The Sculptured Hills of the Taurus Highlands: Implications for the relative age of Serenitatis, basin chronologies and the cratering history of the Moon

Paul D. Spudis,[1] Don E. Wilhelms,[2] and Mark S. Robinson[3]

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[1] New images from the Lunar Reconnaissance Orbiter Camera show the distribution and geological relations of the Sculptured Hills, a geological unit widespread in the highlands between the Serenitatis and Crisium basins. The Sculptured Hills shows knobby, undulating, radially textured, and plains-like morphologies and in many places is indistinguishable from the similarly knobby Alpes Formation, a facies of ejecta from the Imbrium basin. The new LROC image data show that the Sculptured Hills in the Taurus highlands is Imbrium ejecta and not directly related to the formation of the Serenitatis basin. This occurrence and the geological relations of this unit suggests that the Apollo 17 impact melts may not be not samples of the Serenitatis basin-forming impact, leaving their provenance undetermined and origin unexplained. If the Apollo 17 melt rocks are Serenitatis impact melt, up to half of the basin and large crater population of the Moon was created within a 30 Ma interval around 3.8 Ga in a global impact "cataclysm." Either interpretation significantly changes our view of the impact process and history of the Earth-Moon system.

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1. Introduction

[2] The age of the Serenitatis basin has been of some concern to lunar students for many years. Initial studies, noting the old and degraded appearance of Serenitatis, decided that it was one of the very oldest basins on the Moon. Published relative chronologies placed Serenitatis well back in pre-Imbrian time [*Baldwin*, 1963; *Stuart-Alexander and Howard*, 1970; *Hartmann and Wood*, 1971; *Wilhelms and McCauley*, 1971; *Howard et al.*, 1974]. Study of the composition and ages of Apollo 17 highland samples [e.g., *Wood*, 1975; *Winzer et al.*, 1977; *James et al.*, 1978] and the assumption that such rocks must be fragments of ejecta from the Serenitatis basin [e.g., *Wolfe and Reed*, 1976; *Wolfe et al.*, 1981] forced reconsideration of this old age assignment. The revised idea held that Serenitatis must be a relatively *young* lunar basin, only slightly older than Imbrium. In this interpretation, the degraded appearance of Serenitatis must be caused by the blanketing and eroding effects of ejecta deposition by the subsequent Imbrium basin [*Head*, 1979; *Wolfe et al.*, 1981]. This re-interpretation of the relative age of Serenitatis never sat well among some lunar students and the contorted reasoning to accommodate it was sometimes evident [*Wilhelms*, 1987].

[3] The abundant impact melts in the Apollo 17 collection require assignment to some large impact or series of impacts; as the Serenitatis basin is the nearest large feature to the site, it emerged as the probable source early in sample studies [*Warner et al.*, 1976; *Winzer et al.*, 1977]. The Apollo 17 impact melts are roughly basaltic in composition, have a KREEP-enriched trace element signature, and formed around 3.87 Ga ago [*Winzer et al.*, 1977; *Spudis and Ryder*, 1981]. The subdivision of Apollo 17 melts into two broad groups, the poikilitic "melt sheet" and the aphanites [*Spudis and Ryder*, 1981] confused matters somewhat, although most investigators preferred to interpret all Apollo 17 melt breccias as products of the Serenitatis basin-forming impact [*Wood*, 1975; *James et al.*, 1978]. Although subsequent work has documented other compositions present in the Apollo 17 highlands [e.g., *Jolliff et al.*, 1996], most workers still ascribe Serenitatis basin origins to virtually all of the impact melts found at that site [e.g., *Stöffler et al.*, 2006].

[4] New data from recent orbiting spacecraft are revolutionizing our view of the Moon and its history. A key piece of geological evidence for the relative age of lunar basins lies in the distribution and geological relations of basin-related units. In this paper, we describe the geological relations around the rim of the Serenitatis basin and interpret

[1] Lunar and Planetary Institute, Houston, Texas, USA.
[2] U. S. Geological Survey (retired), San Francisco, California, USA.
[3] ASU School of Earth and Space Exploration, Tempe, Arizona, USA.

