Icarus 278 (2016) 62–78

Contents lists available at ScienceDirect

Icarus

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

The origin of lunar concentric craters

David Trang*, Jeffrey J. Gillis-Davis, B. Ray Hawke

University of Hawai'i at Mānoa/Hawai'i, Institute of Geophysics and Planetology, 1680 East-West Road, Honolulu, HI 96822, USA

ARTICLE INFO

Article history:
Received 9 February 2016
Revised 21 May 2016
Accepted 1 June 2016
Available online 16 June 2016

Keywords:
Moon, surface
Impact processes
Geological processes
Moon

ABSTRACT

Lunar concentric craters are a unique class of impact craters because the interior of the craters contains a concentric ridge, but their formation mechanism is unknown. In order to determine the origin of concentric craters, we examined multiple working hypotheses, which include eight impact-related and endogenic processes. We analyzed data sets that originated from instruments onboard Clementine, Kaguya, and the Lunar Reconnaissance Orbiter to characterize the morphology, spatial distribution, composition, and absolute model ages of 114 concentric craters. Concentric craters contain five key properties: (1) a concentric ridge, (2) anomalously shallow floors, (3) their occurrence is concentrated near mare margins and in mare pond regions (4) the concentric ridge composition is similar to the surrounding area and (5) concentric crater ages are Eratosthenian and older. These five key properties served as constraints for testing impact-related and endogenic mechanisms of formation. We find that most impact-related hypotheses cannot explain the spatial and age distribution of concentric craters. As for endogenic hypotheses, we deduce that igneous intrusions are the likely mechanism that formed concentric craters because of the close relationship between concentric craters and floor-fractured craters and the concentration of both features near mare-highland boundaries and in mare ponds. Furthermore, we observe that floor-fractured craters are common at crater diameters > 15 km, whereas concentric craters are common at crater diameters < 15 km. We suggest that igneous intrusions underneath small craters (<15 km) are likely to form concentric craters, whereas intrusions under large craters (>15 km) produce floor-fractured craters.

1. Introduction

The changes in lunar crater geometry and morphology with increasing crater diameter and age is well understood (e.g., Pike, 1974, 1980; Wood and Andersson, 1978; Pohn and Offield, 1970; Trask, 1971; Soderblom and Lebofsky, 1972; Head, 1975). However, a class of lunar craters called concentric craters appears to deviate from size- and age-related morphologies (Fig. 1). Wood (1978) defined concentric craters as bowl-shaped craters with an inner ring. The inner ring geometry ranges between doughnut-shaped, rounded ridges, steep crater rims, or flattened mounds. We refine the concentric crater definition as craters with a doughnut-shaped ridge or platform concentric to the crater rim crest on the crater wall and/or crater floor. We call this 'inner ring' the *concentric ridge* (Fig. 1). Within the concentric ridge is a relatively flat floor or a bowl. The crater that the concentric ridge resides in is called the *parent crater* (Schultz, 1976b).

Most explanations for formation involve impact and igneous-related processes, but currently there is no consensus on the origin of concentric craters. Sekiguchi (1970) hypothesized that concentric craters formed as a result of a tidally split meteoroid that successively impacted the same point. A suggestion by Wöhler and Lena (2009) is that concentric craters are a consequence of an impact into a two-layered target where the surface layer is weaker than the underlying layer. Previous workers also suggested non-impact related processes. For instance, it was proposed that lava produced the concentric ridge (e.g., Schultz, 1976b; Wood, 1978). Another endogenic explanation is that the concentric ridge is a product of a ring dike (Cameron and Padgett, 1974) or a volcanic dome (Smith, 1973). Another idea involved the accumulation of magma underneath the crater, which uplifts the crater floor (Wöhler and Lena, 2009). A non-igneous-related idea suggested by Schultz (1976b) is that the concentric ridge is a product of mass wasting of material off the walls and onto the floor creating a ring talus.

The purpose of this study is to resolve the origin of lunar concentric craters. To determine the most likely mechanism of formation, we categorized the properties of concentric craters into four groups: morphology and morphometry, spatial distribution, composition, and age. Morphology and morphometry involve notable features within concentric craters and relationships between concentric crater dimensions (i.e., crater depth, crater diameter, rim

* Corresponding author.
E-mail address: dtrang@higp.hawaii.edu (D. Trang).

