Development of a Miniature Scanning Electron Microscope to Facilitate In-situ Lunar Science and Engineering

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ABSTRACT

Returning humans to the Moon for prolonged periods will require extensive information on the properties and compositions of the lunar regolith, its resource potential, and *in-situ* characterization of the effects of space weathering of the soil and equipment. To address these concerns, we are developing a miniature Scanning Electron Microscope (mSEM), a project led by the NASA Marshall Space Flight Center (MSFC), for use on the lunar surface. Working within the lunar environment and at low-power provides opportunities to simplify the instrument, as well as sample preparation. The natural lack of an atmosphere eliminates the need and complexity of a vacuum chamber on the instrument and introduces the possibility of a "point-and-shoot" configuration for the mSEM. Imaging with low-power does not require sample coatings of carbon or gold, or the use of a gas, to mitigate surface charging on the sample; this low-power greatly simplifies sample preparation. Engineering and science activities on the lunar surface will benefit from the presence of an mSEM and its ability to determine particle size distribution (PSD), mineral chemistry, and the general characteristics of the regolith.

INTRODUCTION

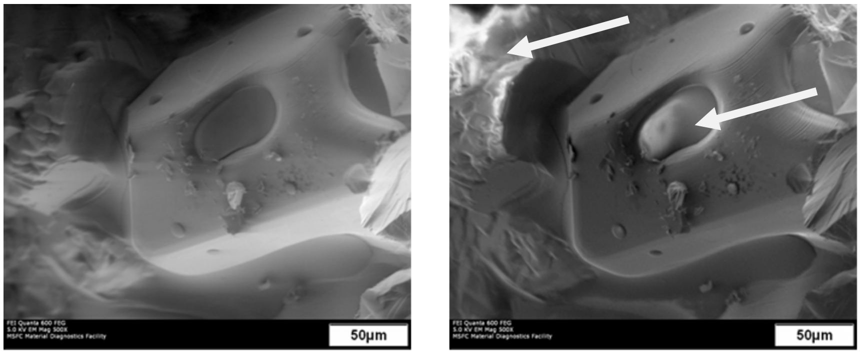
Over the last several years, China, Japan, India, Europe, and the United States have all sent satellites to the Moon. Of these, India and the United States also included impactors, which were designed to analyze the lunar surface and subsurface in much greater detail than could be attained from an orbital platform. All of these missions have been successful to varying degrees, but cannot provide the kind of detailed information about the lunar regolith that will be required for extended surface activities. Although considerable research has already been performed on the Apollo and Luna rocks and soils, these samples represent less than ten percent of the lunar surface and are significantly biased toward the nearside equatorial region. In addition to this limited sample distribution, the collection and transportation methods were not designed to preserve the characteristics of the fine- to coarse-particle layering that occurs at the lunar surface (Heiken et al., 1991). In spite of this, innumerable insights have been made into the origin and formation of the Moon (Smith et al., 1970; Wood et al., 1970; Warren, 1985), characterization of the lunar soil formational processes (McKay et al., 1974; Taylor et al., 2001), space weathering, and its implications for remote sensing, on airless bodies (Keller et al., 1998, 2000; Pieters et al., 2000). So much so, that the Moon has become our standard for understanding space weathering on airless bodies in our solar system. But, there are still several fundamental questions that remain to be answered about the processes involved in space weathering and lunar volcanism (Space Studies Board, 2007). This is in addition to the speculation, which will necessitate in-situ study, that a fraction of the lunar dust may be electrostatically levitated, transported, and redeposited as a thin layer across the lunar surface (e.g. Stubbs et al., 2006).

The renewed interest in human exploration beyond low-Earth orbit, whether it is to our moon, the asteroids, or the moons of Mars, requires a thorough understanding of the regolith on airless bodies, which we do not currently possess. With plans to return humans to the Moon for prolonged periods of time, additional information will be required on the properties and composition of lunar regolith, its particle size distribution (PSD), the potential for the regolith as a usable resource, and an understanding of the *in-situ* effects of space weathering. In addition to providing fundamental knowledge about the lunar surface, the study of the regolith will also provide invaluable information for the design and development of the equipment that will be used on the Moon, or the surface of any other airless body in the solar system. The equipment that will be exposed to the lunar surface will continuously encounter dust, and an understanding of the size, general characteristics, and composition of this dust can lead to mitigation strategies which will prolong operational lifetimes. *In-situ* resource utilization (ISRU) of the lunar regolith and the search for suitable feedstocks, for processes such as oxygen production, will also require knowledge of the PSD, mineral abundances, and chemistry (e.g., Taylor, 1992a, 1992b; Chambers et al., 1994, 1995). In order to study the lunar soil/dust directly on the lunar surface, we are working as part of a team at the Marshall Space Flight Center (MSFC) on the development of a miniature Scanning Electron Microscope (mSEM) with Energy Dispersive Spectroscopy (EDS) capabilities. This mSEM design is intended for possible deployment on a lunar rover.