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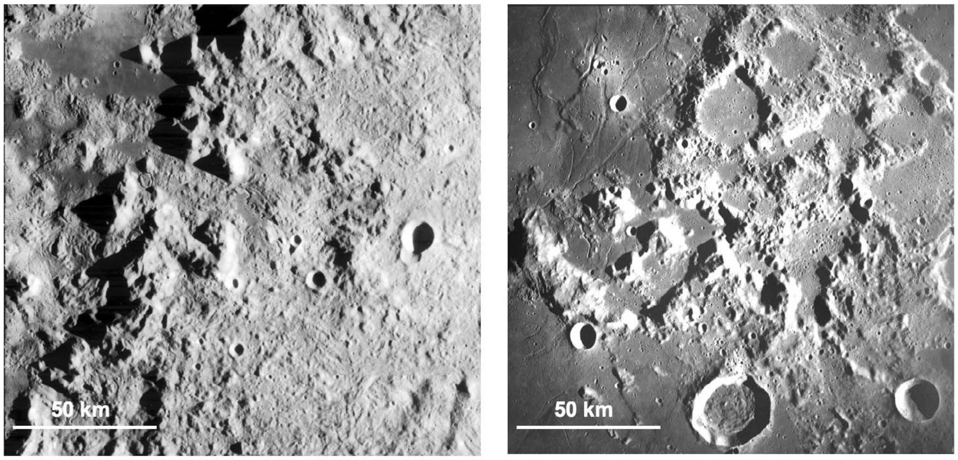

Figure 1. Comparison of the (left) Montes Rook Formation of the Orientale basin (north at top, centered at 22°S, 82°W; LO IV-181-H_1) and (right) Sculptured Hills material of the Montes Taurus highlands (north at top, centered at 21°N, 32°E; AS17–447). The similar morphology has led many to postulate similar origins for the two units [after *Wolfe et al.*, 1981].

them in terms of the relative age of the Serenitatis basin and its implications for the history of the Moon.

2. Geology of the Orientale Basin: A Clue to the Geology of Serenitatis Basin?

[5] "Sculptured Hills" is an informal name given to a knobby, highlands unit found near the massifs of the Apollo 17 landing site (Figure 1) [*Head*, 1974a; *Wolfe et al.*, 1981]. It is found near the massifs of the Apollo 17 landing site and Station 8 was situated to sample it during the last surface traverse [*Wolfe et al.*, 1981]. Remote sensing data suggest that the Sculptured Hills have a very complex and highly variable chemical composition [*Robinson and Jolliff*, 2002].

[6] The near-pristine Orientale basin has long been used as an archetype from which to generalize the geology of older, more degraded basins [*Head*, 1974b; *Moore et al.*, 1974; *McCauley*, 1977; *Scott et al.*, 1977]. The interior of Orientale displays a knobby unit, the Montes Rook Formation [*Scott et al.*, 1977], with surface morphology similar to the Sculptured Hills (Figure 1). The Montes Rook Fm. occurs primarily between the main basin rim Cordillera scarp and the inner, adjacent Outer Rook ring. In detail, it consists of clusters of knobs that appear to overlie terrain undulations and abuts massifs that make up the Outer Rook ring. It is interpreted as a facies of ejecta from the Orientale basin, emplaced nearer and within the rim of the basin at higher angles of ejection than the apparently low-angle ejected, radially textured Hevelius Fm. [*McCauley*, 1977].

[7] Several investigators have used the similarity in appearance between the Montes Rook Fm. and the Sculptured Hills to argue that they are equivalent in origin [*Head*, 1974a, 1979; *Wolfe et al.*, 1981]. In the case of the Sculptured Hills, the supposition is that this material is a facies of ejecta from the Serenitatis basin impact, as the Montes Rook Fm. is a facies of Orientale ejecta. The Sculptured Hills occurs between a ring that may be the basin rim (Vitruvius ring; *Head* [1979]) and an adjacent inner ring (Figure 2) and as such, would consist of the deepest, nearest rim ejecta deposits from the Serenitatis basin. This interpretation implies that all the highland samples from the Apollo 17 landing site are probably related somehow to the Serenitatis basin, either as pieces of basin ejecta or fragments of massif material (which has complex, and uncertain, origins [see *Wilhelms*, 1987]).

[8] This interpretation is widely accepted and would appear to be congruent with the interpretation that the Apollo 17 highland melt breccias are fragments of the Serenitatis basin "melt sheet" [*Warner et al.*, 1976; *Winzer et al.*, 1977]. In such a reconstruction, the North and South Massifs at Apollo 17 make up fragments of an inner Serenitatis basin ring (analogous to massifs of the Outer Rook Mountains of Orientale basin) and the Sculptured Hills are Serenitatis basin ejecta, analogous to the Montes Rook Fm. ejecta of Orientale basin [*Head*, 1974b, 1979; *Wolfe et al.*, 1981].

