Icarus 247 (2015) 260–278

Contents lists available at ScienceDirect

Icarus

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

Using martian single and double layered ejecta craters to probe subsurface stratigraphy

Eriita Jones [a,b,*], Gordon R. Osinski [a,b,c]

[a] Centre for Planetary Science and Exploration, University of Western Ontario, London, ON N6A 5B7, Canada
[b] Dept. of Earth Sciences, University of Western Ontario, London, ON N6A 5B7, Canada
[c] Dept. of Physics and Astronomy, University of Western Ontario, London, ON N6A 5B7, Canada

ARTICLE INFO

Article history:
Received 10 January 2014
Revised 7 October 2014
Accepted 9 October 2014
Available online 19 October 2014

Keywords:
Mars
Impact processes
Cratering
Mars, surface

ABSTRACT

Martian craters with fluidized ejecta – including single-layered, double-layered and multiple-layered craters – have been studied extensively, with their formation generally suggested to require some presence of volatiles in the subsurface. However, experimental reproduction of these morphologies, impact modelling, and the occurrence of layered ejecta in putative volatile poor regions suggests that other factors may also play important roles. A recent extensive catalogue of martian impact craters (Robbins, S.J., Hynek, B.M. [2012a]. J. Geophys. Res. 117, E05004) classifies crater ejecta along with their location, diameters and ejecta extents, potentially providing new information on the links between these morphologies and the subsurface. We utilise this catalogue to examine the regional variation in ejecta mobility, onset diameter and the correlation between ejecta mobility and diameter for single- and double-layered ejecta craters on Mars. A simple regional stratigraphic model is developed to explain the observed trends through the viscosity of the layers within the target. Using this model, the potential relative thickness and burial depths of low viscosity layers in the martian subsurface are hypothesised, and compared to other observations and models of subsurface volatiles and how they have varied throughout time.

1. Introduction

Layered ejecta craters are an extremely prevalent morphology on the martian surface, comprising a large fraction of the craters with observable ejecta (Barlow, 2005a; Robbins and Hynek, 2012a). These craters have a distinct morphology that is not observed on the Moon; however, they do appear on other Solar System bodies such as Ganymede (Boyce et al., 2010) and potentially on Earth (Osinski et al., 2011). They display a continuous, often lobate, ejecta blanket that appears to have been emplaced on the surface as a ground-hugging fluidized flow (Gault and Greeley, 1978; Mouginis-Mark, 1979), rather than through purely ballistic emplacement. Early names for these craters included rampart craters for the observed elevated terminus at many of their ejecta blankets (McCauley, 1973); and type 1 and type 2 craters, referring to one and two continuous ejecta layers respectively (Carr et al., 1977; Mouginis-Mark, 1979). More recently, three types of fluidized ejecta impact craters have been proposed (Barlow et al., 2000), classified on the basis of their appearance in Viking Orbiter imagery. Single layered ejecta craters (SLEs) are defined as having a single continuous fluidized layer of ejecta, with double layered ejecta craters (DLEs) displaying two and multi-layered ejecta (MLE) craters more than two layers. The classic ballistic rayed ejecta pattern observed on the Moon is also observed on Mars, and is classified as radial ejecta (Barlow et al., 2000). Since their discovery, fluidized ejecta morphologies have been used in the search for subsurface volatiles (e.g., Kuzmin et al., 1988; Mouginis-Mark, 1981). Despite many indicators of the role of volatiles in the emplacement of layered ejecta and morphological similarities with those produced by laboratory and numerical simulation experiments involving water ice (e.g., Baloga et al., 2005), there is as yet only indirect evidence that water ice or liquid water was necessarily involved in their formation. Understanding the potential connections between layered ejecta craters and subsurface volatiles is, therefore, of high importance, particularly given the astrobiological implications of locating subsurface water ice below the seasonal melting isotherm (Jones et al., 2011). If some subset of the diverse population of layered ejecta craters are tracers of subsurface water, they could be utilised to identify environments that may be have been hospitable in the martian past, or may still be hospitable if volatiles persist at depth (Cockell, 2002).

Considerable variation is observed within the SLE and DLE crater populations – for example, in the mobility of their ejecta, the

* Corresponding author at: Centre for Planetary Science and Exploration, University of Western Ontario, London, ON N6A 5B7, Canada.

http://dx.doi.org/10.1016/j.icarus.2014.10.016
0019-1035/

lobateness of the ejecta blanket, the topography of their ejecta layers and morphology of their rampart, and their preservation state (Fig. 1). Furthermore, several sub-populations have been recognised, including low-aspect-ratio layered ejecta craters (LARLE) (Barlow and Boyce, 2012, 2013) and excess ejecta craters (EEC) (Black and Stewart, 2008). Perched craters (Pr) (Boyce et al., 2005; Garvin et al., 2000) and pedestal craters (Pd) (Barlow, 2006; Kadish et al., 2009) have also been identified as potential erosional end-members of some layered craters in icy terrains where significant volumes of material have been removed (Kadish et al., 2009; Meresse et al., 2006).

