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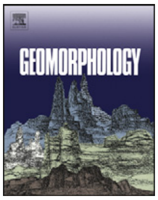

Morphology of the Morasko crater field (western Poland): Influences of pre-impact topography, meteoroid impact processes, and post-impact alterations

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ABSTRACT

Small impact craters (<1 km) developed in unconsolidated sediments are expected to be relatively common on Earth; however, only a few tens of them have been documented thus far. Among the reasons for this small number of documented craters are the post-impact erosion and sedimentation processes that modify craters and the lack of universal identification criteria to allow the differentiation of impact structures from landforms of other origins. Here, we focus on the well-preserved impact craters on the Morasko Hill push moraine in western Poland. These craters were formed by iron meteoroid impacts in unconsolidated sediments of glacial and fluvial origins ca. 5000–6000 years ago. We provide a new high-resolution topographic model of the crater field to identify the influences of the pre-impact topography, impact processes, and post-impact modifications on the final morphology of the craters. The topographic model obtained from airborne LiDAR data and total station surveying consists of DEMs related to the recent and reconstructed pre-impact topographies. Parameterization of recent topography in terms of slope gradients, slope curvatures, and roughness allowed us to delimit the boundaries of the craters and to calculate their Feret diameters, ellipticities, slope gradients, crater depths, and volumes. The novelty of our study lies in the estimation of the last two parameters based on the reconstructed pre-impact topography and modelled paraboloids related to each crater. The obtained results show that the studied craters are circular, bowl-shaped features displaying different cross-sectional asymmetries that resulted from the interplay between the trajectories of the bombarding projectiles and the topographies of the primary pre-impact glacial and post-glacial landforms. The oblique impacts likely influenced the asymmetric distribution of ejecta during the excavation of the craters and are considered as factors conditioning mass movements during the post-impact modification of the craters. The compilation of the existing data on terrestrial small-impact craters reveals that they are susceptible to post-impact geometry modification (shallowing and widening) and that many craters have depth/diameter ratios lower than are typical for simple impact craters.

1. Introduction

The observations of numerous craters on the surfaces of the Moon, Mars, and other bodies indicate that impact cratering is probably one of the most common geological processes in the Solar System. However, the detail studies of this process have been conducted relatively late, as summarised for instance in review works by Melosh (1989) and Osinski and Pierazzo (2013). On Earth, only 190 impact structures have been verified thus far, as listed in the Earth Impact Database (2017). The majority of these structures are large (mostly 1 to 160 km in diameter) and old impact structures in hard rock substrates. However, impacts of extra-terrestrial hypervelocity bodies capable of forming smaller craters are expected to be much more frequent (French, 1998). Hergarten and Kenkmann (2015) presented analysis based on the Near Earth Object (NEO) population, the Lunar crater size frequency distribution, and the mean erosion rate on Earth and estimated that 200–300 impact craters are still to be discovered on Earth and that the missing craters should be small. Bland and Artemieva (2006) assessed the frequency of impacts on Earth's land area by iron bodies of several metres in diameter, which form craters of ca. 0.1 km in diameter, to be at least 1/500 years. Thus, one expects small impact craters on Earth to be relatively common. However, only 16 impact structures < 0.3 km in diameter are listed in the mentioned Earth Impact Database (2017). The reasons for this small number of impact structures include erosion and sedimentation processes that mask the crater forms as well as the difficulties in the identification of impact craters from landforms of different origins, particularly in the cases of impacts in unconsolidated sediments (French and Koeberl, 2010). For instance, in areas glaciated during the Pleistocene, at least two types of landforms are known to be similar to

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rimmed and circular impact craters. Kettle holes result from melting of glacial dead-ice, and depressions originate from thermokarst periglacial processes related to pingo degradation (e.g., Evans, 2009; van Vliet-Lanoë et al., 2016).

Small impact craters are bowl-shaped depressions surrounded by uplifted rims and are called simple craters. Simple craters typically have a depth/diameter ratio of 1:5 to 1:7 (Melosh, 1989). The forms of the small impact structures may also be affected by the pre-impact topography (e.g., Kenkmann et al., 2009), modification stage during crater formation, and post-impact processes (e.g., Gnos et al., 2013). The influence of the pre-impact topography on crater geometry has rarely been studied but appears to be significant (Aschauer and Kenkmann, 2017). For instance, the important role of the pre-impact topography was shown in studies of craters on Vesta, where numerous craters formed on the slopes that locally exceeded 40° (Jaumann et al., 2012; Krohn et al., 2014a). It cannot be excluded that this factor, which interacts with impact trajectory and impact energy, can influence not only the shape but also the size of the developing craters (Elbeshausen and Wünnemann, 2011). This may have important implications because the crater size is the key variable used in crater modelling experiments (e.g., Wünnemann and Ivanov, 2003; Bronikowska et al., 2017). Moreover, the detailed recognition of these interactions allows us to improve the understanding of impact processes and also, to some extent, post-impact changes. The spatiotemporal scale and nature of post-impact changes of terrestrial small craters developed in unconsolidated sediments have been discussed in very few works (e.g., Kenkmann et al., 2009). Most studies focused on impact craters that developed in flat-lying, hard rock substrates and show the post-impact changes in terms of the lowering of the crater rims, the degradation of internal crater slopes, and the filling and flattening of crater floors by fluvial, aeolian, and mass wasting processes (Grant, 1999; Komatsu et al., 2014).