[9] A problem with this interpretation was noted by *Spudis and Ryder* [1981]. They pointed out that the Sculptured Hills appears to overlie large craters (e.g., Littrow, Le Monnier) that are themselves superposed on top of the Serenitatis basin rim (Figure 2). This superposition creates a stratigraphic problem: the Sculptured Hills cannot be a facies of Serenitatis basin ejecta if it post-dates large craters that are themselves superposed on (and therefore post-date) the basin rings. Moreover, *Spudis and Ryder* [1981] noted that north of the Apollo 17 site, the knobby texture of the Sculptured Hills grade into strongly radially lineated terrain, whose orientation and morphologic prominence suggests a probable relation to the Imbrium basin. On the basis of these observations, *Spudis and Ryder* [1981] suggested that the Sculptured Hills might be a facies of Imbrium basin ejecta and the outcrop of such a unit near the Apollo 17 site calls into question the supposed exclusive Serenitatis basin provenance of rocks collected there. *Spudis and Ryder* [1981] suggested that the Apollo 17 aphanitic breccias [e.g., *Wood*, 1975; *James et al.*, 1978] might be candidates for an Imbrium basin origin, but they accepted the Serenitatis basin origin of the poikilitic "melt sheet" and subsequent studies

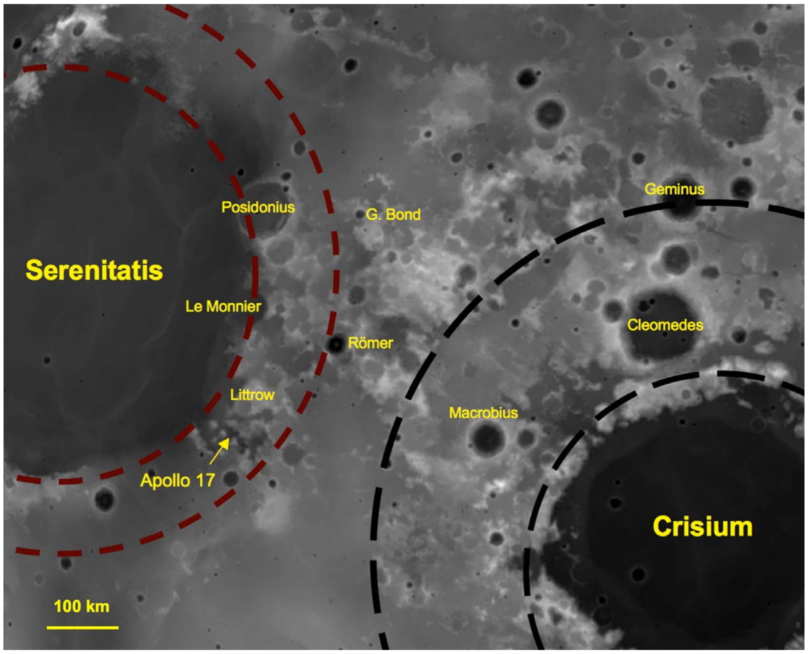

Figure 2. Topographic image from the LROC WAC Digital Terrain Model of the area between the Serenitatis and Crisium basins, showing the rings of *Head* [1979] for Serenitatis (brown) and the rings of *Wilhelms and McCauley* [1971] for Crisium (black). Centered at 29°N, 42°E; north at top. LROC Wide-angle Camera Digital Terrain Map [*Scholten et al.*, 2011].

have also assumed likewise [e.g., *Warren*, 1992; *Dalrymple and Ryder*, 1996; *Jolliff et al.*, 1996; *Ryder et al.*, 1997].

[10] Photographic coverage of the eastern rim of Serenitatis basin prior to the flight of LRO was very poor. The systematic coverage provided by Lunar Orbiter IV of the lunar nearside was largely unusable in this part of the Moon due to a fogged camera lens issue that was not resolved until special procedures to avoid it were developed [*Wilhelms*, 1993, p. 162]. As a result of the fogged images obtained for this part of the Moon, the geological relations between and among highland units could not be established with any degree of certainty. However, the new WAC images acquired from the Lunar Reconnaissance Orbiter show the geology of the highlands between Serenitatis and Crisium in superb detail with topography derived from stereo imaging [*Speyerer et al.*, 2011]. We have studied these images for clues to the relative ages of the Serenitatis and Crisium basins and to better understand the probable origins of the Sculptured Hills material and the provenance of samples collected at the Apollo 17 landing site.

3. New Insights Into the Origin of the Sculptured Hills and Apollo 17 Highland Samples

[11] The new LROC global image mosaic [*Speyerer et al.*, 2011] shows that the Sculptured Hills are not localized around the Apollo 17 site, but are widespread throughout the Taurus Mountains. It extends from the eastern shore of Mare Serenitatis, 600 km from the rim of Imbrium, into the highlands north of Crisium basin (Figures 2 and 3), up to 1000 km from the Imbrium rim, a radial extent of Imbrium deposits is comparable to that recognized in the central highlands (e.g., the Apollo 16 landing site is about 1000 km from the Imbrium basin rim). The Sculptured Hills unit is widespread though out the Montes Taurus highlands, occurring in conjunction with Cayley plains-like flat units throughout the intermountain terrae. It shows several morphological facies, including knobby, undulate, radially lineated and rolling, plains-like terra (Figures 3–5).

