TRUE MODAL ANALYSES OF LUNAR MARE SOILS: X-RAY DIGITAL-IMAGING John G. CHAMBERS, Lawrence A. TAYLOR, Allan PATCHEN, Planetary Geosciences Inst., Dept. of Geol. Sci., Univ. of Tennessee, Knoxville, TN 37996; and David S. McKAY, Johnson Space Center, Houston TX 77058.

The lunar surface is blanketed by a mixture of loosely consolidated rock, mineral, and glass fragments, termed the regolith. This regolith with its < 1 cm fraction, the soil, is mainly the product of weathering caused by meteorite and micrometeorite impacts on the lunar surface. Recent developments in X-ray digital imaging analysis have provided actual modal data (including glass phases) for the 90-150 μm fraction of mare soils from the Apollo 11, 12, 15, and 17 sites. This is the first collection of *true* modal data for soils from all Apollo "mare" sites. Comparison of these new data to those from traditional particle-counts demonstrates that total mineral content is underestimated by factors of 2-17 by assuming the latter represent modes. These true modes of minerals are significant for soil spectral reflectance calibrations and resource evaluation.

Previous petrographical studies of lunar soil have employed "particle counting" for characterization **[e.g., 1]**. These analyses provide detailed information about the abundance of rock fragments, mineral fragments, impact-produced glasses, pyroclastic glasses, and glass-bonded aggregates (*e.g.*, agglutinates). Unfortunately, the data were generally referred to as the soil modal composition **[e.g., 2]**. However, in geology **modes** or **modal percentages** are strictly defined as the actual abundances of mineral constituents expressed as volume or weight percentages **[3]**. Particle counts *do not* provide such information, as the procedure was not developed to determine the fraction of mineral grains locked in various rock fragments and fused-soil particles. These locked mineral grains add significantly to the total concentration, as reported by Chambers et al. **[4-5]**.

True modal analyses must be performed on lunar soils to quantitatively appreciate the mineralogical developments during maturation. In addition, mineral resource evaluation requires such data for comparison of mare soils and basalts as raw materials. X-ray/SEM digital-imaging analysis was shown to be an adequate method for obtaining this mineralogical data from lunar material **[4-9]**. In addition, particle-count data are determined by this method **[10-11]**.

Table 1. Phase modal abundances of the mare soils (90-150 μm size fraction) characterized by this study. Data are from X-ray digital-imaging analyses and are in terms of volume percentages. Particle-count data are presented for ilmenite, plagioclase, and pyroxene for comparison to true modes. I$_s$/FeO values are listed also [*Morris*, 1978].

	10084	12001	12030	15041	15071	70181	71061	71501	79221
I$_s$/FeO	78	56	14	94	52	47	14	35	81
ilmenite	6.0	0.9	1.7	0.8	1.8	7.9	9.8	12.6	5.8
ilmenite[†]	*0.9*	*0.1*	*0.1*	*0.3*	*1.0*	*3.5*	*4.1*	*5.6*	*1.9*
Cr-spinel	0.2	0.2	0.2	0.3	0.5	0.1	0.1	0.2	0.1
plagioclase	15.8	12.3	14.9	16.2	21.9	15.7	19.1	15.9	17.1
plagioclase[†]	*5.2*	*3.9*	*3.9*	*6.5*	*12.9*	*8.9*	*9.5*	*6.9*	*5.6*
pyroxene	32.6	31.1	43.2	28.1	38.2	34.0	34.6	38.5	21.8
pyroxene[†]	*15.2*	*13.3*	*23.3*	*13.2*	*25.1*	*16.9*	*16.9*	*16.9*	*7.5*
olivine	1.9	8.8	6.5	5.5	4.5	2.9	3.5	3.4	3.1
cristobalite	0.3	0.3	0.3	0.3	1.8	0.2	0.7	0.5	1.2
Fe-metal	tr	tr	tr	tr	tr	tr	0.4	tr	tr
troilite	0.1	0.1	0.1	0.1	tr	tr	0.2	tr	tr
K-rich glass	1.0	1.5	1.7	1.6	0.9	0.5	0.7	0.5	0.8
Ti-rich glass	7.9	1.4	1.4	0.6	0.6	11.3	13.2	7.7	8.4
FeMg-rich glass	6.5	7.8	7.8	12.0	12.9	2.7	2.5	2.8	2.6
Al-rich glass	27.6	37.3	23.2	35.6	19.6	25.1	15.6	18.3	39.3
Total	99.9	99.9	99.9	100	99.9	99.9	99.8	99.8	99.8

[†]Free mineral particle % as determined by digital-imaging petrography **[10-11]**.

