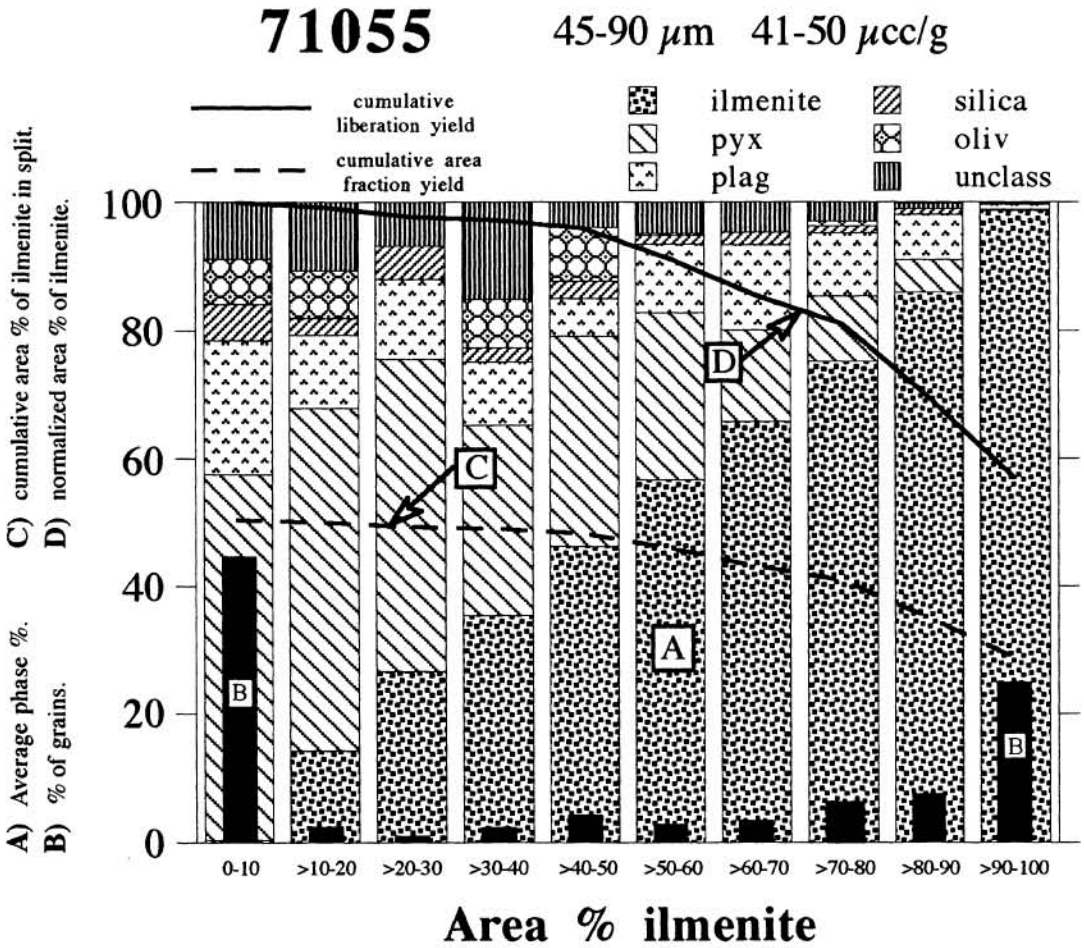
EVALUATION OF LUNAR ROCKS AND SOILS FOR RESOURCE UTILIZATION: DETAILED IMAGE ANALYSIS OF RAW MATERIALS AND BENEFICIATED PRODUCTS. Lawrence A. TAYLOR[1], John G. CHAMBERS[1], Allan PATCHEN[1], Eric A. JERDE[1], David S. McKAY[2], John Graf[2], and Robin R. ODER[3]. 1 = Planetary Geosciences Institute, Dept. of Geol. Sci., Univ. of Tennessee, Knoxville, TN 37996; 2 = Mission Sci. & Tech. Office, Code SN14, Johnson Space Center, Houston, TX 77058; 3 = EXPORTech Co., Inc., New Kensington, PA.

