AGU PUBLICATIONS

Geophysical Research Letters

RESEARCH LETTER
10.1002/2016GL071429

Impact melt of the lunar Crisium multiring basin

P. D. Spudis[1] and M. U. Sliz[1,2,3]

[1]Lunar and Planetary Institute, Houston, Texas, USA, [2]School of Earth and Environmental Sciences, University of Manchester, Manchester, UK, [3]Now at Physics Institute, Space Research and Planetary Sciences, University of Bern, Bern, Switzerland

Key Points:
- New mapping reveals impact melt sheet of the lunar Crisium basin
- Crisium impact melt is more mafic than that of Orientale basin
- Crisium melt deposit is prime target for future sample return mission

Correspondence to:
P. D. Spudis,
spudis@lpi.usra.edu

Citation:
Spudis, P. D., and M. U. Sliz (2017), Impact melt of the lunar Crisium multiring basin, *Geophys. Res. Lett.*, *44*, 1260–1265, doi:10.1002/2016GL071429.

Received 30 SEP 2016
Accepted 30 JAN 2017
Accepted article online 1 FEB 2017
Published online 13 FEB 2017

Abstract New geological mapping of the Crisium basin on the Moon has revealed exposures of the basin impact melt sheet. The melt sheet has a feldspathic highland composition, somewhat more mafic than the melt sheet of the Orientale basin, but less mafic than comparable deposits around the Imbrium basin. These newly recognized deposits would be ideal locations to directly sample Crisium basin impact melt, material whose study would yield insight into the composition of the lunar crust, the time of formation of the basin, and the large impact process.

1. Introduction

The formation of multiring impact basins on the Moon produced thousands of cubic kilometers of shock-created melt; this melt was largely concentrated within the basin interior, although some was ejected with the clastic materials that make up most of the continuous ejecta blanket surrounding basins [e.g., *Wilhelms*, 1987; *Spudis*, 1993]. Recent geological mapping of the Orientale [*Spudis et al.*, 2014] and Imbrium [*Murl et al.*, 2015] impact basins has documented the presence of deposits of impact melt created during the formation of these basins. During the compilation of a new geological map of the Crisium basin [*Sliz and Spudis*, 2016], we found the remnants of the melt sheet from that basin impact. Here we briefly review the occurrence and morphology of impact melt deposits in craters, the properties of impact melt at the lunar Orientale and Imbrium basins, and describe the newly recognized impact melt sheet of the Crisium basin. Study of these basin impact melt rocks is important for what it can tell us about crustal compositions, the absolute ages of basin-forming events, and the process of basin formation. Determining where basin melt occurs is also significant to lunar exploration because such exposures are prime targets for future robotic or human sample return missions [*Ryder et al.*, 1989].

2. Impact Melts of Lunar Craters and Basins

Impact melt deposits have distinct and well-defined morphologic features that permit their recognition in images taken from orbit [*Howard and Wilshire*, 1975; *Hawke and Head*, 1977; *Wilhelms*, 1987]. Typically, melt deposits are concentrated on the floors of fresh craters, showing rough, fissured, and cracked surfaces. Impact melt often occurs as a veneer on irregular surfaces and are found as ponds perched on terraces of crater walls and as flows that travel downslopes along the walls and rims of complex craters, such as Tycho [*Shoemaker et al.*, 1968; *Howard and Wilshire*, 1975; *Hawke and Head*, 1977; *Plescia and Spudis*, 2014]. Although concentrated within and near crater rims, they sometimes are found distant from the crater rim, where melt can be expressed as flows that have segregated from adjacent clastic debris. Large melt deposits are sometimes found near crater rims within topographic lows, such as the large pond of impact melt north of King crater [*Howard and Wilshire*, 1975; *Hawke and Head*, 1977].