[12] The LRO Wide-angle Camera (WAC) images confirm that the Sculptured Hills unit overlies the rims of numerous post-Serenitatis basin craters, including Le Monnier, Littrow, Littrow A, Posidonius A, G. Bond B and Miraldi. Widespread distribution of the Alpes Formation, a knobby type of ejecta from the Imbrium basin (Figure 4a) and radially textured Fra Mauro Fm. (Figure 4b) occur north of Mare Serenitatis (Figure 3) [*Wilhelms and McCauley*, 1971; *Wilhelms*, 1987]. The Alpes and Fra Mauro Formations north of Posidonius transition into Sculptured Hills south of the crater G. Bond (32°N, 36°E; Figure 3). Both knobby (Figure 4c) and radially textured (Figure 4d) facies are evident in the Sculptured Hills [*Spudis and Ryder*, 1981]. Careful study shows that radial terrain of the Sculptured Hills (Figure 4d) is radial to the Imbrium basin, not to either the Crisium or Serenitatis basins (except where the radial to basin centers of the two coincide, south of Römer). The similarity of morphology with the Imbrium units, the distribution, inter-relation with other terra units and relative age of the Sculptured Hills all suggest that it is a facies of ejecta from the Imbrium, and is not from the Serenitatis or Crisium basins.

[13] If the Sculptured Hills unit is not ejecta from Serenitatis but rather, related to the Imbrium basin, then the provenance of all Apollo 17 impact melt breccias becomes suspect. As long as the highland units around the Apollo 17 landing site were attributed primarily to Serenitatis basin

