has its fair share of the most common lunar resources, which are clinging soil; high vacuum; extreme temperatures ($\sim -170^\circ$ to 120°C); half-time sunlight; long, hot days ($\sim 14 \times 24$ hours); and long, cold nights [1]. With experience, we will come to view them as assets rather than just as obstacles. Harnessing the Sun's energy requires reflectors, pointable mirrors, photovoltaic and other devices for converting radiation to electrical energy, and heat engines. Vacuum is handy in casting molten materials. Proposed uses for unprocessed soil include thermal insulation, radiation shielding, and spacecraft ballast. Exactly how to use the soil, dig it up, and pile it on remain research topics.

Converting soil to structural material with adequate mechanical strength adds complexity. Proposed forms include bricks [6-8], cast basalt products (see Glass and Ceramics), glasses (see Glass and