Multiring basins are the largest impact craters on the Moon and formed early in lunar history; most of these basins are older than 3.8 Ga [e.g., *Wilhelms*, 1987]. Their great age means that pristine surface morphologies of their deposits have been largely erased or at best, greatly subdued as a result of impact erosion and burial by subsequent units (e.g., mare basalt infilling). The youngest basins preserve some of their original surface morphologies; the 930 km diameter Orientale basin has sparse mare flooding and an exposed interior structure [*Head*, 1974; *Moore et al.*, 1974; *McCauley*, 1977; *Scott et al.*, 1978; *McCauley et al.*, 1981; *Spudis*, 1993]. A basin interior deposit there consists of smooth, undulating highland plains that grade into a fissured and cracked unit where it drapes basin interior topography (Figure 1); this unit is called the Maunder Formation [*Scott et al.*, 1978; *McCauley*, 1977] and is interpreted as the impact melt sheet of the Orientale basin [*Scott et al.*, 1978; *Wilhelms*, 1987]. The Maunder Formation is remarkably uniform in composition,

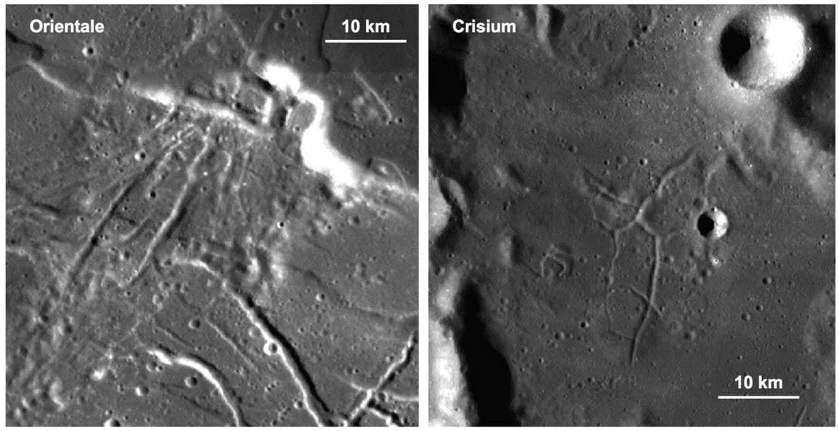

Figure 1. Comparison of surface texture of the (left) Orientale basin Maunder Formation at 24.3°S and 95.7°W and cracked and fissured floor deposits of the (right) Crisium basin at 15.2°N, 50.2°E. The Crisium deposit is a highland kipuka, embayed by mare basalt on all sides, and has highland spectral and chemical compositions. Lunar Reconnaissance Orbiter Camera (LROC) Wide Angle Camera (WAC) global mosaic.

with no evidence of any variation in its chemical makeup, either laterally [*Bussey and Spudis*, 1997] or vertically [*Spudis et al.*, 2014]. Portions of another Orientale basin unit, the Montes Rook Formation (defined primarily by its knobby texture), appear to have flowed in some locations [*Spudis et al.*, 2014] and may consist, at least in part, of a significant quantity of impact melt [*McCauley*, 1977].

Assuming that most lunar basins originally resembled the unflooded Orientale basin, the surface morphology, distribution, and occurrence of the Orientale melt sheet (Maunder Formation) may serve as a guide to the identification of impact melt deposits within older, more degraded, and partly flooded basins. Basin melt sheets occur principally within and adjacent to the two innermost basin rings. Where the melt is thicker, it forms smooth plains having moderately high albedo; the melt sheet at Orientale has a highland composition (generally, ~4–5 wt % FeO) and displays orthopyroxene, not clinopyroxene, as the mafic mineral phase [*Spudis et al.*, 2014]. Similarly, the melt sheets of other basins probably will display a highland composition and show similar surface morphologies. In addition to the impact melt sheet expected within the basin interior, we often find small, isolated deposits of similar morphology outside the basin rim, occurring as the floor units within craters (10–20 km diameter). These features are dispersed among the basin ejecta deposits, and their irregular rim morphology suggests that they are basin secondary impact craters [*Wilhelms*, 1976, 1987]. Although not common, basin secondaries from both the Orientale and Imbrium basins [*Schultz*, 1976; *Spudis and Murl*, 2015] have been identified that contain cracked and fissured floor materials. These floor materials have a highland composition and are found as isolated features within the basin ejecta blanket. The Orientale secondaries filled with melt have chemical compositions identical to that of the main melt sheet (Maunder Formation) in the basin interior [*Spudis et al.*, 2014; *Spudis and Murl*, 2015].

