SIMULATED DEGRADATION OF LUNAR IMPACT CRATERS AND A NEW METHOD FOR AGE DATING LOCAL GEOLOGIC UNITS. Robert A. Craddock1,2 and Alan D. Howard2, 1Center for Earth and Planetary Studies, National Air and Space Museum, Smithsonian Institution, Washington, DC  20560 (craddock@ceps.nasm.edu), 2Department of Environmental Sciences, University of Virginia, Charlottesville, Virginia 22903

The surface of the Moon is subjected to continual bombardment by cosmic debris that creates craters of all sizes. Comminution produces many more smaller particles than larger ones so that over a given interval of time many more smaller impact craters will form on a surface than larger ones. As a result, the morphology of craters is slowly degraded by the influx of smaller objects. Craters can also be buried by emplacement of crater ejecta from new, neighboring craters or from volcanic deposits, but these materials can typically be recognized by their superposition relations. The morphology and size of degraded craters has been used as a way of determining the relative age of local geologic units [1 and references therein]. These techniques were developed so that the small areas of interest to Apollo landings could be placed into a regional stratigraphic context. The important assumptions made are that the original crater morphology was the same as fresh craters on the same unit and that the surface has been worn down continuously over the entire lunar surface in proportion to the time of the unit's emplacement. The resolution and the extent of coverage obtained by instruments onboard the Clementine spacecraft permit the study of small areas at scales larger than has ever been possible before. Clementine data will also allow new, small units to be distinguished based on both morphologic characteristics and spectral reflectance. Age dating these materials using degraded crater morphology is the only tool available, and this technique can be improved using the Clementine data.

Existing Techniques for Age Dating Geologic Units
The most commonly accepted method for age dating geologic units on planetary surfaces is crater counting. Diameters of all the craters within a given unit are measured, and the cumulative number of craters at any given diameter is plotted on a log-log scale. For comparison to other units, the cumulative number of craters is generally normalized to some specified area (e.g., 10⁶ km²), and estimates of age are made by either measuring the slope of the curve(s) or by determining the cumulative number of craters at a certain diameter. This technique, however, is subject to large errors when the areal extent of the geologic unit is small. During the Apollo era, scientists recognized the importance of developing a reliable age dating technique that could be applied to astronaut-scale geologic units investigated at the landing sites. Several were developed that are still in use today. The simplest, qualitative method was originally developed by Trask [2, 3] and was eventually modified slightly [4, 5]. From Lunar Orbiter data they observed the morphological differences between fresh and degraded craters and assumed that fresh craters undergo modification from impacts of small objects by erosion of the rim crest and infilling of the crater floor. Because there is proportionally less material to erode on smaller diameter craters, they deduced that smaller diameter craters would take less time to erode completely than larger diameter craters. A template showing representative craters at given diameter and degrees of modification is used for age dating. In order to get reliable ages from this method, the largest diameter crater that is still visible must be identified within the geologic unit.

A more quantitative approach was first devised by Soderblom [6, 7], who presented a theoretical model of crater erosion operating in the assumed steady state environment. Similar to Trask's [1969, 1971] technique, the largest modified crater is sought. However, Soderblom recognized the fact that the largest diameter crater is not always easy to identify. On a given surface, craters slightly larger in diameter than the saturation diameter, Cs, will be less obliterated. He found that typically such craters have interior slopes of 1° and their diameter, DL (in meters), can be related to the Cs diameter by the relation: 

\[ DL = 1.7 Cs \]

Values of DL can be determined by two separate techniques [8, 9], and their values are fairly reliable for mare units but are not as reliable for units contained in the lunar highlands--the Apollo 16 landing site in particular [1]. In addition, successful application of the DL technique is conditional. Typically it requires photographs limited to Sun-illumination angles between 8° and 30° [8]. In addition, the sample area must be at least 100 km² for young surfaces and 1,800 km² for highland surfaces [9]. At the time the DL techniques were developed, only shadow measurements were available for describing the crater geometry, and the morphometry of both fresh and degraded craters were idealized from these data. Use of the DL techniques is also arduous in that it requires the investigator to examine all the craters within a given unit. While these techniques remain important for placing small geologic units into a regional context, a simpler, more accurate method can be developed from Clementine images.

Age Dating from Clementine Data
Because Clementine data are digital, it is now possible to make photoclinometric measurements of lunar features. The symmetric (or two-profile) method developed by Davis and Soderblom [10] is particularly useful for deriving the morphometry of impact craters. RATIOing the two profiles cancels out the effects of the intrinsic reflectivity of the surface, but this requires using the Minnaert photometric equation:

\[ I(\mu, \mu_0, \alpha) = B_0 \cos^k \iota \cos^{-k-1} e \]

where \( I(\mu, \mu_0, \alpha) \) is the reflectance function, which is defined as the intensity of scattered light with the geometry indicated by \( \mu \) (the cosine of the emission angle), \( \mu_0 \) (the cosine of the
Sun-illumination angle), and $\alpha$ (the phase angle) divided by the incident solar flux times $\pi$, $B_0$ is the surface normal albedo, $i$ is the Sun-illumination angle, and $e$ is the spacecraft emission angle. The Minnaert coefficient, $k$, is a function of wavelength and increases directly with phase angle. A problem with the Minnaert function is that it diverges toward infinity as emission angles approach $90^\circ$ so it is inappropriate to use with oblique viewing geometries. The Minnaert coefficient also does not offer a unique solution at low phase angles, so Clementine data taken at latitudes less than $\sim 10^\circ$ cannot be used.

In order to use the Clementine data for deriving photoclinometric profiles of lunar craters, the obvious first step was to determine the Minnaert coefficient for the 750 nm bandpass used in both the UVVIS and HiRes cameras. Crater profiles derived at a given Minnaert coefficient were compared to depth estimates made on Lunar Topographic Orthophoto (LTO) maps. The Minnaert coefficient was adjusted until measured depth equated depths given in the LTO maps. This iterative process will continue as we examine data taken at a wider variety of phase angles ($\alpha$).

Profiles of fresh impact craters collected during this analysis allow us to model crater degradation in cross section where rate laws are expressed in cylindrical coordinates. Modification by micrometeorite bombardment is a diffusional process (e.g., [6]), and our simulations are based on the drainage basin evolution model presented by Howard [11]. Fresh crater profiles will be subjected to a number of iterations simulating lunar crater degradation through time. The resulting degraded crater profiles will be compared to actual profiles collected in geologic units of known ages (i.e., the higher latitude Apollo and Luna sites). This will allow us to estimate the rate of erosion, which is directly related to the impact flux rate. By eventually including Eratosthenian and Copernican age craters, it might be possible to determine temporal variations in the impact flux rate. Understanding this rate will allow age dates of individual craters to be made. Estimates of the age of small geologic units could be made by analyzing several craters within the units.

A remaining problem is that the photoclinometric measurements must be made in PICS as the necessary module (TVPROF) has not be converted to ISIS. This requires an extra step in translating the calibrated Clementine images so they can be read in PICS. We have received the necessary funds from the Smithsonian Institution to do the module conversion. Ideally, the photoclinometric-derived age dating method we are developing could eventually be integrated as part of this ISIS-based module so that age estimates of small geologic units could be made quickly and easily.

References