The rocks and soils of the Moon will be the raw materials for fuels and construction needs at a lunar base. This includes sources of materials for the generation of hydrogen, oxygen, metals, and other potential construction materials. For most of the bulk material needs, the regolith, and its <1cm fraction, the soil, will suffice. But for specific mineral resources, it may be necessary to concentrate minerals from rocks or soils, and it is not always obvious which is the more appropriate feedstock. Besides an appreciation of site geology, the mineralogy and petrography of local rocks and soils is important for consideration of the resources which can provide feedstocks of ilmenite, glass, agglutinates, anorthite, etc. In such studies, it is very time-consuming and practically impossible to correlate particle counts (the traditional method of characterizing lunar soil petrography) with accurate modal analyses and with mineral associations in multi-mineralic grains. But x-ray digital imaging, using x-rays characteristic of each element, makes all this possible and much more (e.g., size and shape analysis). In this paper, we demonstrate an application of beneficiation image analysis, in use in our lab (Oxford Instr. EDS and Cameca SX-50 EMP), to study mineral liberation from lunar rocks and soils.

The high-Ti basalt studied was lunar sample 71055 [12.8 wt% TiO_2], which we reported on last year [1]. This rock is a fine-grained, vesicular, subophitic to ophitic, olivine-bearing ilmenite basalt composed of ilmenite [20 vol%; with traces of ulvöspinel], clinopyroxene [42%], olivine [3%], plagioclase [29%], tridymite [5%], and traces of troilite (FeS), Fe metal, and apatite. Ilmenite forms skeletal blades with amoeboid rims, mostly 0.2-0.3 x 1-3 mm. It also occurs as discrete subhedral to euhedral grains, 0.1-0.4 mm across.. Rock chips of this basalt were lightly crushed in a "shatterbox", sieved into size fractions >150, 90-150, 45-90, 20-45, and <20 μm, and then magnetically separated with a Frantz Isodynamic



Separator, instrumented for both separations and magnetization measurements. A polished grain mount was prepared from a 5-10 mg portion of each magnetic split from the size fractions. Grains were characterized and counted using reflected- and transmitted-light optical microscopy. In addition, X-ray image analysis on our Cameca SX-50 EMP of portions of each grain mount has resulted in a plethora of data which have been applied to this study of beneficiation, with primary interest in the mineral ilmenite. Below, we present some of the results of this image analysis and thereby demonstrate the power of the application of such analysis to studies of size, shape, mineral associations, modal mineralogy, etc. for the resource evaluation of lunar rocks and soils.

MINERAL LIBERATION ANALYSIS: As an illustration of the power of these analyses, we have applied them to a grain mount of the 45-90 μm size split of ground basalt 71055, more specifically, that sample with a magnetic susceptibility of 41-50 μcc/g. Figure 1 illustrates the results from the modal/association portion of the analysis of this sample. This figure will be explained in some detail to provide an understanding and appreciation for the power of these image analyses.

Figure 1 is a composite of four graphs, A-D. The X-axis is divided into intervals each based upon the area % of ilmenite (since this is a 2-dimensional analysis) of the particles on this grain mount. That is, in the bin labeled >70-80, each grain has 71-80 area % ilmenite.

The **A portion of the figure** refers to the shaded bars of the diagram, which are the area % of different minerals in each bin. Note that the area % of ilmenite matches the label at the bottom of each bin. These shaded columns give the area % of each mineral in the "average" grain within the bin. For example, within the >40-50 area % ilmenite bin, the grains average 46 area % ilmenite, 33 % pyroxene, 5.9 % plagioclase, 2.7 % silica (tridymite), 8.5 % olivine, and 3.9 % unclassified. In reality, the unclassified region contains troilite, native Fe, apatite, cracks, and portions of grain edges which were unclassifiable; each is small in area % and the amounts were lumped together as "unclassified".