OBJECTIVES & METHODOLOGY

The primary objectives of this project are identifying the minimum capabilities that will be required to constrain the developmental parameters of the mSEM, as well as determining what kind of sample preparation will be necessary for adequate analysis of the regolith. Experiments have been conducted at the University of Tennessee-Knoxville (UTK) and MSFC, with commercial SEM and environmental Scanning Electron Microscopes (ESEM). These were performed on returned Apollo soil samples (varying sizes <1 mm), and powdered mineral samples of terrestrial origin, to aid in establishing the desired mSEM capabilities and to set design parameters. We are studying sample charging effects, resolution limits, and capability to perform EDS under various SEM settings and sample preparation techniques.

Commercially available SEM and ESEM are being utilized to identify the desired capabilities that will be designed into the mSEM. A variety of several operational parameters, including accelerating voltage, spot size, aperture size, vacuum pressure, and possible use of an environmental gas, are being explored in order to determine the combinations that provide the most useful imaging capabilities. In addition to the mSEM configuration, a primary concern is the simplification of sample preparation. Callus (2000) observed that low-current imaging of uncoated Mars soil simulants produced satisfactory results. We are currently working with Apollo lunar samples that are adhered to a standard aluminum SEM sample stub with double-sided carbon tape. In order to minimize the required sample preparation, we have examined uncoated lunar samples under high-vacuum versus uncoated lunar samples under a low-vacuum with the addition of an environmental gas at 5 kV and 10 kV, a 'normal' ESEM situation. It has been established that an environmental gas in the sample chamber is not necessary if a lower incident electron beam current is used. As can be seen in Figure 1, imaging quality for these Apollo samples was not significantly reduced by the lack of a surface coating of carbon or gold, or the presence of an environmental gas in the sample chamber, at 500x magnification. The ability to reduce moving parts in this mSEM instrument and to make use of the natural vacuum (10^{-12} torr) that exists at the Moon's surface should greatly simplify this lunar mSEM design.



With environmental gas Without environmental gas

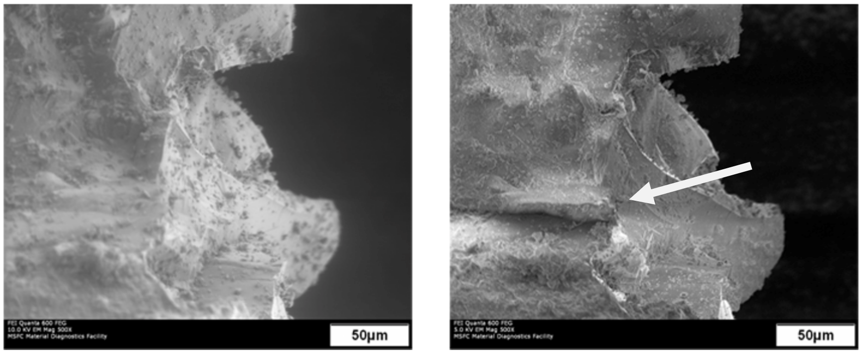


Figure 1. Images of uncoated Apollo 17 regolith grains using an environmental gas at low-vacuum (left) and no environmental gas at high-vacuum (right). Although minor charging effects are observed (arrows), significant differences are not present in these samples. However, charging effects of other samples indicate that there is significant dependence on sample composition.

In order to determine what resolution would be suitable, or even possible, with uncoated samples, terrestrial samples of olivine, pyroxene, and plagioclase were prepared. These terrestrial mineral samples, which are *similar* to lunar minerals, were used to mitigate the potential of losing lunar sample during experimentation and act as a known standard during testing. These minerals were ground to a fine powder using a mortar and pestle and then prepared as grain-mounts, examined both as individual powders and mixed together to simulate a loose multi-component soil. This was done in order to determine if significant charging effects could be recognized in these samples and with preferred mineral substrates. These samples were also used to determine the lower-size limit of particles that could be analyzed with EDS. The ability to resolve grain morphology can be done on pieces that are as small as 500 nm on uncoated samples. Examination with EDS performed on the same particle identified a significant carbon presence from the carbon tape used to adhere this pyroxene grain to the sample stub (Fig. 2). Grains sizes of approximately 2-3 μm no longer register carbon peaks and *appear* to represent the minimum grain size for complete EDS analysis.