The Imbrium basin (1160 km diameter) is older than Orientale and is mostly filled with mare basalt, concealing much of the basin floor. The basin rim (Montes Apenninus ring) displays extensive slumping near Mons Bradley (20.8°N, 2.3°W), on top of which occur pools of low albedo, fissured and cracked deposits. These features have been interpreted as ponds of Imbrium basin impact melt [*Wilhelms*, 1980]. At one time, the planar Apennine Bench Formation (26°N, 2.5°W) had been thought to be the Imbrium equivalent of the Orientale Maunder Formation, i.e., the impact melt sheet of the Imbrium basin [*Wilhelms*, 1980; *McCauley et al.*, 1981]. However, pristine volcanic potassium, rare earth element, and phosphorus (KREEP) basalts found at the nearby Apollo 15 landing site are likely to be pieces of this material, and thus, the Apennine Bench Formation probably consists of early volcanic flows of nonmare basalt that filled the Imbrium basin [*Spudis*, 1978; *Taylor et al.*, 2012].

The small ejected melt deposits identified around the Imbrium basin are more mafic (i.e., higher FeO) than similar features found at Orientale but are comparable to basaltic impact melts found in the Apollo collection that have been interpreted as Imbrium basin melt rocks [*Ryder and Bower*, 1977]. Typical Imbrium impact melt has FeO content between 8 and 10 wt %, significantly higher than the 4–5 wt % of the Orientale basin impact melt. The Imbrium basin melt deposits fall broadly within the compositional field defined by the Fra Mauro Formation [*Spudis and Murl*, 2015], the clastic ejecta blanket of the basin [*Wilhelms*, 1987]. These results indicate that the target rocks for the Imbrium basin impact were distinctly different from those of the Orientale basin, consistent with its position within the Procellarum-KREEP geochemical province [*Jolliff et al.*, 2000].

3. Crisium Basin Ejecta and Impact Melt

The geology of the Crisium basin has been studied previously [e.g., *Wilhelms and El-Baz*, 1977; *Wilhelms*, 1987; *Spudis*, 1993], but new high-resolution images from the Lunar Reconnaissance Orbiter and compositional data from the Clementine and Lunar Prospector missions permit a more detailed study of this region. Crisium is a multiring impact basin of Nectarian age [*Wilhelms*, 1987] and is morphologically complex, with features suggesting that it may have been subjected to postimpact modification by lithospheric adjustment [*Spudis*, 1993]. The size of the Crisium basin has been subject to dispute; current best estimates suggest that the discontinuous, concentric scarp about 1000 km in diameter represents the topographic rim of the basin [*Wilhelms*, 1987; *Fassett et al.*, 2012]. The unusual elongated shape and morphology of the basin [*Wichman and Schultz*, 1994; *Schultz*, 1996; *Schultz and Stickle*, 2011] suggest that it was created during a low-angle (oblique) impact (less than 10° from the horizontal, traveling west to east), with the top portion of the decapitated projectile scouring terrain downrange of the main basin center (i.e., to the east of Mare Crisium).

New geological mapping of the highland units around the Crisium basin was undertaken in order to determine the basin's geological structure, stratigraphy, and evolution [*Sliz and Spudis*, 2016]. Units were defined on the basis of relative age, surface texture, albedo, and extent and position in regard to the basin center. This new geologic map shows the extent of Crisium basin ejecta and its composition and allows us to compare that composition with those of other basins in better states of preservation [*Sliz and Spudis*, 2016; *Spudis and Sliz*, 2016].