The **B portion of the figure** designates the percentages of the grains relative to the total grain population which have a certain area % ilmenite, that is, are within a particular bin. For example, the >90-100 area % ilmenite bin contains about 25 % of the total grains in the sample. It should be noted that about 45 % of the grains have 0-10 area % ilmenite; that is, almost half of the particles are essentially free of ilmenite. These observations indicate that the grinding process did a reasonably good job of liberating ilmenite from the silicates. This same magnetic susceptibility sample at a finer grain size would obviously show even a better separation.

The **C curve on the figure refers to the Cumulative Area Fraction Curve**. This curve shows the percentage of the total area of all grains that is ilmenite in a bin and those bins above it (i.e., to the right). For example, in the >90-100 area % ilmenite bin, the ilmenite represents about 30 % of the total grain area of all bins; that is, 30 % of the total area of all grains analyzed is ilmenite in grains composed of 90-100 % ilmenite. Further, in the >50-60 area % ilmenite bin, the curve is at 46% meaning that 46% of the total area of all grains is ilmenite in grains with 50-100 area % ilmenite (i.e., all bins above it [to the right], hence the name cumulative). Since the curve is cumulative, the highest point on the curve is equal to the area % of ilmenite in the sample – that is, the modal % of ilmenite. The importance of this curve is that it illustrates the principle that although only 26% of the particles analyzed were >90-100 % ilmenite, the ilmenite constitutes about 30% of the total area analyzed. That is single-grain ilmenite makes up 30 modal % of the sample.

The **D curve on the figure refers to the Cumulative Liberation Yield Curve** which illustrates the area % which a bin, plus those above it (i.e., to the right), represents of the total amount of ilmenite in the sample. For example, approximately 55% of all ilmenite in this sample is located in the >90-100 area % bin. This curve is simply the normalized area % of ilmenite in each bin and those bins above it. This curve is interesting because one can see that over 80% of the ilmenite in this sample is in grains composed of >70 % pure ilmenite.

SUMMARY OF MODAL % ILMENITE AND MINERAL ASSOCIATIONS: Figure 1 should not be over-interpreted since it is data from only one of many grain mounts of a particular size range and magnetic susceptibility. However, some interesting speculations are possible. There exist two modes of particles: 25% with 90-100% ilmenite and 45% with 0-10% ilmenite. About 30% of the particles are intermediate in their ilmenite content (i.e., 10-90%). If the liberation was absolutely complete, these two modes would total almost 100%, and the intermediate grains would not exist, but this is not the case here. Therefore, the grinding did not completely liberate the ilmenite. Perhaps even more important is the observation that the magnetic separation failed to effectively separate the near-clean ilmenite grains from those with less than 10% ilmenite and made up large of pyroxene and olivine (78%). The degree of liberation will undoubtedly be better at finer grain sizes, but the separation of pyroxene and ilmenite grains may remain about the same. However, in this one grain mount studied, over 85% of the ilmenite particles are >70 area % ilmenite.

MORPHOLOGICAL MEASUREMENTS: In addition to accurate modal analyses and mineral association determinations, the imaging software allows many morphological measurements to be made on individual grains and compared to each other. Some of the parameters include aspect ratio (length/width), area, perimeter, hydraulic radius (area/perimeter). The hydraulic radius, which is analogous to the inverse of the well-known surface area/volume ratio, is a parameter which is important to producing feedstock for processes which are based upon surface-controlled reactions. Certain processes of ilmenite and glass reduction for oxygen production may apply here. Also, these measurements could prove important in attempts to compare two high-Ti basalts which have ilmenite of approximately the same size but with markedly different shapes (e.g., skeletal vs. blocky vs. bladed/needle-like) and mineral associations.

CONCLUSIONS: In essence, this prototype of x-ray image analysis, demonstrated above, will be extremely useful in correlating ilmenite morphology, size, and modal abundance in the raw material (rock or soil) with the nature and amount of clean, single-grained ilmenite produced by various beneficiation schemes. This is the very nature of mineral liberation studies.

REFERENCES: [1] Taylor, L.A., et al., 1992, Magnetic beneficiation of hihg-Ti mare basalts: Petrographic analyses, LPSC XXIII, 1415-1416.