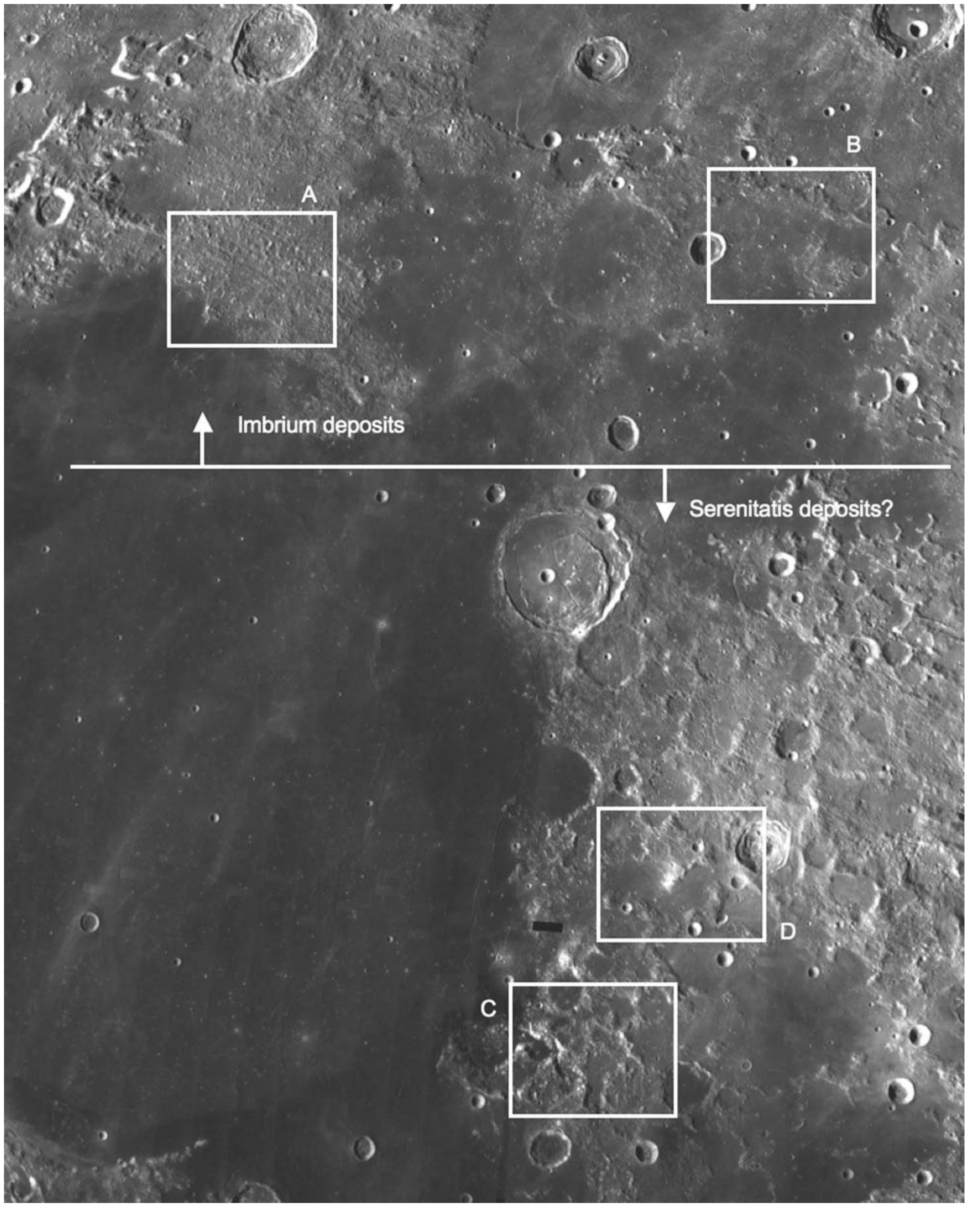

Figure 3. Geological units in the Taurus highlands. The Imbrium-basin related Alpes and Fra Mauro Fm. are both exposed in highlands north of the white line; the highlands south of this line (Montes Taurus) traditionally have been thought to be Serenitatis basin ejecta. Box outlines locate the close-up views shown in Figure 4; Boxes A and B correspond to the Imbrium basin Alpes and Fra Mauro Fm., respectively, while Boxes C and D show different facies of the Sculptured Hills unit. LROC WAC mosaic [*Speyerer et al.*, 2011] is centered on 32°N, 28°E; north at top, area shown is approximately 800 by 900 km.

origins, it was hard to imagine that ejecta from that event did not dominate the Apollo 17 highland samples. *Spudis and Ryder* [1981] suggested that while a Serenitatis origin for the poikilitic "melt sheet" is likely, the aphanites show chemical, petrological and physical features that suggest they may have originated in a different event(s). The new relations seen in the LROC images suggest that additionally, we must now re-consider the postulated Serenitatis origin of the Apollo 17 poikilitic melt rocks as well. The Sculptured Hills unit occurs adjacent to and on the backslope of both North and South Massifs [*Spudis and Ryder*, 1981] (Figure 5); such relations imply that if Imbrium emplaced, the Sculptured Hills could be the source of many to all of the highland breccias collected by the Apollo 17 mission.

[14] If none of the Apollo 17 impact melts are from the Serenitatis basin, what might they represent? *Haskin* [1998] and *Haskin et al.* [1998] suggested that all impact melt rocks containing KREEP are ultimately derived from the Procellarum region and dispersed over the Moon by the Imbrium impact. This suggestion took the sample community aback in that such an origin was at variance with our understanding of the nature of impact melting [*Simonds*,

Figure 4. Morphology of Imbrium basin units and the Sculptured Hills; locations of these close-ups are shown in Figure 3. (a) Imbrium basin Alpes Fm. showing knobby texture. (b) Imbrium basin Fra Mauro Fm. showing radially lineated surface texture. (c) Sculptured Hills showing knobby texture. (d) Sculptured Hills showing radially textured surface. Both in terms of surface morphology and radial position with respect to Imbrium, the Sculptured Hills and the Imbrium basin ejecta units are equivalent. LROC WAC global image [*Speyerer et al.*, 2011]; north at top, each area shown is approximately 100 by 150 km.

1975; *Dence et al.*, 1976; *Floran et al.*, 1976; *Grieve et al.*, 1977; *French*, 1998] and the amount of diversity observed in lunar impact melts [*Ryder*, 1990]. Although we believe that the Haskin *et al.* model for producing melt heterogeneity is physically implausible [see *Haskin et al.*, 1998, Figure 3], reported evidence from the Popigai crater in Russia partly supports the idea of incomplete melt homogenization, particularly for ejected impact melt [*Kettrup et al.*, 2003]. The fact remains that we do not know how much compositional variation an event of such large magnitude as a basin-forming impact may create in impact melts [e.g., *Spudis*, 1993].

