MIXING OF THE MARE REGOLITH: A CLEMENTINE TEST Paul D. Spudis, *Lunar and Planetary Institute*, Houston TX 77058, spudis@lpi.usra.edu ; Stephen M. Baloga, *Proxemy Research*, Laytonsville MD20882 steve@proxemy.com

It was noted in the Apollo 11 samples that fragments of feldspathic rock were a fairly common, if minor, component of the mare regolith and, in fact, were used to infer the petrologic make-up of the highlands (e.g., [1]). This "highland fraction" is present as a chemical, as well as lithologic, component [2]. It was originally thought that the highland component in mare regolith was derived from the rays of craters several kilometers from the sample sites [1]. However, detailed study showed that the bulk of highlands debris in mare regolith comes directly from beneath relatively thin, mare flows, derived dominantly by *vertical* mixing [2, 3].

One of the most comprehensive studies of regolith evolution relevant to its composition was by Quaide and Oberbeck [4], who used an earlier Monte Carlo growth simulation [5] to understand how the regolith is mixed and overturned. In particular, the Quaide and Oberbeck model [4] looked at the issue of exotic material in the regolith and its likely provenance. From their results, a model mare regolith (median regolith thickness 4.7 m, equivalent to an Apollo 12-age (3.15 by) flow) would have at least a few percent of the debris derived from depths greater than several tens of meters. This result is important for understanding the origin of vertically mixed, highland debris in mare regoliths. Using Clementine data, we can test this model of regolith growth and evolution and, if necessary, modify it so that it accurately accounts for the amounts of highland debris seen in the mare regoliths.

Methods The data needed for this task come from Rose and Spudis [5], who mapped the stratigraphy and thickness of lavas in Mare Nubium. For this initial study, we picked two small, early Eratosthenian mare units east of the crater Guericke, south of the Apollo 14 site at Fra Mauro. We used full resolution Clementine FeO and TiO_2 maps [e.g., 7, 8] to characterize typical compositions of the mare surface, mare bedrock as revealed by fresh small craters, and typical highlands composition, representing the sub-mare, highlands "bedrock." Due to natural variations in the measurements, we have used replicate measurements in all areas sampled and a statistical approach to inference. Measurements and descriptive statistics for FeO content are summarized in Table 1. Summary data and inferences for the mare flows as a whole are summarized in Table 2.

We are aware of several potential sources of error in this work. Our statistical approach is intended to characterize the magnitude of these errors and statistically estimate the differences with the predictions of Quaide and Oberbeck. The fundamental assumption is that vertical mixing is the predominant process that adds highland debris to mare regoliths. Although this concept is supported by several other studies [2,3], we recognize that locally, lateral transport and mixing can dominate and overwhelm the vertically mixed debris, especially in the presence of mapable rays from large craters [9, 10]. We keep such error at a minimum by avoiding obvious ray-covered areas. As the amounts of lateral mixing increase abruptly as the mare-highland contacts are approached [2], we confine our data collection to mare interiors, at least 5-10 km from a contact. We also avoid areas near large, post-mare craters, which can spread undetectable ejecta over large regions (e.g., Lichtenberg; [10]).

Results and Analysis In our initial efforts, we have focused on collecting FeO data for statistical analysis for two lava flows (ms), nearby highlands (H), and fresh crater ejecta (fce; Table 1). For the flows and highlands material, representative pixels were selected to avoid obvious geologic structures, craters, rays, and other types of anomalies. On the flows themselves, well-defined ejecta were selected that completely penetrate the lava flows exposing highland material in the ejecta. Twelve data points were collected for each of the two flows, highlands, and crater ejecta.

The descriptive statistics appear in Table 1. The FeO values for the flow surfaces, craters, and highlands have remarkably similar mean values for each of the two flows. It is somewhat remarkable for natural data that the Relative Standard Deviation % (Coeff. of Variation in Table 1) is only a few percent. By contrast, the highlands have about a 10% variation. These mean values are very tightly constrained. This is indicated by the small values of the standard error (on the mean) even for the highlands values.

We have also computed statistical measures of the symmetry (skewness) and peakedness (kurtosis) of the individual distributions. These statistics have been 'standardized' for convenient comparison to the normal (Gaussian) distribution. With such a standardization, values less in magnitude than plus or minus 2, are considered insignificant. Inspection of Table 1 shows that all the individual data categories are insignificant in both skewness and kurtosis.

Because we are justified in using a normal distribution, we have plotted the means with 95% confidence intervals for the mean values. It is clear that the ejecta, flow surface, and highlands populations are all distinct (because the "error bars" do not overlap). However, on the basis of the FeO data, the flow surfaces, crater ejecta, or highlands materials are not statistically distinguishable between the two flows, even though initial examination indicates the flows have distinct Ti content (3.0-3.6 wt.% TiO_2 for flow 1 *vs*. 4.0-4.4 wt.% TiO_2 for flow 2). What is most intriguing is that the FeO values appear to be nonlinear for pure basalt, regolith, and highlands substrate (Tab. 1). We are currently considering different explanations for this relation, including the presence of material from non-local sources, inhomogeneities and geologic structures in the highlands, factors associated with the excavation process, and weathering.