The significant heterogeneity within each type of fluidized crater morphology is not fully understood and is difficult to explain through any single formation model. Formation models typically attempt to broadly unify the formation of these craters through either (i) requiring significant volatiles, with the morphologies arising from impacts into a volatile rich substrate – varying volatile content then results in some heterogeneity in ejecta mobility, lobateness, etc. (Gault and Greeley, 1978; Mouginis-Mark, 1979); or (ii) not requiring significant volatiles, with the morphologies arising from the interaction of the ballistic ejecta cloud with the martian atmosphere – heterogeneity then arises from variation in particle size, cohesion, atmospheric pressure, and possibly some small incorporation of volatiles from the subsurface and/or atmosphere (Barnouin-Jha et al., 2005; Schultz, 1992). The competing roles of atmosphere, melt content, and volatile-rich vapour plumes in the ejecta emplacement process are debated within these two broad schemes (Komatsu et al., 2007).

In reality, it is not unreasonable that to account for the significant variety of layered ejecta craters both volatile rich and volatile poor processes may play an important role. Consistent with this, observations of craters on Earth indicate that variations in particle size and particle cohesion within the target, as well as melt content (Osinski, 2006; Osinski et al., 2011), play an important role in how ejecta is emplaced on the surface and in the observed final crater properties. The apparent correlation of layered ejecta craters on Mars with recent ice deposition and stability (Barlow et al., 2001; Demura and Kurita, 1998) – through the latitudinal dependence of crater occurrence, onset diameter and ejecta mobility – as well as the presence of fluidized morphologies on Ganymede (Boyce et al., 2010), provides the strongest evidence that volatiles frequently play a role in these morphologies. Nonetheless, the occurrence of fluidized morphologies on lava flows and in thick, dusty deposits suggests that they can occur in putative volatile poor regions and that other target properties are also significant factors.

Table 1
% Agreement between ejecta classifications.

Region	# Craters examined	Robbins classification	
		SLE	DLE
Utopia Planitia	630	78.5	80.0
Hesperia Planum	222	84.0	77.8
Noachis Terra	211	91.2	87.3

Craters with more than one fluidized layer of ejecta are typically thought to originate from a multi-layered target, as a result of a gradient in volatile content and/or particle size distribution (Boyce and Mouginis-Mark, 2006; Horner and Greeley, 1981; Stewart and Valiant, 2006; Weiss and Head, 2013; Wulf et al., 2013). Both impact modelling (Collins et al., 2002; Senft and Stewart, 2008) and observations of terrestrial craters (Osinski et al., 2011) demonstrate that variations in target stratigraphy result in significant and measureable effects on the resulting final crater, particularly in the maximum runout distance of ejecta, the topographic profile of the ejecta blanket, the crater depth, and the size of the central uplift. Furthermore, distinct ejecta layers may originate from different subsurface depths, as observed at the Haughton and Ries impact structures on Earth (Osinski, 2004; Osinski et al., 2005).

Given the above discussions, the emplacement of ejecta surrounding martian craters is potentially strongly sensitive to subsurface stratigraphy, and can be used to probe layer thickness, volatile content, particle size and cohesion of the top ~100s of metres to kilometres of the martian subsurface. In particular, ejecta mobility – the runout distance of ejecta scaled to the crater size (Mouginis-Mark, 1979) – is expected to be dominated by the viscosity of the subsurface materials excavated, with highly mobile and therefore low viscosity ejecta resulting from either a high volatile content and/or fine grained ejecta (Barlow and Boyce, 2013; Barlow, 2004; Costard, 1989; Gault and Greeley, 1978; Osinski

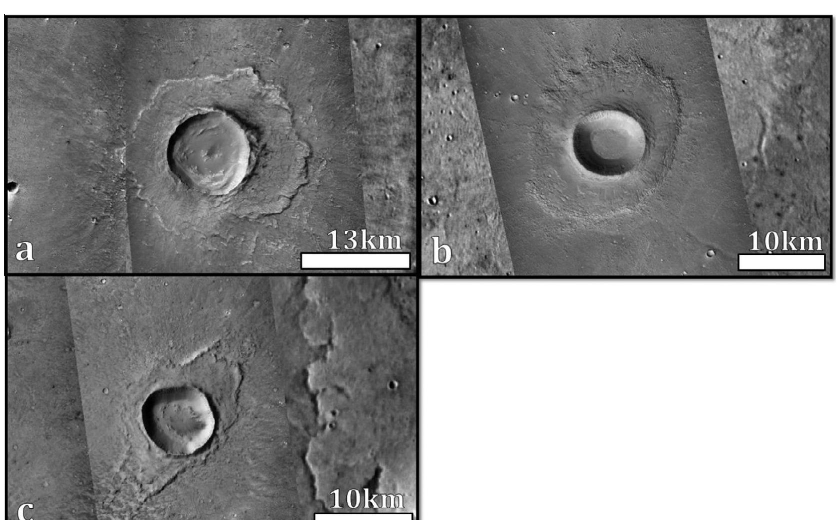

Fig. 1. Variations in single layered ejecta craters, seen in the MRO Context Camera (CTX). Images are superimposed on the THEMIS daytime-IR mosaic. (a) Belz crater, Chryse Planitia (316.8E, 21.6), B19_016909_2009_XN_20N043W; (b) crater in Utopia Planitia (114.2E, 31.8), P12_005814_2120_XI_32N245W; (c) crater in Elysium Planitia (155.0E, 13.1), B01_009913_1922_XN_12N204W. Image credits: CTX, NASA/JPL/Malin Space Science Systems.