[15] If the Sculptured Hills are a facies of Imbrium ejecta unrelated to the Serenitatis basin, then the Apollo 17 samples need not have had to directly date the age of the Serenitatis basin impact. Thus, there is no requirement that Serenitatis be young; it may be relatively old, as many investigators originally thought [*Baldwin*, 1963; *Stuart-Alexander and Howard*, 1970]. A large number of old, degraded craters seem to be superposed on top of the Serenitatis basin structure (Figure 3 and Table 1). We believe that the new image data confirm the senior age status of Serenitatis; our counts of large (D > 20 km) primary craters superposed on top of the Serenitatis basin rim suggest a density of 108–175/million km^2 (Table 1). Although there is some uncertainty in this estimate owing to the possible secondary crater origins of some of these large highland craters, it is still significantly more densely cratered than both the Crisium and Nectaris basins (Table 1), making Serenitatis one of the older pre-Nectarian basins on the Moon (Figure 6). The original basin-forming chronologies made Serenitatis one of the oldest lunar basins, older than Nectaris, Crisium and Imbrium [e.g., *Baldwin*, 1963; *Stuart-Alexander and Howard*, 1970]. We concur with this age assignment and believe that the pre-Nectarian Serenitatis basin may be one of the oldest basins on the Moon (Figure 6). A possible objection to this idea is that as Serenitatis basin contains a significant mascon, it must be relatively young. This objection is countered by the observation of a mascon at the clearly pre-Nectarian (on the basis of crater density) Smythii basin, which ranks in the middle of the lunar basin pre-Nectarian sequence (Figure 6). Apparently, mascon preservation is related more to local lithospheric conditions than to age, a supposition supported by the preservation of extreme basin rim topography [e.g.,

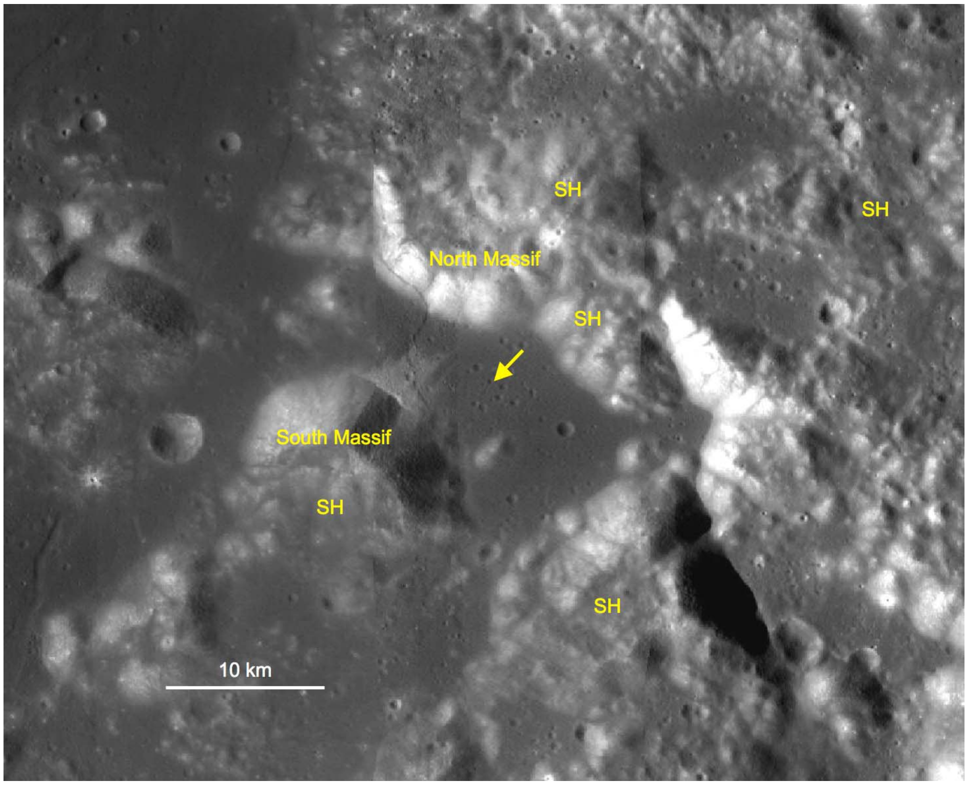

Figure 5. Close-up of the Apollo 17 landing site (arrow), showing Sculptured Hills (SH) material occurring on the backslopes of both the South and North Massifs, both of which were sampled by the astronauts. This relation suggests that samples collected from the base of these massifs could be ultimately derived from Sculptured Hills material, interpreted here as Imbrium-basin related. LROC WAC global mosaic [*Speyerer et al.*, 2011]; north at top, centered at 20°N, 31°E.

Spudis et al., 1994] associated with the South Pole-Aitken basin, the oldest observable basin on the Moon.

4. Implications for the Cratering History of the Moon

[16] The consequences of an old relative age for the Serenitatis basin are more significant than might appear at first glance. Much of the timescale for early lunar evolution and cratering history is keyed around the radiometric ages of the Apollo highland samples, specifically, the timing and spacing in time of the creation of the observable impact record of the lunar highlands [*Wilhelms*, 1987; *Ryder*, 1990; *Stöffler et al.*, 2006]. If Serenitatis is now recognized as an "old" (pre-Nectarian) basin, then its absolute age is critical to the issue of whether the Moon underwent a terminal impact cataclysm [*Tera et al.*, 1974; *Ryder*, 1990] or not [*Hartmann*, 2003].