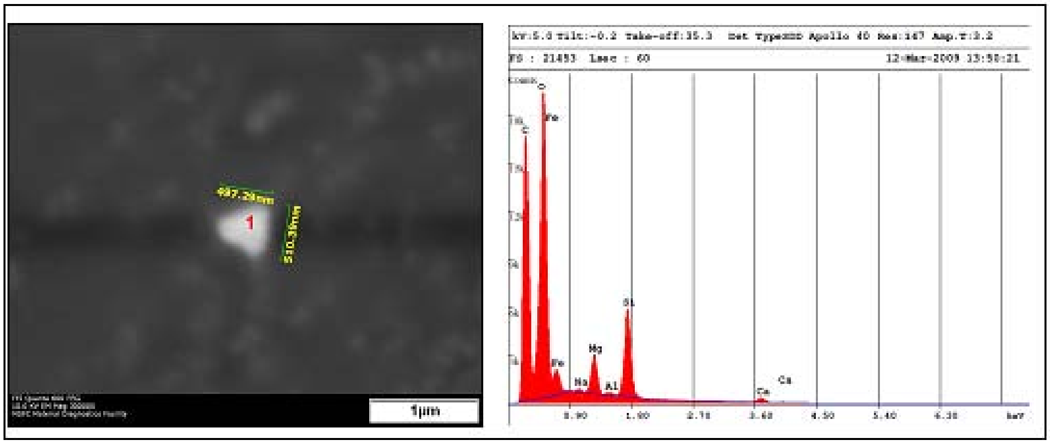


Figure 2. Terrestrial Pyroxene grain at 30,000x magnification (left) and EDS analysis (right) from location marked 1. Although grain morphology can be resolved at this magnification, the grain is too small for complete EDS analysis (notice C peak in energy spectrum).

We have also performed SEM imaging and EDS analysis on samples that were loose and/or electrostatically attached to larger grains; these larger grains were attached to the carbon tape. The results were of mixed quality, in that the amount of sample charging was highly dependent on sample type and size. Future experiments with loose material will be required to determine whether or not sample stabilization prior to imaging is required. During operations that utilize high magnifications, surface charging was sufficient to cause smaller particles to be displaced from their original locations, negatively influencing imaging capabilities. The longer dwell times associated with the use of EDS to generate sufficient x-rays, especially during x-ray mapping, sometimes resulted in significant charging and often caused smaller, loose particles to migrate, as shown in Figure 3. The migration of smaller particles during EDS examination can also influence measurement repeatability; it appears that further work is necessary to mitigate these issues.