The geological units associated with the Crisium impact basin are typical of lunar basins and include irregular massifs, platform massifs, smooth highland plains, and hilly and furrowed terrain, all of Nectarian age. Irregular massifs occur around central Mare Crisium and make up a basin ring 740 km in diameter [*Spudis*, 1993]. These massifs are equant in shape and stand topographically higher than the majority of the surrounding terrain. Platform massifs are similar to the irregular massifs in their blocky structure but possess relatively flat, mesa-like summits. Hilly and furrowed terrain is the principal highland unit surrounding the basin and is the main manifestation of Crisium basin ejecta; the hilly unit may extend as far as 750 km from the basin center. The highlands surrounding Mare Crisium often display trough and range morphology, with roughly polygonal outlines [*Spudis*, 1993]. These troughs are filled with smooth highland plains that may be a facies of Crisium ejecta [*Sliz and Spudis*, 2016] or distal ejecta plains from the younger Imbrium basin [*Wilhelms*, 1987].

During mapping, we identified fissured and cracked material near the western base of the mare-bounding ring of Crisium at 15.2°N, 50.2°E (Figure 1). This deposit is embayed on all sides by mare basalt but is exposed as an unflooded kipuka with little (if any) mare cover. The cracked unit has lower FeO content (~8.3 wt %) than would be expected for mare basalt (Crisium basalts have FeO $>$15 wt %) and has orthopyroxene as its principal mafic component (Figure 2) [*Spudis and Sliz*, 2016]. Continued mapping identified additional exposures of this unit elsewhere within the basin (Figure 3), in all instances occurring near the inner mare-highland boundary of the basin interior. Although some of these melt patches have no cracks, they all show a "highland" pyroxene signature on the Clementine RGB image (Figure 2) and have FeO between 8 and 10 wt % (Figure 3). On the basis of its morphological similarity to the fissured facies of the Maunder Formation of Orientale (which displays both cracked and smooth facies; Figure 1) and its highland compositional affinities, we interpret this unit as the remnant of the Crisium basin impact melt sheet, presumed to originally cover the entire basin floor, but currently buried beneath the extensive mare basalt flows of Mare Crisium. This relation suggests that a contiguous melt sheet is present at depth within the basin, covered by basalt and exposed only in unflooded, topographically high areas near the margins of the maria.

Using Clementine images [*Lucey et al.*, 2000], the chemical composition of the newly identified Crisium basin melts was determined and compared with previously recognized melt deposits from the Orientale and Imbrium basins (Figure 4) [*Spudis et al.*, 2014; *Spudis and Murl*, 2015]. We note that because exposures of Crisium melt are small and all are embayed by mare basalt, it is likely that some impact mixing with the mare lava has occurred during regolith formation, possibly making our estimates of basin impact melt composition

