Icarus 274 (2016) 163–194

Contents lists available at ScienceDirect

Icarus

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

Polygonal impact craters on Dione: Evidence for tectonic structures outside the wispy terrain

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ARTICLE INFO

Article history:
Received 7 August 2015
Revised 24 February 2016
Accepted 20 March 2016
Available online 1 April 2016

Keywords:
Saturn, satellites
Cratering
Tectonics
Impact processes

ABSTRACT

Plan-view impact crater geometries can be indicative of pre-impact structures within the target material. Impact events that occur on a pre-fractured surface generate craters exhibiting one or more straight rim segments, termed polygonal impact craters (PICs). Impact craters that appear to be PICs are abundant on the surface of Saturn's icy satellite, Dione, both within the wispy terrain, a region with large visible fractures, and also outside the wispy terrain (the 'non-wispy terrain'), where less evidence for fracturing has been observed. In the non-wispy terrain, subtle lineaments are hypothesized to be NE–SW, NW–SE, and E–W trending fractures, suggesting that tectonism may have been an important process in this terrain.

Results of previous studies have shown that PIC straight rim segment azimuths ('PIC azimuths') commonly parallel pre-impact fracture azimuths, although disagreements about this relationship exist in the literature. We investigated the hypothesis that fractures, either subtle or nonvisible with available spacecraft images, are present within Dione's non-wispy terrain. Our first step was to assess the relationship between PICs and pre-existing fracture azimuths in the wispy terrain. Our results from this initial assessment show a parallel relationship between PIC azimuths and fracture azimuths. Based on this correlation in the wispy terrain, we find it likely that this relationship would hold true in the non-wispy terrain if PICs are present.

We tested for PICs using crater rim azimuth data collected from randomly distributed study locations throughout the non-wispy terrain. From these data, we identified widespread PICs in this terrain, which supports the hypothesis that subtle fractures are also present. Analysis of the PIC azimuth data yield a pattern for these inferred fractures across Dione's surface that is consistent with the hypothesized global deformation that would result from a combination of satellite despinning and volume expansion. Our results provide evidence for these previously hypothesized events in Dione's history and demonstrate that mapping PICs and their azimuths is a useful tool for investigating subtle fractures on Solar System bodies.

1. Introduction

Impact craters commonly exhibit circular plan-view geometries (Fig. 1a), and are inferred to result from impact events in homogenous target material (e.g., Melosh, 1989). However, where pre-existing fractures exist in the target material, impact craters commonly exhibit plan-view geometries with straight rim segments, creating polygonal plan-view geometries (Fig. 1b) (e.g., Fielder, 1961a, 1961b; Kopal, 1966; Shoemaker, 1962, 1963; Roddy, 1978; Öhman et al., 2005, 2008). Whereas other types of impact crater morphologies, including those with non-circular plan view geometries, are caused by various conditions other than pre-existing fractures, the only known cause for the formation of polygonal impact craters (PICs) is the influence of pre-existing sub-vertical structures within the target material (e.g., Öhman, 2009). These structures include faults, joint sets, and lithologic boundaries (e.g., Fielder, 1965; Eppler et al., 1983; Öhman et al., 2005,2008; Öhman, 2009; Aittola et al., 2010). For simplicity, we refer to these sub-vertical structures as fractures.

Fractures that affect crater geometries may not always be visible on the surface of a planetary body, and PICs may reveal the presence of these fractures (e.g., Eppler et al., 1983; Öhman et al., 2005). Consequently, these circular impact craters (CICs) (Fig. 2a,b) and PICs (Fig. 2c,d) may be useful tools to distinguish between homogenous and tectonized terrains on the

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http://dx.doi.org/10.1016/j.icarus.2016.03.020
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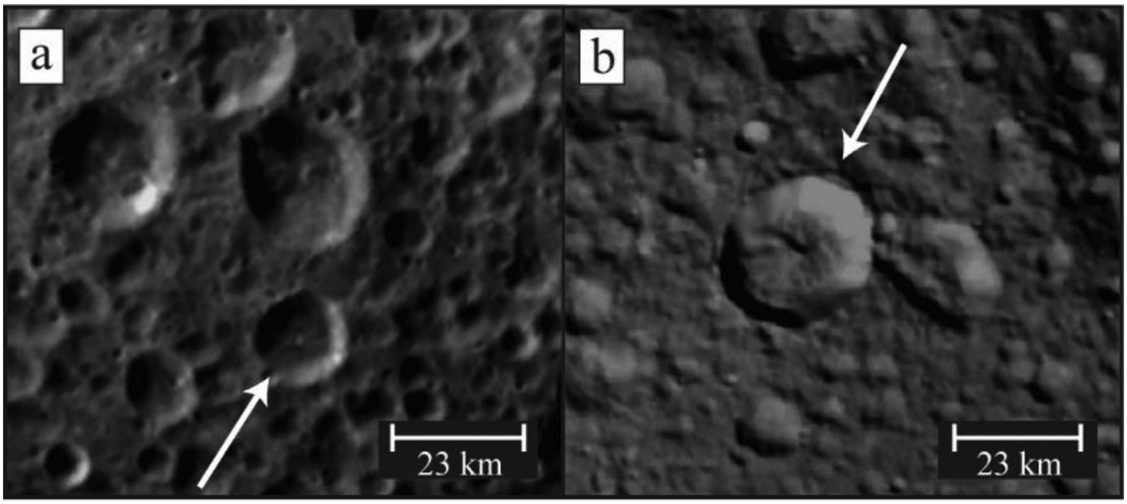