[17] Early geological studies emphasized the relation of the Apollo 17 landing site to the nearby Serenitatis basin [*Schmitt*, 1973; *Head*, 1974a; *Wolfe and Reed*, 1976] and most subsequent studies came to equate the radiometric ages of impact melt breccias (strongly clustered around 3.89 Ga) from the Apollo 17 highlands with the absolute age of the Serenitatis basin [e.g., *Winzer et al.*, 1977; *Stöffler et al.*, 2006]. Our work does not resolve the source of these impact melts, but we believe that the re-ranking of Serenitatis as a relatively "old" basin and the recognition that one of the major highland units in this region of the Moon does not have an origin as Serenitatis basin ejecta should give pause to those (including ourselves) who have traditionally made this equation without much thought in the past.

[18] If the Apollo 17 impact melts are products of the *Imbrium* (rather than Serenitatis) basin-forming impact, then we are left with no clear indications of the absolute age of the Serenitatis impact. Traditional assignments of 3.89 Ga for the Serenitatis basin are based largely on the interpretation of the crystallization ages of the poikilitic "melt sheet" [*Winzer et al.*, 1977; *Spudis and Ryder*, 1981; *Stöffler et al.*, 2006]. This interpretation may still be true; although the Sculptured Hills material is Imbrium basin-related, recognition of this fact does not directly resolve the origin and

Table 1. Relative Ages of Some Selected Basins on the Basis of Density of Primary Superposed Impact Craters (D > 20 km)[a]

Basin	Number (D > 20 km)	Area (10^6 km^2)	Density
Crisium	45	0.843	53
Nectaris	79	1.286	79
Apollo	57	0.48	119
Grimaldi	15	0.154	97
Serenitatis	18–29	0.166	108–175
Lomonosov-Fleming	63	0.356	177

[a]Data from *Wilhelms* [1987], except for Serenitatis (this paper).

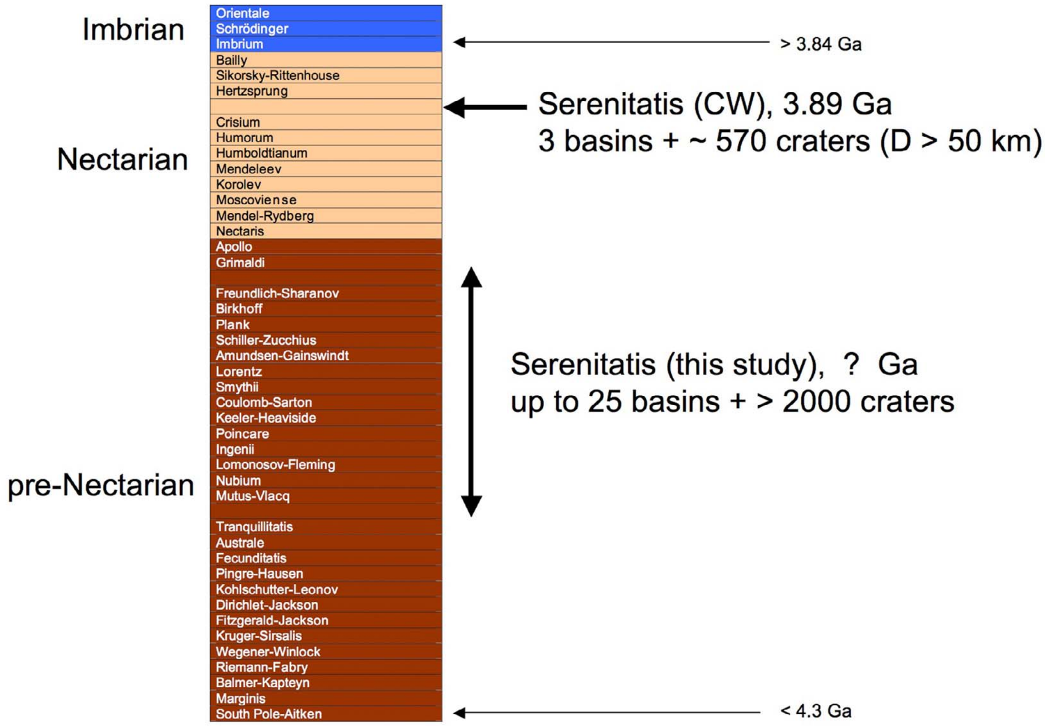

Figure 6. Reinterpretation of the sequence of basin formation based on the observations reported here. The conventional wisdom (CW) that Serenitatis is relatively young means that only a few basins and craters formed between that impact and the one forming the Imbrium basin. If Serenitatis is old (as we advocate), either the Moon underwent a major impact cataclysm at 3.8 Ga or the provenance of Apollo 17 impact melts is open to reinterpretation. Basin names and relative age rankings are after *Wilhelms* [1987] and *Spudis* [1995].

