Icarus 283 (2017) 232–253

Contents lists available at ScienceDirect

Icarus

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

The compositional and physical properties of localized lunar pyroclastic deposits

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ARTICLE INFO

Article history:
Received 25 June 2015
Revised 26 August 2016
Accepted 19 September 2016
Available online 21 September 2016

Keywords:
Moon, surface
Moon
Radiative transfer
Geological processes
Radar observations
Volcanism

ABSTRACT

Lunar localized pyroclastic deposits are low albedo deposits with areas $< 2500\,\text{km}^2$. These deposits were difficult to study before the turn of the millennium because of the lack of available high spatial-resolution data. With the launch of the Lunar Reconnaissance Orbiter, Kaguya, and Chaandrayan-1, new sets of diverse high spatial-resolution data are now available. Using several of these data sets, we conducted a study of 34 localized pyroclastic deposits globally. For each localized pyroclastic deposit, we examined topography to estimate pyroclastic volume and juvenile proportions, S-band radar backscatter, thermal-infrared-derived measures of surficial rock abundance and regolith density, and mineral abundances. Our goals are to (1) quantitatively characterize the physical and mineralogical properties of each localized pyroclastic deposit, (2) investigate the physical and mineralogical variations among localized pyroclastic deposits, (3) compare these properties of localized ($< 2500\,\text{km}^2$) to regional pyroclastic deposits ($> 2500\,\text{km}^2$), and (4) provide useful parameters for future volcanological modeling. From this study, we find that: (1) localized pyroclastic deposits exhibit low relief structures, (2) the surface rock abundance and circular polarization ratio of localized pyroclastic deposits display a wide range of values (0.2–0.5% and 0.3–0.6, respectively), (3) the glass abundance of localized pyroclastic deposits vary between ~0 and ~80 wt.%, (4) there are four types of localized pyroclastic deposits based upon the surface rock abundance and glass abundance parameters, (5) pyroclastic deposits within the same floor-fractured crater tend to have similar properties, and (6) localized pyroclastic deposits are diverse with respect to regional pyroclastic deposits, but a subset of localized pyroclastic deposits have similar physical and mineralogical properties to regional pyroclastic deposits.

1. Introduction

Lunar pyroclastic deposits are conspicuous features because of their low albedo relative to the surrounding area. Gaddis et al. (1985, 2000) divided lunar pyroclastic deposits into two groups based upon area: regional pyroclastic deposits ($> 2500\,\text{km}^2$) and localized pyroclastic deposits ($< 2500\,\text{km}^2$). The properties of regional pyroclastic deposits are well defined from spectral studies (e.g., Adams et al., 1974; Weitz et al., 1998; Gaddis et al., 2003; Wilcox et al., 2006] and radar studies [e.g., Pieters et al., 1973; Zisk et al., 1977; Gaddis et al., 1985; Carter et al., 2009). In contrast, the small areas of localized pyroclastic deposits and the paucity of high spatial-resolution global data sets before the Kaguya, Lunar Reconnaissance Orbiter (LRO), and Chaandrayan-1 missions resulted in few detailed studies. These early studies included spectral and albedo analyses (e.g., Hawke et al., 1989; Gaddis et al., 2000; Gaddis et al., 2003). The most detailed studies (e.g., radar, morphology, composition) concentrate on a handful of localized pyroclastic deposits in Alphonsus crater, (e.g., Head and Wilson, 1979; Coombs et al., 1990). While these deposits are informative, they may not be representative of localized pyroclastic deposits globally.

Detailed information regarding the physical and compositional characteristics of localized pyroclastic deposits on a global scale could improve future mission planning by providing data to match with science or lunar colonization objectives. For instance pyroclastic deposits with high olivine content could be good candidates for understanding the mantle composition and petrogenesis. Geochemical analyses of pyroclastic glass (e.g., high Ni and Mg abundance) could show that they represent primitive material from the lunar interior (Delano, 1986). Moreover, pyroclastic deposits

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http://dx.doi.org/10.1016/j.icarus.2016.09.025
0019-1035/

contain valuable chemical resources, such as titanium, iron, oxygen, and helium-3 (Hawke et al., 1990; Hawke and Coombs, 1994), which would serve as resources for potential future colonization.

Data acquired by LRO, Kaguya, and Chaandrayan-1 missions fill the gap in the need of diverse and high spatial-resolution global data sets that would enable detailed characterization of localized pyroclastic deposits. The purpose of this study is to use these available data sets from LRO and Kaguya to characterize the physical and mineralogical properties of 34 localized pyroclastic deposits previously identified by Gaddis et al. (2003) and Gustafson et al. (2012). In this study, we will: (1) characterize the shape, thickness, and volume of localized pyroclastic deposits, (2) describe the rock and regolith properties on the surface and subsurface, (3) investigate the mineralogical abundances, (4) look for relationships between the physical and mineralogical characteristics, (5) compare the physical and compositional properties of localized pyroclastic deposits from the same floor-fractured crater, and (6) examine the differences between localized and regional pyroclastic deposits. As a result of this work, future studies will be able to use our physical and compositional descriptions of localized pyroclastic deposits to model the emplacement, the eruptive behavior, and the geological history of these deposits. As localized pyroclastic deposits are commonly found on floor-fractured craters, volcanological modeling derived from our results could lead to an improved understanding of the magma body's migration through the crust and their occurrence underneath floor-fractured craters (e.g., Schultz, 1976; Jozwiak et al., 2012).