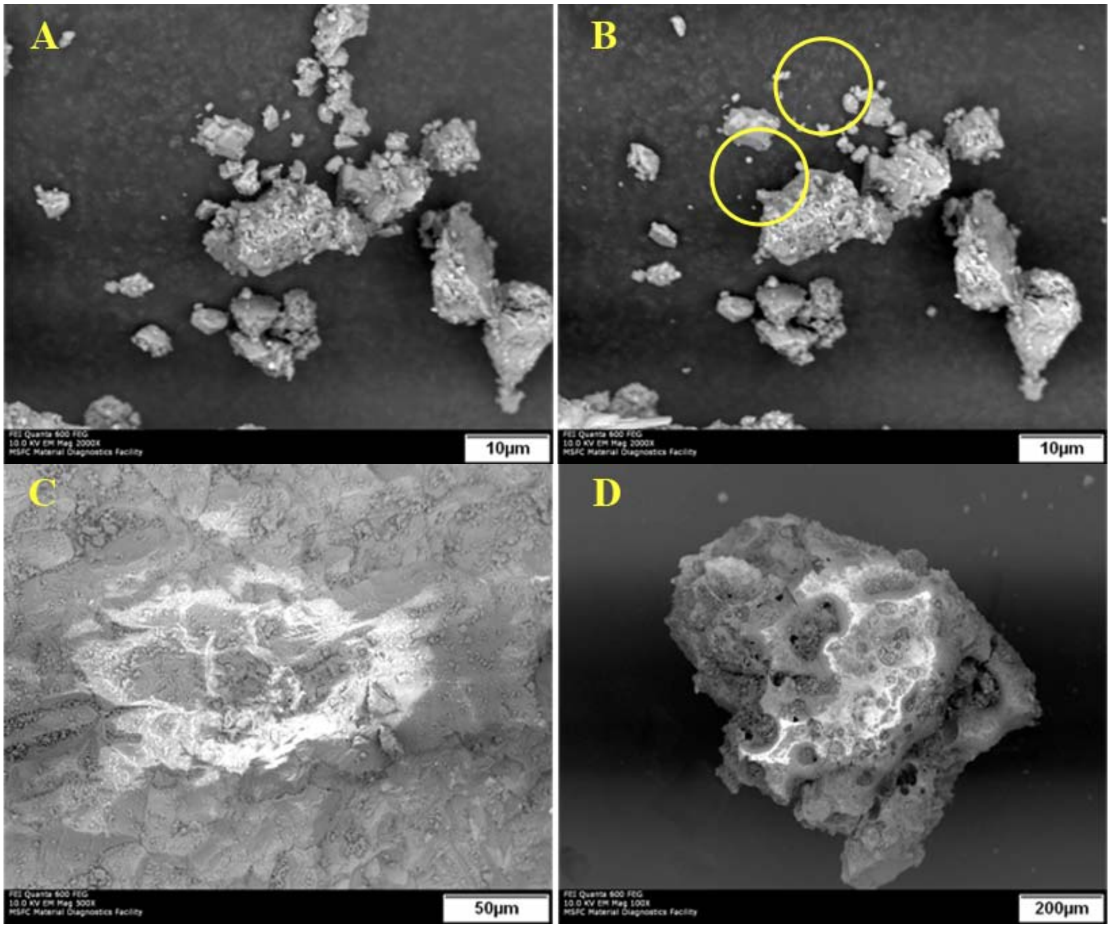


Figure 3. Charging effects can be recognized at different magnifications and may result in "jumping" of some smaller particles, as can be seen in the top images (A before EDS and B after EDS analysis). At higher magnifications, a brightening of a surface due to electron build-up may occur, as seen in the bottom images (C and D), especially during longer dwell times associated with EDS collection or high magnification.

DISCUSSION

The use of uncoated lunar and terrestrial samples, under reduced power conditions, has proven to be a viable alternative to a carbon or gold coating or the use of an environmental gas in the mSEM. However, most of the samples tested to this point have been adhered to an SEM sample stud with double-sided carbon tape. This tape may aid in dissipating excess charge and most certainly aids in holding the samples in place during image and EDS acquisition. Therefore, further testing of loose material is still required in order to determine if a sample chamber with an adhering substrate will be required or a simpler "point-and-shoot" configuration can be adopted. The movement of small particles due to excess-charge build-up may prove to be beneficial in some aspects. For example, inasmuch as charging can remove a thin coating of dust from a surface; this may be an effective cleaning process for mineral and glass surfaces prior to EDS analysis. However, here again, additional testing will be required before this type of procedure can be fully appreciated and developed.

Some of the potential scientific and engineering benefits that can be addressed with a lunar mSEM are a more thorough understanding of the processes that occur during space weathering. Space weathering has a significant impact on remote sensing capabilities, is a fundamental process in soil development and will have a significant influence on equipment exposed on the lunar surface; this can have significant implications for rovers, landers, solar arrays, and communication equipment that will remain on the surface. Another benefit of such a tool on the lunar surface is in the study of lunar volcanic pyroclastic deposits, a subject of major concern. In fact, the ability to distinguish between volcanic glass beads from impact-generated glass spherules, which can be done through the identification of vapor-deposited coatings on the surface of volcanic glass beads, is important for the interpretation of pyroclastic deposits (Delano and Livi, 1981). These glass beads also have the potential of being used as a feedstock for ISRU oxygen production (McKay, 1991).

The electrostatically levitated “dust clouds” that were postulated by Stubbs et al. (2006) to exist along the terminator and the large-voltage changes associated with them could be dangerous to personal and equipment on the surface. This fine dust should be a dominant layer across the Moon, according to their reasoning. An in-situ mSEM could evaluate if there actually is a fine layer of such dust present and determine if this phenomenon exists at all.

SUMMARY

The ability of an mSEM to identify micron and sub-micron soil particle characteristics directly on the lunar surface will be a great aid to future exploration of the Moon, both for scientific and engineering endeavors. The incorporation of chemical and mineralogical information with PSD of regolith will be paramount to identifying potential ISRU feedstocks, as well as dust mitigation strategies that will be essential for a prolonged human presence on the Moon. The indigenous atmosphere (i.e., extreme vacuum) of the lunar environment provides an opportunity to simplify an mSEM and sample preparation. The natural effective lack of an atmosphere eliminates the need and complexity of a vacuum chamber on the mSEM and introduces the *possibility* of a “point-and-shoot” configuration for the instrument. Digital imaging with low-power does not require sample coating with carbon or gold, or the use of an environmental gas, to mitigate charging and greatly simplifies the sample preparation process. Such an instrument, presently under design and development, will greatly aid many needs as mankind strives to settle and occupy this heavenly body – our Moon.

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