Icarus 235 (2014) 86–122

Contents lists available at ScienceDirect

Icarus

journal homepage: www.elsevier.com/locate/icarus

Integrated topographic, photometric and spectral analysis of the lunar surface: Application to impact melt flows and ponds

Christian Wöhler [a,*], Arne Grumpe [a], Alexey Berezhnoy [b], Megha Upendra Bhatt [c], Urs Mall [c]

[a] Image Analysis Group, TU Dortmund University, Dortmund, Germany
[b] Sternberg Astronomical Institute, Moscow State University, Moscow, Russia
[c] Max Planck Institute of Solar System Research, Katlenburg-Lindau, Germany

ARTICLE INFO

Article history:
Received 14 March 2013
Revised 7 March 2014
Accepted 8 March 2014
Available online 21 March 2014

Keywords:
Data reduction techniques
Impact processes
Moon
Photometry
Spectroscopy

ABSTRACT

This study provides an analysis of the impact melt deposits (melt flows and ponds) associated with eight lunar craters with diameters between 9 and 96 km in terms of their topographic, photometric and spectral properties. Our analysis is based on an integrated method for construction of digital elevation models (DEM) of high lateral resolution, pixel-wise photometric modelling, construction of topographically corrected normalised reflectance maps, extraction of spectral parameters and estimation of elemental abundances based on Moon Mineralogy Mapper (M^3) hyperspectral data and data of the Lunar Prospector Gamma Ray Spectrometer instrument. Most of the examined geologically fresh impact melt flows are characterised by lower albedos than the surrounding surface and tend to originate from topographically low parts of the source crater rim. As an exception, we find that the impact melt deposits northeast of crater Aristillus lack any optical signature and are not visible in monochrome images, but can only be observed by their anomalously smooth surface inferred from the DEM. Some impact melt flows and ponds exhibit photometric anomalies in terms of the asymmetries in the single-particle scattering function and the slope of that parameter with respect to wavelength. These photometric anomalies may be due to impact melt specific anomalies of the surface structure, e.g. consolidated rock rather than regolith, or anomalies in size or shape of the geometric surface elements (e.g. individual grains or their aggregates) on submillimetre spatial scales. The strength of the hydroxyl absorption displays a negative anomaly with respect to the surrounding surface for the majority of the examined impact melt flows. As an impact melt specific spectral behaviour, we find a decrease in the absorption band depth around 2000 nm and (in several cases) a simultaneous increase of the absorption band depth near 1000 nm. These observations are consistent with the laboratory analyses by Tompkins et al. (Tompkins, S., Pieters, C.M. [2010]. Meteorit. Planet. Sci. 45 (7), 1152–1169) of chemically uniformly composed mixtures between crystalline and glass material. For several impact melt flows, their data allow to roughly estimate the fraction of glass material based on our spectral analysis.

1. Introduction

Many lunar craters of various sizes display flow structures and flat-surfaced ponds which are usually attributed to impact melt (e.g. Howard and Wilshire, 1975), i.e. material molten by the energy of the crater-forming impact. Impact melt accumulating in topographic lows formed melt ponds. These impact melt deposits are usually of lower albedo than the surrounding, as it is the case for the annulus of impact melt around the crater Tycho (e.g. Tompkins and Pieters, 2010). The melt material may also be intermixed with solid blocks (Howard and Wilshire, 1975), where the relative amount of unmolten material has a strong influence on the melt viscosity and the period of time during which it remains fluid (e.g. Bray et al., 2010). Several previous studies consider the physical processes relevant during impact crater formation (e.g. transient cavity formation, crater floor rebound, ejecta fallback) and their temporal sequence (e.g. Hawke and Head, 1977; Bray et al., 2010).

Our main goal in the study of lunar impact melt deposits is the analysis of their topographic setting as well as their photometric and spectral properties. The topography of the surface on which

* Corresponding author. Fax: +49 231 755 3685.
E-mail addresses: christian.woehler@tu-dortmund.de (C. Wöhler), arne.grumpe@tu-dortmund.de (A. Grumpe), ber@sai.msu.ru (A. Berezhnoy), bhatt@mps.mpg.de (M.U. Bhatt), mall@mps.mpg.de (U. Mall).

http://dx.doi.org/10.1016/j.icarus.2014.03.010
0019-1035/

impact melt is deposited is a crucial factor implying whether a flow or a pond is formed. The exploration of differences in the photometric scattering behaviour and its wavelength dependence between impact melt deposits and surrounding material may reveal peculiarities in the surface structure of the melt on spatial scales comparable with the grain size of the surface material. The study of impact melt deposits in terms of their spectral behaviour is motivated by the fact that they exhibit spectral characteristics which are not only governed by the mineralogy but also by the non-crystalline (glass) vs. crystalline fraction of the melt material, which in turn is an indicator of the nature of the cooling process (Tompkins and Pieters, 2010). Disentanglement between the spectral properties related to composition and glass fraction might allow for an estimation of the crystalline vs. glass fraction by the comparison of remotely sensed spectra with laboratory analyses such as those performed e.g. by Tompkins and Pieters (2010).