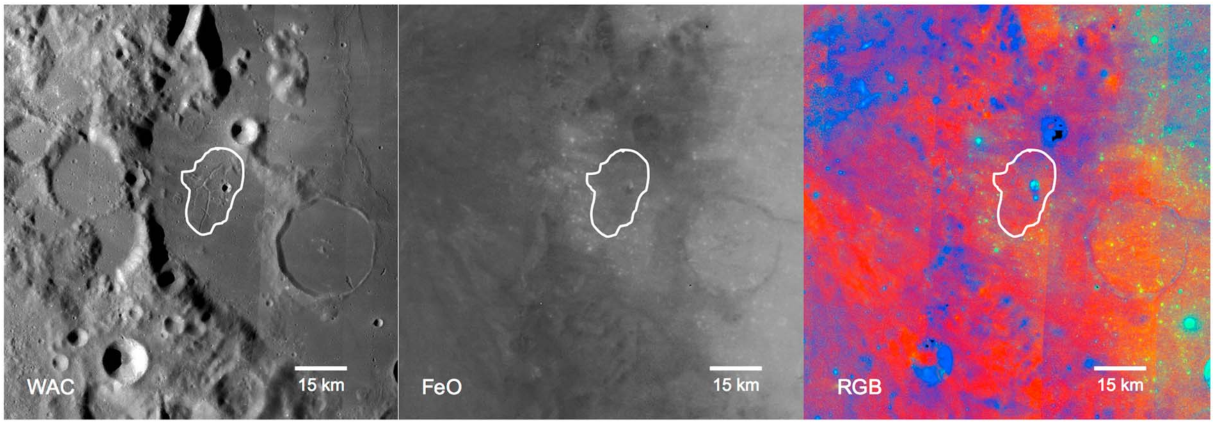

Figure 2. Inferred impact melt deposit (outlined in white) on the floor of the Crisium basin at 15.2°N, 50.2°E. The LROC WAC view of the deposit (left), the Clementine FeO map (middle), and the Clementine RGB false color composite (right) are presented. Melt deposit displays lower FeO content (i.e., darker) than the surrounding (embaying) mare basalts (Figure 2, middle). In Figure 2 (right), the deposit shows the blue/red signature of feldspathic highlands, comparable to impact melt deposits identified around other lunar basins [*Spudis et al.*, 2014].

somewhat more iron-rich than they actually are. Nonetheless, our findings are consistent with a highland basaltic composition for Crisium basin melt, similar to that found at the Imbrium basin [*Ryder and Bower*, 1977; *Spudis and Murl*, 2015]. The small areal extent of the Crisium melt units precludes determination of their Th content, as the field of view for Lunar Prospector gamma-ray data (~20–30 km [*Lawrence et al.*, 2007]) is larger than these exposures. However, the generally low Th content of the region [*Lawrence et al.*, 2007] suggests that the Crisium basin melt deposits are probably also relatively low in Th (~1–2 ppm).

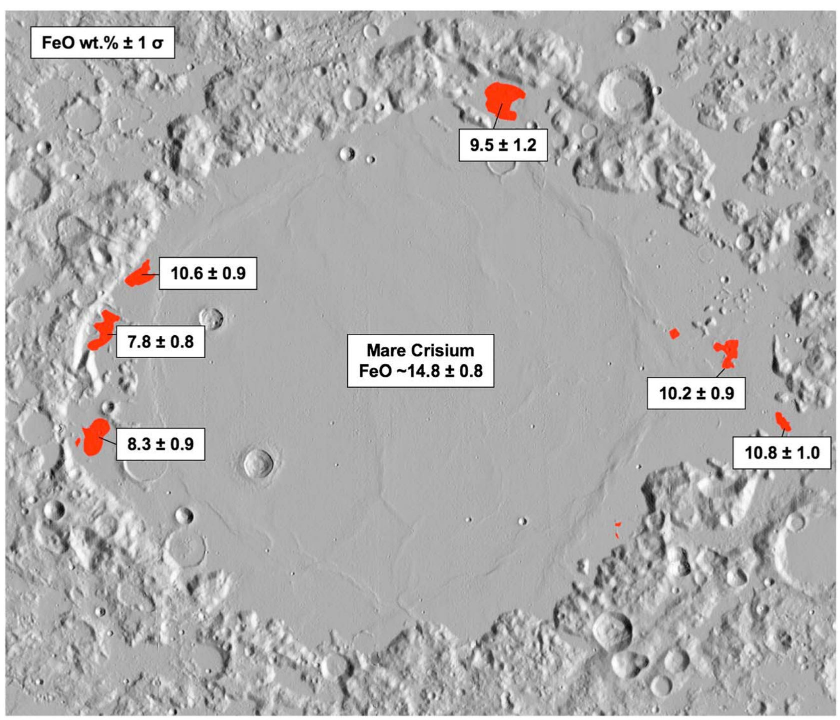

Figure 3. Distribution of newly recognized Crisium basin impact melt deposits on the floor of the basin. Melt sheet exposures occur near the margin of the mare-highland boundary of the main massif ring and are found as kipukas of highland material, unflooded by mare basalt. FeO contents of major recognized exposures of the melt sheet as determined from Clementine iron concentration maps are shown; the main mare basalt fill of Mare Crisium is much higher in FeO content and displays clinopyroxene as its main mafic mineral phase. Base is a shaded relief rendition of a portion of LROC GLD100 global DTM [*Scholten et al.*, 2012].