http://dx.doi.org/10.1016/j.icarus.2016.06.001
0019-1035/

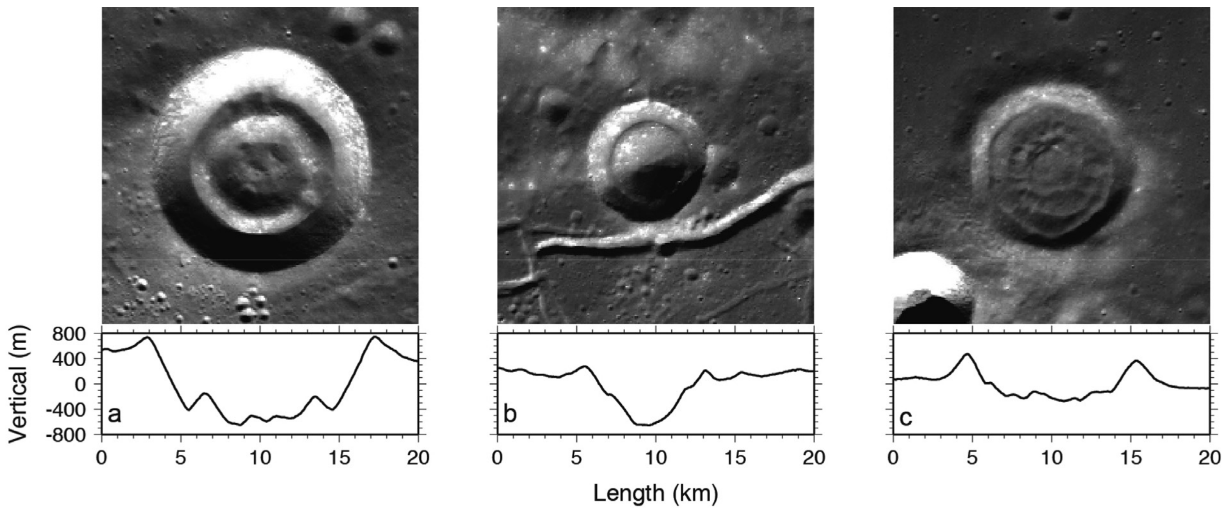

Fig. 1. The three concentric crater classes with a WAC image and a LOLA profile through the center of the crater from left to right (vertically exaggerated 4x) for each type. The LOLA length profiles are to scale with the WAC images. (a) Toroid (Hesiodus A-15 km crater, 17.1°W, 30.1°S) (b) Meniscus (Repsold A-8 km crater, 77.0°W,51.8°N) (c) Bulbous (Louville DA-10.4 km crater, 51.7°W, 46.6°N). The concentric ridge resides inside of the parent crater.

Table 1
Data sets used in this study.

Data sets spacecraft	Instrument	Use
Clementine	UV–vis	Examine concentric crater morphology
		Produce FeO and TiO_2 maps
LRO	LROC (WAC)	Examine concentric crater morphology
		Survey for concentric craters
		Measure crater and concentric ridge diameter
		Rank the degradation state of concentric craters
	LROC (NAC)	Examine concentric crater morphology
	LOLA	Measure crater depth, rim width and height, and concentric ridge height
Kaguya	TC	Examine concentric crater morphology
	MI	Examine concentric crater morphology

height, rim width, concentric ridge height, concentric ridge diameter) and dimensions of other crater classes (i.e., fresh, degraded, and floor-fractured craters). Next, we examined the spatial distribution of concentric craters and their proximity to major geologic terranes and other morphological features. FeO and TiO_2 abundances were measured to determine the composition of the concentric ridge. To determine the age of each concentric crater, we evaluated their crater degradation state. The degree to which various impact-related and endogenic mechanisms were able to replicate these properties was then assessed and used to determine the likely origin of concentric craters.

The origin of concentric craters is important to understanding lunar geologic processes. If concentric craters formed as a result of specific properties of the impactor and/or the target, then this study will provide an opportunity to expand and modify current cratering models. On the other hand, if concentric craters are products of a non-impact process, then this work will improve current understanding of processes occurring on the lunar surface and subsurface (e.g., Schultz, 1976a; Parmentier and Head, 1981; Forsberg-Taylor and Howard, 2004).

2. Methods

2.1. Data sets

Characterizing the properties of concentric craters require the use of several data sets from instruments on board the Clementine, Kaguya, and lunar reconnaissance orbiter (LRO) spacecrafts (Table 1). The only instrument that we used from the Clementine spacecraft is the UV–vis camera. All five bands (i.e., 415, 750, 900, 950, and 1000 nm) of the calibrated UV–vis data set at 100 m/pixel are available on the USGS (United States Geological Survey) Map-a-Planet website (http://astrogeology.usgs.gov/tools/map) (Eliason et al., 1999). We used the UV–vis data set to examine concentric crater morphology and determine their FeO and TiO_2 abundance.

LRO provides two instrumental data sets for this study, the lunar reconnaissance orbiter camera (LROC) and the lunar orbiter laser altimeter (LOLA). LROC consists of two instruments, the wide angle camera (WAC) and the narrow angle camera (NAC) (Robinson et al., 2010). A product of the WAC data set is a global morphologic map at 100 m/pixel. The morphologic map is composed of WAC images taken at incident angles of 60–80° to accentuate topography, such as concentric ridges. We used the WAC morphologic map to conduct a survey for concentric craters, examine their morphology, rank their degradation state, and measure crater dimensions. The NAC instruments primary role in this study is to allow us to examine concentric craters at high spatial resolutions (0.5 m/pixel), which is advantageous to making detailed morphological observations. The LROC data can be obtained at the LROC homepage (http://wms.lroc.asu.edu/lroc). The LOLA laser altimeter measures the elevation of the surface at five spots for each laser shot, which are distributed in an "X" pattern where each shot is separated by about 50 m and each spot is separated by about 10–12 m with an elevation precision of 0.1 m (Smith et al., 2010). We used the LOLA data set to measure crater dimensions. The LOLA data can be obtained from the Planetary Data Systems (http://ode.rsl.wustl.edu/moon/indextools.aspx).

In addition to the LROC data set, we employed the Kaguya Multiband Imager (MI), a multispectral instrument with a spatial resolution of 20 m/pixel (Ohtake et al., 2008) for 750-nm albedo