Phases Present in Mare Soils - Mare soils have two main sources of phases: inherited basaltic mineralogy **(primary)** and impact-produced glasses **(secondary)**. Minor amounts of pyroclastic glasses are also present. For this study, the primary phases include pyroxene (low and high-Ca pyx), plagioclase, olivine, ilmenite, Cr-spinel, cristobalite (SiO_2), Fe-metal, and troilite (FeS). Glasses were subdivided into four chemical groups: Ti-rich glass (7-10 % TiO_2), FeMg-rich glass (pyx-like composition), K-rich glass, and Al- rich glass

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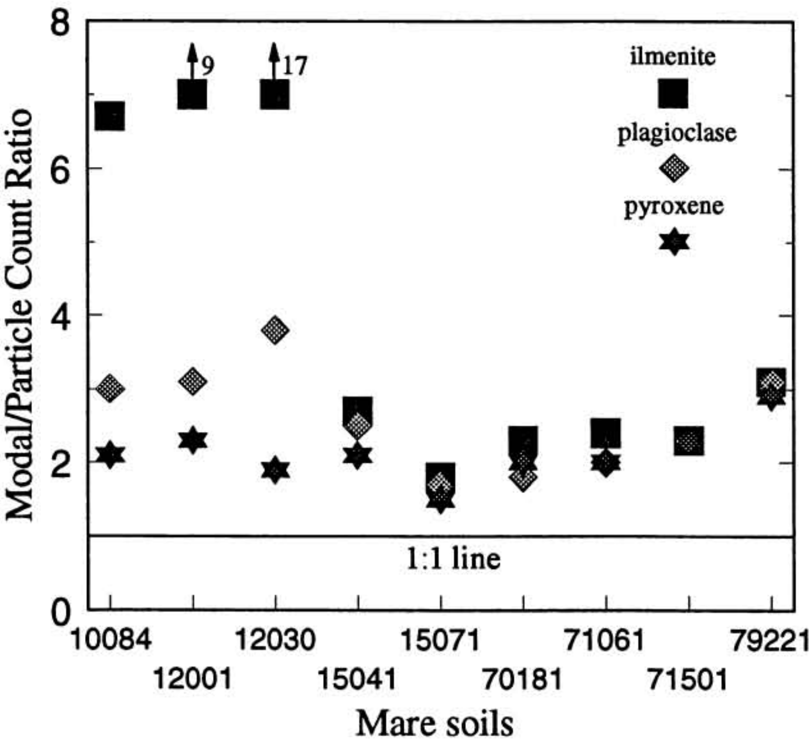

Figure 1. Ratio of modal mineral abundance (volume %) to particle count data (volume %). Data are from this study and are reported in Table 1. Note the lack of 1:1 correspondence between the modal data and particle-count data.

(10-20 %Al_2O_3). The Ti-rich glass occurs as pyroclastic material and as impact glass derived from ilmenite-rich targets. FeMg-rich glass is variable in composition and is a "broad" phase produced by pyroclastic activity (similar to A-15 low-Ti glasses **[12]**) and impact melting of mafic minerals. K-rich glass is formed in the mesostases of basalts and impact melts of KREEPy material. Al-rich glass is the most abundant glass. It is the major impact-produced glass phase in agglutinates, breccias, impact-melt beads, and impact-melt rocks.

True Modal Data of a Suite of Mare Soils - The 90-150 µm fraction of nine mare soils from Apollo 11, 12, 15, and 17 sampling sites were analyzed by X-ray digital-imaging techniques in order to obtain *true* modal and particle-count data (Table 1). Figure 1 displays the ratio of actual modes and particle-count "modes" for ilmenite, plagioclase, and pyroxene. If particle counts estimate total mineral content, the points would plot near the 1:1 line. However, Figure 1 (and Table 1) shows that mineral concentrations are underestimated by factors ~ 2-17 if one assumes that particle percent equals mineral modal percent. To a first approximation, it appears that ilmenite, plagioclase, and pyroxene content can be estimated from particle-count data by multiplying by a factor of 2.5-3. Most importantly, these results show unequivocally that traditional particle-count data do not estimate true mineral abundances.

Conclusions - The data presented herein indicate that true modal analyses are warranted for the lunar soils. This information is invaluable to mineral resource evaluation, especially for comparing basalts and soils as raw materials. Furthermore, remote sensing calibrations are performed with particle-count modes, and recalibration with true modal data will provide for better estimation of soil mineralogy by this technique. Detailed modal data will enhance the overall petrologic understanding of lunar soils.

References **[1]** Heiken and McKay, 1974 PLPSC V 843-60; **[2]** Lunar Source Book, 1991; **[3]** Bates and Jackson, 1990 AGI Glossary of Geol.Terms; **[4]** Chambers et al. 1994, PLPSC XXV, 235-36; **[5]** Chambers et al. 1995 JGR-Planets *in press*; **[6]** Heiken and Vaniman, 1990, PLPSC XX , 239-47; **[7]** Heiken et al., 1992, Space 92, ASCE, 555-64; **[8]** Taylor et al., 1993, PLPSC XXIV 1409-10; **[9]** Chambers et al., 1994, Space 94, ASCE, 878-88; **[10]** Higgins et al., 1994 PLPSC XXV, 547-48; **[11]** Higgins et al, 1995 in press; **[12]** Delano, 1986, PLPSC XI, 251-88.