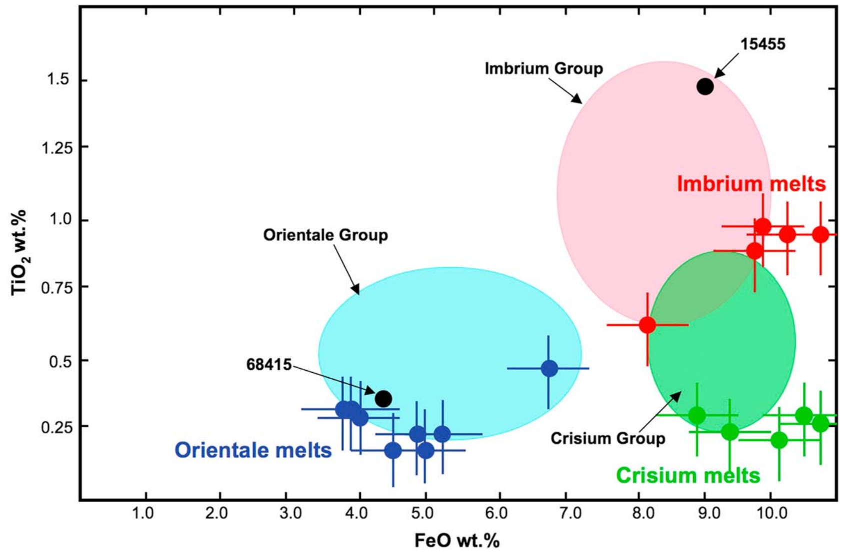

Figure 4. Composition of Orientale (blue), Imbrium (red), and Crisium (green) basin ejecta (envelopes) and impact melt deposits (dots), after *Spudis and Murl* [2015]. Apollo impact melt samples [*Lunar Sample Preliminary Examination Team*, 1973; *Ryder and Bower*, 1977] shown by black dots.

The impact melt of a given basin tends to be chemically homogeneous and of broadly highland composition, although significant differences may exist among different basins. Crisium melt appears to be more mafic than the melt from the Orientale basin, but it is not as Ti-rich as the impact melt from Imbrium basin (Figure 4). These data support the notion that a given basin impact melt sheet is (more or less) homogeneous from a single event, but that melt sheet compositions may vary widely among different basins, depending upon the regional composition of the basin crustal target. It also implies that the lunar crust is laterally heterogeneous and consists of distinct provinces of variable composition [*Jolliff et al.*, 2000].

4. Conclusions

We have identified remnants of the impact melt sheet of the Crisium basin, a Nectarian age feature thought to have been completely buried by mare flooding. The exposed melt deposits around the basin are all similar in composition to each other but distinct from the melt deposits of both the Orientale and Imbrium impact basins, with Orientale being the most feldspathic (noritic anorthosite), Imbrium being more mafic and gabbroic (highland basalt) and Crisium being generally mafic, like Imbrium (having similar iron, but less titanium).

The identification of these melt features offers the possibility of directly sampling basin impact melt of reasonably certain provenance by robotic sample return missions [e.g., *Ryder et al.*, 1989]. Basin impact melt is scientifically important for several reasons. The radiogenic isotopes of melt are completely re-set during the impact, and thus, this material provides the most reliable source of information on the absolute ages of impact events [e.g., *Schärer*, 2003]. Second, the creation of a multiring basin melts enormous volumes of the crust, and samples of the impact melt sheet provide information on the average chemical and mineralogical makeup of the lunar crust in the basin target areas. The study of basin impact melts can help us understand regional variations in crustal composition on the Moon and provide clues to the original differentiation history of that body. Finally, impact melts hold clues to the large body impact process itself, both in terms of the petrogenesis of the melt rocks (e.g., depth of origin and geochemical signature of the impacting projectile) and through the study of deep-seated clastic material that such melt often contains (which provide information on melt movement during the impact event). Study of basin impact melt contributes to a wide variety of lunar problems, and finding this material in place—from a known basin—makes these new units high-priority targets for future exploration and study. Such samples could answer many questions about lunar crustal composition, the impact process, and cratering history.