Fig. 1. Cassini ISS images of craters with different plan-view geometries. (a) Cassini image N1662197108_1 of a circular impact crater (CIC) in Dione's non-wispy terrain. (b) Cassini image N1507741460 of a polygonal impact crater (PIC) in Dione's non-wispy terrain. PICs exhibit straight rim segments (see Fig. 2).

surfaces of planetary bodies. In this work, we define a PIC as any impact crater that has at least one straight rim segment. Our definition differs from that given in other studies, in which, for example, a PIC has been defined as a crater with at least two adjacent straight rim segments with an angle between them (e.g., Öhman, 2009). Because even a single straight rim segment can reflect a controlling fracture, we use this more general definition to capture more completely the possible presence of fractures. Thus, our results may be more inclusive than those of other studies. However, when we compared our results to those of previous studies (Section 5), we reanalyzed our data to conform to this definition given by others.

Multiple PIC formation models predict that azimuths of PIC straight rim segments, which we term 'PIC azimuths', parallel surrounding target fracture azimuths (Eppler et al., 1983; Kumar and Kring, 2008; Poelchau et al., 2008,2009; Öhman, 2009). This relationship is agreed upon in the literature for complex PICs, although not for simple PICs (Eppler et al., 1983; Kumar and Kring, 2008). One of the three proposed PIC formation models for simple craters predicts a 45° offset between PIC azimuths and controlling fracture azimuths (Eppler et al., 1983; Poelchau et al., 2009). However, more recent studies show that evidence supports a parallel PIC-fracture azimuth relationship (Kumar and Kring, 2008; Öhman et al., 2008). In support of this parallel relationship, simple and complex PIC azimuths have been found to be indistinguishable in the same study areas (Öhman et al., 2008), contradicting findings by Eppler et al. (1983).

Both CICs and PICs are widespread throughout the Solar System, existing on both rocky and icy planetary bodies (e.g., Öhman, 2009). On Saturn's icy satellite, Dione, apparent CICs (Fig. 1a) and PICs (Fig. 1b) are visible in both Voyager Imaging Science Subsystem (ISS) images (Plescia, 1983; Moore, 1984) and Cassini ISS images, and those appearing to be PICs seem to be widespread across the satellite. Dione's surface also exhibits a region of heavily tectonized terrain, termed the wispy terrain (Fig. 3a) (Plescia, 1983; Moore, 1984), and less discernibly tectonized terrain elsewhere, which we term the 'non-wispy terrain' (Fig. 3b). Evidence for tectonism within Dione's non-wispy terrain is ambiguous, although subtle features termed 'lineaments' have been identified and are hypothesized to be subtle fractures (Moore, 1984). If these lineaments are fractures, then they may provide insight into Dione's tectonic and orbital history. We further examine the interpretation of the non-wispy terrain lineaments as fractures by investigating the presence of PICs within this region.

2. Background

2.1. Impact processes and controls on morphology

An impact event is a complex process that can be divided into a contact and compression stage, an excavation stage, and a modification stage (e.g., Gault et al., 1968). During the contact and compression stage, a compressional shock wave is produced, and during the excavation stage, a tensile, rarefaction wave forms in response to the compressional shock wave passing through the free surface of the trailing end of the projectile. A resulting excavation flow of material creates a transient crater and ejecta (e.g., Shoemaker, 1960; Dence, 1968; Gault et al., 1968; Grieve, 1987; Melosh, 1989; French, 1998), and can lead to the formation of nearby secondary impact craters (e.g., Roberts, 1964), characterized by their small sizes, irregular plan view geometries, shallow floors, and occurrences in chains and clusters (e.g., Shoemaker, 1962; Oberbeck and Morrison, 1973). During the modification stage, little collapse of the crater rim takes place for simple craters, whereas complex craters form central uplift structures and terraces along the rim (Gault et al., 1968).

Differences in properties of both the impactor and target material affect the resulting impact crater morphology. As summarized in De Pater and Lissauer (2010), for a given impactor and impact velocity, the diameter of an impact crater will be larger on planets and satellites with low gravity and low target material density, such as Dione. Higher velocity impacts will form craters with larger diameters, as will an increase in density or size of the impactor. Impact crater geometries also depend on the angle of impact (e.g., Herrick and Forsberg-Taylor, 2003), whether or not impacts are clustered (e.g., O'Keefe and Ahrens, 1982; Schultz and Gault, 1985a; Cochrane and Ghail, 2006), projectile shape (Schultz and Gault, 1985b,1986), topography of the target area (e.g., Gifford and Maxwell, 1979), layering of the target material (Quaide and Oberbeck, 1968), erosion (Ronca and Salisbury, 1966), post-impact tectonic modification (e.g., Pappalardo and Collins, 2005; Watters and Johnson, 2010), and the presence of pre-existing sub-vertical structures within the target material (e.g., Eppler et al., 1983; Poelchau et al., 2009).

While many variables affect the resulting morphologies of impact craters, PICs only form when pre-existing sub-vertical structures are present within the target material (e.g., Schultz, 1976; Öhman, 2009). These sub-vertical structures include normal, thrust, and strike-slip faults, joint sets, and lithologic boundaries