According to these considerations, in this study we will first outline our integrated framework for photometric and spectral analysis and construction of DEMs of high lateral resolution based on the Chandrayaan-1 M^3 (Pieters et al., 2009) hyperspectral data. These methods will be applied to a total of five lunar craters (Joule T, Korolev X, Paraskevopoulos R, Gerasimovich D, small crater on the southern wall of Donner) associated with fresh impact melt deposits, one crater (Lowell) exhibiting large melt ponds on its floor and a conspicuous melt flow originating from a small fresh crater on its eastern wall, one crater (Copernicus) displaying a large impact melt deposit of unknown nature on its floor, and melt deposits outside a large crater (Aristillus). Similarities and differences in the encountered photometric and spectral properties will be discussed, especially regarding the topography of the impact melt deposits, the phase angle dependent scattering properties of the surface, the parameters inferred from the absorption bands centred at approximately 1000 nm and 2000 nm, the depth of the "hydroxyl absorption" near 3000 nm, and the inferred elemental abundances.

2. Related work on lunar impact melt deposits

In their photogeologic study based on ground-based and orbital images, Hawke and Head (1977) identify 55 lunar craters associated with impact melt deposits. They observe that impact melt deposits outside of their source crater tend to occur at the lowest parts of the crater rim. Thin veneers of impact melt are common around smaller craters, while impact melt ponds and flows more frequently emerge from larger craters and may superpose morphological features formed during the modification of the transient cavity (Hawke and Head, 1977). However, the recent study by Neish et al. (2012a) indicates that impact melt flows frequently occur also around small craters and may extend considerable distances from their rims. Impact melt deposits around small, subkilometre lunar craters are identified by Stopar et al. (2012), who also discuss possible reasons for differences in melt abundance and distribution.

Several recent photogeologic studies concentrate on the analysis of small impact melt deposits based on images acquired by the Narrow Angle Camera (NAC) (Robinson et al., 2010; image download from Planetary Data System archive at http://lroc.sese.asu.edu/data/) carried by the Lunar Reconnaissance Orbiter (LRO) (Chin et al., 2007) with their lateral resolution of better than 1 m per pixel (e.g. Hawke et al., 2010; Denevi et al., 2012; Koeber et al., 2012; Bray et al., 2010). More than 20 short and narrow melt flows as well as small melt ponds associated with the rim of the crater Byrgius A are detected by Hawke et al. (2010). Denevi et al. (2012) map impact melt flows around 15 lunar craters and model the physical properties of the impact melt using GLD100 topographic data by Scholten et al. (2012). Koeber et al. (2012) identify a total of 35 lunar craters associated with impact melt deposits outside of the main crater rim and examine the correlation between the topographic elevation along the rim and the origin of the melt flow. The cooling process of impact melt is simulated by Bray et al. (2010).

Several previous studies address the spectral properties of lunar impact melt deposits and draw conclusions about their composition. The spectral characteristics of different kinds of lunar impact melt are examined by Tompkins and Pieters (2010) based on laboratory analyses. They establish systematic differences in the properties of the absorptions near 1000 nm and 2000 nm for different relative amounts of glass melt vs. crystalline material. Based on Kaguya Multiband Imager (MI) data, Hirata et al. (2010) spectrally divide the floor of the crater Jackson into several units consisting of crystalline and glassy melt material. The spectral properties of impact melt deposits in the crater Tycho, especially on its central peak, are analysed by Dhingra and Pieters (2012) based on Chandrayaan-1 Moon Mineralogy Mapper (M^3) hyperspectral image data and Kaguya TC images. In the study by Kuriyama et al. (2012), impact melt deposits in the craters Tycho and Jackson are examined based on Kaguya MI data and LROC NAC images. Dhingra et al. (2013) have identified a large sinuous impact melt deposit of about 30 km length in the northern part of the crater Copernicus based on spectral parameters inferred from M^3 hyperspectral image data (cf. also Section 4.2). They observe a short minimum wavelength of the absorption band around 1000 nm for the impact melt deposit and thus infer the presence of Mg-rich pyroxene. Using optical images of the fresh lunar crater Giordano Bruno, Shkuratov et al. (2012) have applied the phase-ratio technique to infer information about the surface roughness. They have specifically examined impact melt deposits and regolith taluses occurring on the crater floor and inner walls.

These photogeologic, photometric and spectral analyses are complemented by recent radar observations using ground-based instruments (Campbell et al., 2010) and from lunar orbit using the Mini-RF instrument (Nozette et al., 2010) carried by the LRO spacecraft (e.g. Neish et al., 2011, 2012b; Carter et al., 2012). These observations reveal impact melt deposits as regions of anomalously high surface roughness.

3. Integrated framework for spectral and photometric analysis and DEM construction based on M^3 hyperspectral image data

This section describes the framework of our analysis technique. The processing steps comprise the construction of a DEM of high lateral resolution of the region under study based on a combination of stereoscopic DEM (GLD100) and radiance image data, the normalisation of the hyperspectral image data to standard geometry, the construction of spectral parameter maps from the normalised spectral data, and the construction of elemental abundance and petrographic maps. In this section only the motivation for the applied techniques and the basic principles are described, while details can be found in the appendix.

3.1. Photometric modelling and 3D reconstruction of the lunar surface

One central aspect of this study is the determination of the photometric properties of lunar impact melt deposits in comparison to surrounding areas. Using the photometric model by Hapke (1981, 1984, 1986, 2002), relations between the model parameters and physical surface parameters can be established, such as the single-scattering albedo and the asymmetry of the single-particle scattering function, which in turn contain information about the surface structure on spatial scales similar to the material grain size. For this analysis, M^3 version 03 level 1B hyperspectral radiance data (download from http://pds-imaging.jpl.nasa.gov/volumes/m3.html) of the