Acknowledgments
This work is partly supported by NASA SSERVI team NNA09DB33A (D.A. Kring, PI). M.U.S. participation in this study is through the 2015 LPI Summer Undergraduate Intern Program. This work is LPI contribution 2004.

References

Bussey, D. B. J., and P. D. Spudis (1997), Compositional analysis of the Orientale basin using full resolution Clementine data: Some preliminary results, *Geophys. Res. Lett.*, *24*, 445–448, doi:10.1029/97GL00178.

Fassett, C. I., J. W. Head, S. J. Kadish, G. A. Neumann, D. E. Smith, and M. T. Zuber (2012), Lunar impact basins: Stratigraphy, sequence and ages from superposed impact crater populations measured from Lunar Orbiter Laser Altimeter (LOLA) data, *J. Geophys. Res.*, *117*, E00H06, doi:10.1029/2011JE003951.

Hawke, B. R., and J. W. Head (1977), Impact melt on lunar crater rims, in *Impact and Explosion Cratering*, edited by D. J. Roddy, R. B. Pepin, and R. B. Merrill, pp. 815–841, Pergamon Press, New York.

Head, J. W. (1974), Orientale multi-ringed basin interior and implications for the petrogenesis of lunar highland samples, *Moon*, *11*, 327–356.

Howard, K. A., and H. G. Wilshire (1975), *Flows of Impact Melt in Lunar Craters*, *J. Res. U. S. Geol. Survey*, vol. 3, pp. 237–251, U.S. Geol. Surv., Reston, Va.

Jolliff, B. L., J. J. Gillis, L. A. Haskin, R. L. Korotev, and M. A. Wieczorek (2000), Major lunar crustal terranes: Surface expressions and crust-mantle origins, *J. Geophys. Res.*, *105*, 4197–4216, doi:10.1029/1999JE001103.

Lawrence, D. J., R. C. Puetter, R. C. Elphic, W. C. Feldman, J. J. Hagerty, T. H. Prettyman, and P. D. Spudis (2007), Global spatial deconvolution of Lunar Prospector Th abundances, *Geophys. Res. Lett.*, *34*, L03201, doi:10.1029/2006GL028530.

Lunar Sample Preliminary Examination Team (1973), The Apollo 16 lunar samples: Petrographic and chemical description, *Science*, *179*, 23–34.

Lucey, P. G., D. T. Blewett, and B. L. Jolliff (2000), Lunar iron and titanium abundance algorithms based on final processing of Clementine ultraviolet-visible images, *J. Geophys. Res.*, *105*, 20,297–20,305, doi:10.1029/1999JE001117.

McCauley, J. F. (1977), Orientale and Caloris, *Phys. Earth Planet. Int.*, *15*, 220–250.

McCauley, J. F., J. E. Guest, G. G. Schaber, N. J. Trask, and R. Greeley (1981), Stratigraphy of the Caloris basin, Mercury, *Icarus*, *47*, 184–202.

Moore H. J., C. A. Hodges, and D. H. Scott (1974), Multi-ringed basins—Illustrated by Orientale and associated features, *Proc. Lunar Planet. Sci. Conf. 5th*, 71-100.

Murl, J. N., P. D. Spudis, and G. Y. Kramer (2015), Geological Mapping of the lunar Imbrium impact basin, *Lunar Planet. Sci. 46*, 1719.

Plescia, J. B., and P. D. Spudis (2014), Impact melt flows at Lowell crater, *Planet. Space Sci.*, *103*, 219–227.

Ryder G. and J. F. Bower (1977), Petrology of Apollo 15 black-and-white rocks 15445 and 15455—Fragments of the Imbrium impact melt sheet?, *Proc. Lunar Planet. Sci. Conf. 8th*, 1895.

