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Young viscous flows in the Lowell crater of Orientale basin, Moon: Impact melts or volcanic eruptions?

N. Srivastava [a,*], D. Kumar [b,1], R.P. Gupta [c,2]

[a] Planetary Sciences and Exploration Programme (PLANEX), Physical Research Laboratory, Room No. 031, Ahmedabad 380009, India
[b] Department of Geological Sciences, Gauhati University, Guwahati, Assam 781014, India
[c] Department of Earth Sciences, IIT Roorkee, Room No. 120, Roorkee 247667, India

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ABSTRACT

Topographical, morphological and spectral reflectance studies have been carried out for a distinct resurface event inside Copernican aged Lowell crater (13.00°S 103.40°W), Orientale basin, using high resolution TC, MI-VIS, LROC-NAC, and M^3 data from Kaguya, Lunar Reconnaissance Orbiter (LRO) and Chandrayaan-1 missions. The resurfacing is predominantly gabbroic/basaltic in composition and is confined to nearly a linear ~17 km long, a 3–6 km wide and a ~100 m deep channel, possibly a graben. It is characterised with distinct surface features such as small uplift with melt pond, several lava-like flows, cracks going up to decimetre size, 20–80 m pits/craters with small central uplifts or depressions and ~100 m craters that emanate liquid. A minimum of three generations of flows have been identified within the unit, the oldest one being less viscous and the subsequent younger ones showing well developed lobes due to the high viscosity. There is a conspicuous absence of unambiguously identified primary impact craters on these flows suggesting their fresh nature. On the basis of these integrated observations we hypothesise that at least the younger portions of this amazingly carved resurfaced unit might be composed of volcanic flows erupted from single or multiple sources subsequent to the emplacement of impact melts from a ~9 km diameter crater on the edge of Lowell crater. Gabbroic/basaltic signatures have also been identified at several other locations inside Lowell crater indicating that it would have impacted on a pre-existing basaltic surface or on a gabbroic pluton. These findings have implications to lunar magmatism and understanding of the genesis of young flows on the lunar surface.

1. Introduction

Melt formation and its subsequent flow and accumulation in and around craters are a natural outcome of cratering from hypervelocity impacts on a planetary surface. They are basically recognised as low albedo resurfacings normally associated with impact craters and impact basins. The quantity of melts produced, their composition and distribution basically depends upon size and velocity of the impactor, the angle of impact and target characteristics (e.g. Pierazzo and Melosh, 2000). On the Moon, since low albedo mare basaltic plains are also mostly associated with impact basins (e.g. Orientale basin (Whitten et al., 2011)) and occasionally with craters (e.g. Tsiolskovsky (Pieters and Tompkins, 1999)), sometimes it is difficult to differentiate between basalts and impact melts using remote-sensing data. For young flows associated with Copernican impact craters such as Giordano Bruno, King, Tycho, and Aristarchus sometimes the observed flow morphologies are also similar to those produced by "Phaoehoe" lava flows in terrestrial settings (e.g. Strom and Fielder, 1968, 1970; Heather and Dunkin, 2003; Bray et al., 2010; Chauhan et al., 2012; Denevi et al., 2012). Therefore, deciphering their explicit origin is a difficult task and the issue has been aptly debated. Volcanic theory cites crater count differences between some of the resurfacings and the host crater surface as the key evidence for post impact volcanic modifications of these recently formed craters (e.g. Strom and Fielder, 1968, 1970). However, evidences such as (a) lack of unambiguous melt sources, (b) proximity in distribution between melt and ejecta, and (c) the conventionally accepted idea of cessation of volcanic activity on the Moon prior to ~1 b.y., have been cited in support of an impact melt origin for various resurfacing flows with a fresh appearance (e.g. Howard and Wilshire, 1975; Hawke and Head, 1977; Denevi et al., 2012).

Data from recent remote sensing missions such as Kaguya, Lunar Reconnaissance Orbiter (LRO) and Chandrayaan-I have revealed new details about the crustal structure and magmatic history of the Moon through identification of fresh thrust faults across the Moon,

* Corresponding author. Tel.: +91 2631 4416; fax: +91 2631 4407.
E-mail addresses: sneeraj@prl.res.in, sneerajprl@gmail.com (N. Srivastava), digantakumar.digu@gmail.com (D. Kumar), rpgupta.iitr@gmail.com (R.P. Gupta).
[1] Tel.: +91 995 401 9352.
[2] Tel.: +91 941 207 2894.

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extended volcanism on the far-side, spinel dominant dense crustal rocks at several locations and young mare units in the Orientale basin (e.g. Haruyama et al., 2009; Watters et al., 2010; Pieters et al., 2011; Jolliff et al., 2011; Whitten et al., 2011; Cho et al., 2012). Further, re-analysis of Apollo seismic data and experimental studies using lunar samples and simulations has deduced a partially molten lower lunar mantle and the core (Weber et al., 2011; Parker et al., 2012). Considering these recent advances in the understanding of lunar geology, possibilities for the occurrence of very young volcanic flows also exist on the Moon in favourable geologic settings such as in an extensional environment. Therefore, young flows on the Moon's surface need to be carefully investigated to decipher their origin.