2. Background

2.1. General properties of localized pyroclastic deposits

Localized pyroclastic deposits are isolated, comprised of low-albedo material, and exhibit an irregular-shaped crater near the center of the deposit (Gaddis et al., 2000; 2003). These deposits are commonly found in floor-fractured craters or along mare margins. Gaddis et al. (2003) compiled a list of over fifty known localized pyroclastic deposits. In part to the recent advancements in instrumentation onboard LRO and Chandraayan-1, as well as Earth-based Arecibo, several recent studies have discovered additional localized pyroclastic deposits across the Moon (e.g., Carter et al., 2009; Gaddis et al., 2011; Gustafson et al., 2012; Besse et al., 2014; Campbell et al., 2014).

2.2. The alphonsus localized pyroclastic deposits

Several workers have examined morphologic, spectral, radar, and volumetric properties of the Alphonsus localized pyroclastic deposits (e.g., Head and Wilson, 1979; Hawke et al., 1989; Coombs et al., 1990; Jawin et al., 2015). In addition to these observations, volcanological models exist for the Alphonsus deposits (i.e., Head and Wilson, 1979), which make them the most thoroughly studied localized pyroclastic deposits. The Alphonsus localized pyroclastic deposits lack lava flows (Head and Wilson, 1979). From Earth-based radar observations, Head and Wilson (1979) shows that these pyroclastic deposits exhibit low X-band (3.8 cm) radar backscatter relative to their surroundings, which suggests that the average rock size in the Alphonsus localized pyroclastic deposits is smaller than the average rock size of non-pyroclastic regolith. Coombs et al. (1990) affirms that the radar backscatters from Earth-based 3.0- and 3.8 cm radar observations in the Alphonsus pyroclastic deposits are low, but radar backscatters from the vents and vent slopes are high, which implies that the vents contain rocks large enough to scatter 3.0- and 3.8 cm radar. Head and Wilson (1979) calculated the volume of juvenile (magmatic material) and non-juvenile (non-magmatic material or country rock) material in Alphonsus pyroclastic deposits by combining information from topographic maps and thickness estimates. For most of the Alphonsus pyroclastic deposits, they estimate that each deposit consists of ~50% juvenile and ~50% non-juvenile material.

To test various eruptive scenarios, Head and Wilson (1979) combined the radar and morphologic observations with the volumetric estimates. They conclude that the observed physical properties of the Alphonsus localized pyroclastic deposits are most consistent with vulcanian-like eruptions. These events were transient eruptions, which ejected juvenile material along with entrained local mare or highland material.

2.3. Spectral observations of localized pyroclastic deposits

The most common minerals on the Moon are plagioclase, pyroxene, olivine, and ilmenite (Papike et al., 1991). Each of the silicate minerals displays characteristic spectral shapes in the visible to near infrared based upon the number, size, and location of spectral absorptions, which arise from the interaction of light with Fe^{2+} housed within a crystal structure (Burns, 1970; Burns, 1993). The spectrum of each silicate mineral is dependent on the geometry of the crystallographic sites as well as the distribution and abundance of Fe^{2+} among those crystallographic sites. Olivine spectra typically exhibit a broad asymmetrical 1 µm absorption (Burns, 1993; Sunshine and Pieters, 1998). Broadly speaking, pyroxene spectra show two major absorptions at 1 and 2 µm (Burns, 1993; Klima et al., 2007; 2011). Fe-bearing plagioclase spectra show a small 1.2 µm absorption (Adams and Goulland, 1978). Ilmenite is a Fe-Ti oxide that displays a nearly flat, low-albedo spectrum except for a small absorption at 0.6 µm (Loeffler and Burns, 1975). Lunar pyroclastic glass spectra show similar shapes as pyroxene with two absorptions located at 1 and 2 µm, but these absorptions are very broad with band centers different than those in pyroxenes (Bell and Mao, 1972).

The basic spectral properties of these minerals aided (Hawke et al. 1989) in classifying nearside localized pyroclastic deposits. Using Earth-based near-infrared telescopic spectra, Hawke et al. (1989) categorizes these deposits into three groups based upon the location and shape of the 1 µm absorption band: Group I displays highland and pyroclastic glass signatures; Group II exhibits mare and pyroclastic glass signatures; Group III shows olivine and orthopyroxene signatures. Hawke et al. (1989) did consider that the Group III 1 µm absorption band could instead be due to pyroxene and pyroclastic glass considering that a spectrum of a binary mixture of pyroxene and pyroclastic glass spectra would produce a similar broad 1 µm absorption shape. However, in a previous spectral study of a Group III deposit (i.e., J. Herschel), McCord et al. (1981) interprets that the 2 µm absorption feature was solely due to pyroxene and the 1 µm absorption was due to olivine instead of pyroclastic glass because glass bands are too weak and would be concealed by the presence of other Fe-bearing minerals. In more recent studies, Besse et al. (2014) and Jawin et al. (2015) examined several localized pyroclastic deposits with hyperspectral data from the Moon Mineralogy Mapper (M^3). Their analyses used the Integrated Band Depth and qualitative assessment of the 1- and 2 µm absorption positions and relative strengths. In contrast to Hawke et al. (1989) and McCord et al. (1981) interpretations, they conclude that Group III contains pyroclastic glass instead of olivine. After determining the three groups and their compositions, Hawke et al. (1989) interprets that these groups are a result of vulcanian eruptions, as modeled by Head and Wilson (1979), with varying proportions of local entrained material, juvenile material, and basaltic cap material.

In another study, Gaddis et al. (2000; 2003) investigated the albedo and band ratios derived from the Clementine UVVIS orbital data set of various near and farside localized pyroclastic deposits.