Ryder, G., P. D. Spudis, and G. J. Taylor (1989), The case for planetary sample return missions: Origin and evolution of the Moon and its environment, *Eos Trans. AGU*, *70*, 1495–1509, doi:10.1029/89EO00356.

Schärer, U. (2003), Dating of impact events, in *Impacts on Earth*, *Lecture Notes on Phys*., vol. 505, edited by D. Benest and C. Froeschle, pp. 157–183, Springer, Berlin.

Scholten, F., J. Oberst, K.-D. Matz, T. Roatsch, M. Wählisch, E. J. Speyerer, and M. S. Robinson (2012), GLD100: The near-global lunar 100 m raster DTM from LROC WAC stereo image data, *J. Geophys. Res.*, *117*, E00H17, doi:10.1029/2011JE003926.

Schultz, P. H. (1976), *Moon Morphology: Interpretations Based on Lunar Orbiter Photography*, pp. 248–249, Univ. of Texas Press, Austin.

Schultz P. H. (1996), Nature of the Orientale and Crisium impacts, *Proc. Lunar Planet. Sci. Conf. 27th*, Part 3, 1147–1148.

Schultz P. H. and A. M. Stickle (2011), Arrowhead craters and tomahawk basins: Signatures of oblique impacts at large scales, *Proc. Lunar Planet. Sci. Conf. 42th*, 2611.

Scott, D. H., J. F. McCauley, and M. N. West (1978), Geologic map of the west side of the Moon, *U.S. Geol. Surv. Map, I-1034*.

Shoemaker E. M., R. M. Batson, H. E. Holt, E. C. Morris, J. J. Rennilson and E. A. Whitaker (1968), Television observations from Surveyor VII, Surveyor VII - A Preliminary Report, *NASA, SP-173*, 13–81.

Sliz M. U. and Spudis P. D. (2016), New geologic map of the lunar Crisium basin, *Proc. Lunar Planet. Sci. Conf. 47th*, 1678.

Spudis P. D. (1978), Composition and origin of the Apennine Bench Formation, *Proc. Lunar Planet. Sci. Conf. 9th*, 3379-3394.

Spudis, P. D. (1993), *Geology of Multi-ring Basins*, pp. 172–180, Cambridge Univ. Press, Cambridge, U. K.

Spudis P. D. and J. N. Murl (2015), Impact melt from lunar multi-ring basins: Orientale and Imbrium, *Proc. Lunar Planet. Sci. Conf. 46th*, 1853.

Spudis, P. D., and M. U. Sliz (2016), Impact melt from the lunar Crisium multi-ring basin, *Lunar Planet. Sci.*, *47*, 1463.

Spudis, P. D., D. J. P. Martin, and G. Kramer (2014), Geology and composition of the Orientale basin impact melt sheet, *J. Geophys. Res. Planets*, *119*, 19–29, doi:10.1002/2013JE004521.

Taylor, G. J., L. M. V. Martel, and P. D. Spudis (2012), The Hadley-Apennine KREEP basalt igneous province, *Meteorit. Planet. Sci.*, *47*(5), 861–879.

Wichman, R. W., and P. H. Schultz (1994), The Crisium basin: Implications of an oblique impact for lithospheric failure and mare emplacement, in *Large Meteorite Impacts and Planetary Evolution: Geol. Soc. of Am, Spec. Pap. 293*, edited by B. O. Dressler, R. A. F. Grieve, and V. L. Sharpton, pp. 61–72, Geol. Soc. of Am., Boulder, Colo.

Wilhelms D. E. (1976) Secondary impact craters of lunar basins, *Proc. Lunar Planet. Sci. Conf. 7th*, 2883-2901.

Wilhelms D. E. (1980) Stratigraphy of part of the lunar near side, *U.S. Geol. Surv. Prof. Pap., 1046-A*, 71.

Wilhelms D. E. (1987) Geologic history of the Moon, *U.S. Geol. Surv. Prof. Pap., 1348*, 302.

Wilhelms D. E., and F. El-Baz (1977), Geologic map of the east side of the Moon, *U.S. Geol. Surv. Map, I-948*.