Recently, a distinct freshly produced resurfacing flow covering an area of ~60 sq km has been reported on the far-side Lowell crater of the Orientale basin (Srivastava et al., 2011; Srivastava and Gupta, 2012). This paper describes the surface topography, morphology and composition of this resurfaced unit based on data from Kaguya mission of JAXA, high resolution imageries from NASA's LRO mission and imaging spectroscopy data from NASA's Moon Mineralogy Mapper (M^3) onboard ISRO's Chandrayaan-1. Attempts have also been made to decipher its plausible origin.

2. Data and methods

Surface morphology has been studied using Kaguya MI-VIS, TC and LROC-NAC images. For surface topography studies Kaguya TC orthorectified DTM has been used. Surface composition has been inferred from photometrically and thermally corrected Level-2 M^3 hyperspectral imageries based on the characteristic spectral reflectance curves. M^3 data mosaicking and spectral analysis have been carried out using ENVI. Principal Component Analysis (PCA) of M^3 data has also been carried out for optimum utilisation of the hyperspectral data. General and technical specifications of the datasets used are provided in Table 1 (Ohtake et al., 2008; Haruyama et al., 2008; Goswami and Annadurai, 2009; Pieters et al., 2009; Robinson et al., 2010).

3. Lowell crater: geology and regional setting

Lowell crater (13.00°S 103.40°W, diameter: 66 km) is located in the NW quadrant of the Orientale basin just beyond the western limb of the Moon (Fig. 1). It is early Copernican in age (McEwen et al., 1993) and occurs in the Montes Rook between the Outer Rook Ring (ORR) and the Cordillera ring. It has prominent central peak, a sharp rim, terraced crater wall which is broader on one side, numerous surface irregularities on the floor and several impact melt deposits both within and outside the crater. Most of the geological units of this crater show the presence of spinel-rich rocks (Srivastava and Gupta, 2012). Other prominent associated rock types include anorthositic gabbro in the central peaks (Tompkins and Pieters, 1999), norites in the crater walls and anorthosites/crystalline anorthosite in other areas (Srivastava and Gupta, 2012). A small superposed rayed impact crater ~9 km in diameter (referred to here as Crater S) is present on its eastern edge. The prominent resurfacing, the main target of the present study (enclosed in a rectangle in Fig. 1) occurs in the eastern-central part of the Lowell crater and extends from Crater S to ~17 km inwards, towards its centre.

4. Observations and results

Here we describe the various observations for surface topography, morphology and spectral reflectance characteristics of the prominent resurfacing inside Lowell crater.

4.1. Surface morphology and topography

The Kaguya TC image revealing the extent and geological context of the recent flows inside Lowell crater and the MI-VIS image view of a part of the resurfacing depicting morphological details are shown in Figs. 2 and 3, respectively. The topographic profiles for the unit derived from TC DTM are shown in Fig. 4.

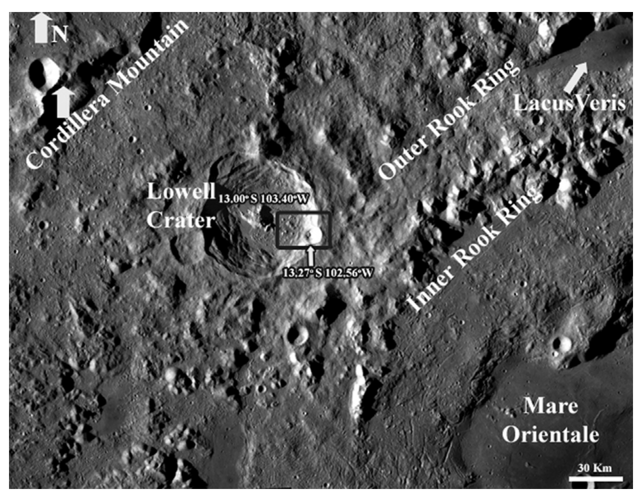

Fig. 1. LROC-WAC image mosaic (from http://wms.lroc.asu.edu/lroc_browse/view/orientale) showing regional geologic setting of Lowell crater on the Moon. The prominent recent resurfacing examined in this study is enclosed within a rectangle.

Table 1
Specifications and archive details of datasets used in the study.

Mission sensor	Data ID	Spatial resolution	Spectral range and resolution	Website (archive)
LRO				
LROC-NAC	M184196652RE M184196652LE M181844927RC M181844927LC M105192594RE	~0.5–1 m	Panchromatic – 400–750 nm	http://wms.lroc.asu.edu/lroc
Kaguya	MVA_2B2 _01_0 2 452S132E2573	~20 m	Multispectral – 5 bands in 415–1000 nm; only 750 nm image is used	https://www.soac.selene.isas.jaxa.jp
MI-VIS	Level 2B			
TC	DTMTCO_03_02785S129E2573SC	~7.4 m		
Chandrayaan-1 M^3	M3G20090422T174330_V01 _RFL M3G20090213T115953_V01 _RFL Level 2: Global mode (photometrically and thermally corrected reflectance data)	~140 m	Hyperspectral – 83 bands in 540–2980 nm with 20–40 nm resolution	http://ode.rsl.wustl.edu/moon/indexProductSearch.aspx