provenance of the materials making up the massifs of the Taurus-Littrow valley. However, images show Sculptured Hills material overlying the backslopes of both North and South massifs (Figure 5) and the Apollo 17 poikilitic melts were collected from boulders and talus found at the base of both of these massifs [*Schmitt*, 1973]. The collected samples may be derived from units that make up the massif interior that became dislodged and rolled downhill or they could be derived from a post-Serenitatis basin cap of Sculptured Hills material that slid down the face of the pre-existing massif. The field relations of these rocks are ambiguous as the outcrop sources for the sampled boulders could not be visited.

[19] As unbelievable as it may sound given the efforts made to acquire the information, we are still uncertain of the absolute age of the Imbrium basin. The current best estimate is merely that Imbrium is older than 3.84 Ga, the age of the volcanic Apollo 15 KREEP basalts [e.g., *Nyquist et al.*, 1975] that are derived from the oldest post-basin unit within Imbrium [*Spudis*, 1978]. This interpretation has been questioned [*Deutsch and Stöffler*, 1987; *Stöffler et al.*, 2006] but not refuted. If the Sculptured Hills unit originally blanketed all of the highlands in the Montes Taurus, it may well have coated the tops of the massifs and hence, the Apollo 17 impact melts could ultimately be derived entirely from Imbrium, rather than Serenitatis, ejecta. In such a case, the 3.89 Ga ages for these rocks might merely reflect the age of the Imbrium basin.

[20] On the other hand, if the Apollo 17 melts are indeed fragments of the *Serenitatis* basin melt sheet, then Serenitatis formed around 3.89 Ga ago [*Stöffler et al.*, 2006]. With the formation of the Imbrium basin well constrained to older than 3.84 Ga (the age of the younger, infilling Apennine Bench Fm. KREEP basalts), such an age would mean that not only Serenitatis and Imbrium, but at least 13 and as many as 25 other large basins (Figure 6) on the Moon (and all other large highland craters stratigraphically sandwiched along with them) formed within an extremely narrow, 50 Ma interval – truly an impact "cataclysm" in its most extreme form [*Ryder*, 1990].

[21] If we did not sample Serenitatis basin melt at the Apollo 17 landing site, then impact melts from this site must be from some other event. These melt rocks contain abundant clasts of plutonic rock fragments and mineral grains derived from such rocks [*Wood*, 1975; *Dence et al.*, 1976; *Warner et al.*, 1976; *James et al.*, 1978; *Ryder et al.*, 1997], indicating that they are not some surficial aggregate but the product of a major, large-body impact. The most likely source is the Imbrium basin [*Spudis and Ryder*, 1981; *Haskin*, 1998; *Haskin et al.*, 1998]. If this is indeed the case, differences in composition and age between these rocks and presumed Imbrium-related impact melts from elsewhere on the Moon indicate that we possess little systematic understanding of the effects of large body impacts – the conventional geological wisdom of impact melt homogenization [*Floran et al.*, 1976; *Grieve et al.*, 1977], distinctive

siderophile signatures [*Hertogen et al.*, 1977], and precision Ar-dating [*Dalrymple and Ryder*, 1996] are wrong at worst or incomplete at best.

5. Conclusions

[22] New images of the Moon obtained by the LROC have clarified the stratigraphy of the highlands terrain east of the Serenitatis basin. On the basis of new geological mapping and current understanding of lunar sample and remote sensing data, we conclude:

[23] 1. The Sculptured Hills material of the Montes Taurus is a distal facies of Imbrium basin ejecta and is not directly related to the Serenitatis basin-forming impact.

[24] 2. The relative age of the Serenitatis basin is pre-Nectarian, about midway in the stratigraphic sequence of these oldest basins.

[25] 3. Impact melt samples returned by the Apollo 17 mission may not be derived from the Serenitatis basin-forming impact but could instead be from Imbrium. In such a case, we have not yet identified impact melt from Serenitatis basin.

[26] 4. If the Apollo 17 impact melts are Serenitatis basin impact melt and date that event, there was a terminal impact cataclysm of substantial proportions, with 13–25 basins and several hundred smaller craters forming within a narrow interval of ~50 Ma.

[27] Continued study of the abundant high quality data currently being returned from LRO and other lunar missions will continue to refine our understanding of lunar history and processes.

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M. S. Robinson, ASU School of Earth and Space Exploration, PO Box 871404, Tempe, AZ 85287-1404, USA.

P. D. Spudis, Lunar and Planetary Institute, 3600 Bay Area Blvd., Houston TX 77058, USA. (spudis@lpi.usra.edu)