Summary data for the two studied flows are given in Table 2. As noted for other mare flows around the Moon [e.g., 2, 5], the mare surfaces (regolith) show lower FeO contents than the bedrock from which they are derived. As shown from the petrology of lunar mare soils [2], this lower FeO content results from the admixture of small amounts of highlands debris into these regoliths. Numerous lines of evidence suggest that this highlands component is largely derived from vertical mixing [2, 3] rather than lateral transport [1]. However, Table 2 shows that for the two flows studied, significant amounts of highlands material are required to explain the FeO content of the of the mare regolith (on the order of 1/3 highlands component.) Although such quantities are not unknown from returned samples (e.g., the Apollo 11 mare regolith contains up to 40% highlands component; [2]), there appears to be a discrepancy between the observed amounts of highland contaminants and the local thickness of lava, inferred by the stratigraphic mapping (new estimates made for this study suggest thinner accumulations of lava (~100-200 m) than estimated by [6]; Table 2). Scaling from the model result of [4], the quantities of highlands debris observed suggest lava thicknesses on the order of 20-30 m, considerably thinner than evidence from local craters penetrating the mare basalt would suggest [6].

We are attempting to understand this discrepancy. Among the many factors that could contribute to the non-agreement between methods are: inaccuracies in the FeO measurement technique, inadequacies in the thickness mapping technique, non-linear mixing of unknown character between mare and highlands in regoliths, and other unquantified possible effects, such as scattered light phenomena [11] in the Clementine sensors. Alternatively, the probabilistic assumptions of the Monte Carlo model [4] may suffer from an invalid assumption or may not be applicable at the scale considered in our study. We will continue our analyses to resolve these alternatives and ultimately reconcile the Monte Carlo model [4] with our interpretation of the Clementine regolith, ejecta, and highland data.

References [1] Wood J. *et al.* (1970) *Proc. Apollo 11 Lunar Sci. Conf.*, 965-988 [2] Rhodes J.M. (1977) *Philos. Trans. Royal Soc. London* **A285**, 293-301. [3] Horz F. (1978) *PLPSC* **9**, 3311-3331. [4] Quaide W.L. and Oberbeck V.R., 1975 *The Moon* **13**, 27-55. [5] Oberbeck V.R. *et al.* 1973 *Icarus* **19**, 87-107 [6] Rose D.E. and Spudis P.D. (2000) *LPS* **XXXI**, 1364 [7] Lucey P.G. *et al.* (1995) *Science* **268**, 1150-1153. [8] Lucey P.G. *et al.* (1998) *JGR* **103**, 3679-3699. [9] Pieters C. *et al.* (1985) *JGR* **90**, B14, 12393-12413. [10] Thomson B. *et al.* (1998) *LPS* **XXIX**, 1820. [11] Robinson, M. (2001) this volume.

Table 1. Summary statistics for FeO content on two Mare Nubium flows

	Count	Average	Standard deviation	Standard error	Minimum	Maximum	Range	Std. Skewness	Std. Kurtosis	Coeff. Of variation
Fce1	12	21.245	0.453	0.13077	20.52	22.13	1.61	0.513037	-0.000196	2.13227
Fce2	12	21.2933	0.587805	0.169685	20.04	21.76	1.72	-1.70324	0.121064	2.76051
Ms1	12	18.675	0.24183	0.0698103	18.31	19.1	0.79	-0.138393	-0.325324	1.29494
Ms2	12	18.7667	0.478242	0.138056	18.08	19.59	1.51	0.772101	-0.211504	2.54836
H1	12	12.9467	1.20198	0.346981	10.94	15.17	4.23	-0.267481	0.228074	9.28407
H2	12	12.7025	1.2153	0.350020	10.07	13.0	3.73	-1.66507	0.34224	9.56745
Total	72	17.6049	3.64314	0.429348	10.07	22.13	12.06	-1.88841	-2.04538	20.6939

Table 2 Summary data for two flows in Mare Nubium

	Flow 1	**Flow 2**
FeO (wt. %) – mare surface	18.68 ± 0.24	18.77 ± 0.49
FeO (wt.%) – lava	21.26 ± 0.45	21.29 ± 0.59
FeO (wt.%) – highlands subsurface	12.95 ± 1.20	12.70 ± 1.22
Percent highlands in regolith	31	34
Estimated lava thickness (m)	120 (*200-300*)*	180 (*160-400*)*
Age (Number of craters, $10^{-2}/km^2$)	3.9 ± 0.5	4.1 ± 0.6
Age (estimated 10^9 yr.)	2.9 ± 0.1	3.0 ± 0.1

* *estimates from Rose and Spudis (2000)*