Although, several terrestrial small impact craters have been relatively well studied (e.g., Carancas, Kaali, Whitecourt, Kamil, and Odessa), a detailed morphometric analysis by means of digital terrain modelling has seldom been presented (e.g., Zanetti et al., 2015). Moreover, among the terrestrial small impact craters, only a few were formed in unconsolidated sediments, which are considered the most common target not only on Earth but also on other planets and moons covered by regolith. The Morasko crater field in western Poland, being the object of the present work, is exceptional, as it is relatively well preserved, taking into account its age of ~5 to 6 ka; and it was formed in unconsolidated sediments of glacial and fluvial origins forming a moraine that exhibits a hummocky topography (Stankowski, 2001).

Morasko, a contemporary part of the city of Poznań, is the region with the largest known iron meteorite shower in Central Europe (Muszyński et al., 2012a). The first piece of iron meteorite was found in the area in 1914. However, this and the following findings were not considered to be related to the nearby depressions with diameters of several tens of metres until Pokrzywnicki (1964) suggested that the fall of the Morasko iron meteorites could have resulted in the formation of at least eight impact craters. This view has been debated for a long time, and an alternative glacigenic origin of these depressions owing to the melting of dead-ice blocks was also considered (Karczewski, 1976). The craters were formed in soft, mainly glacigenic sediments in an area of complex glacial topography, formed during the retreat of the last ice-sheet from this area at ~18,000 years ago. However, later findings proved the age of the crater infills to be ~5000–6000 y BP and, as such, much younger than the last glaciation (Tobolski, 1976; Stankowski, 2001, 2008). Moreover, an ejecta blanket covering paleosols of the same age as the oldest crater infill was recently identified around the craters (Szczuciński et al., 2016). Many additional mineralogical, geochemical, and geochronological studies have provided much data to support the impact nature of the crater field (Stankowski, 2008; Muszyński et al., 2012b). Recently, Bronikowska et al. (2017) combined atmospheric entry modelling, π-group scaling of transient crater size, and hydrocode simulations of impact processes in order to model the Morasko strewn field formation. They used the Morasko crater diameters and distribution as ground truth data. According to their modelling, the most likely entry mass of the meteoroid was between 600 and 1100 tons, the velocity range was between 16 and 18 km s^{-1}, and the trajectory angle 30–43°. The meteoroid was likely subjected to atmospheric breakup, resulting in formation of a strewn field. Bronikowska et al. (2017) suggested that the biggest Morasko crater was likely formed by a projectile 1.5 m in diameter with an impact velocity of ~10 km s^{-1}.

The previous morphometric studies on the Morasko craters were initiated by Pokrzywnicki (1964), who presented the first documentation of the crater morphologies and provided their basic dimensions. Later, several standard hypsometric maps of the crater field were made, including that presented by Karczewski (1976). However, no detailed high-resolution modelling of the topography or geomorphological analysis has been performed.

The objectives of the present study are to provide a new high-resolution topographic model of the Morasko crater field where small impact craters formed in unconsolidated sediments and to apply the obtained model in an attempt to identify the influences of pre-impact topography, impact processes, and post-impact modifications on the final morphology of craters.

2. Study area

The study area is located in the northern part of the Morasko Hill push moraine (Fig. 1), marking a major retreat phase of the last glaciation, i.e., the so-called Poznań Phase, ca. 18,500 y BP (Kozarski, 1995). The primary topography of this moraine resulted from glaciotectonic deformation produced during the Vistulian and probably the Saalian glaciations (Karczewski, 1976; Stankowski, 2001). Most of the sediments affected by the glaciotectonic deformation are Quaternary glacial tills, sands, and gravels and Neogene clays, silts, and sands. The maximum elevation of the Morasko Hill push moraine is 153.8 m asl, whereas the topography of the sandur plain extending to the SE varies between 85 and 105 m asl. The minor geomorphologic features are ice-marginal landforms, including small-scale ridges and undrained depressions of evorsive and dead-ice melting origin. The small-scale ridges probably originated through the decay of ice-cored moraines (Ewertowski and Rzeszewski, 2006). In the southern part of the Morasko Hill, these landforms are well-developed, elongated, and linear topographic features oriented ENE-WSW. More irregularly shaped and shorter small-scale ridges tend to form a few lobe-shaped belts in the northern part of the Morasko Hill. These landforms are mainly composed of Vistulian glacial sands and gravels. The glacial landforms were subjected to erosion by small intermittent streams during the post-glacial and Holocene periods and formed the currently dry and small valleys. Some of these valleys are interpreted as beaded valleys (Fleisher, 1986), wherein the wide segments alternate with narrow ones. The wide segments are remnants of depressions produced by dead-ice melting, which were partially reworked by the erosion of intermittent streams.

The impact craters were formed before 5000 y BP, as indicated by the radiometric ^{14}C dating of the oldest organic strata filling the craters (Stankowski, 2001). This age is also consistent with the palynological data, which indicate the beginning of organic sedimentation during the middle Atlantic period, between ~5500 and 5000 y BP (Tobolski, 1976). Moreover, the thermoluminescence dating of the melting-weathering crust produced by the impact processes gives similar ages of 4700–6100 y BP (Stankowski, 2008). The maximum age of the impact, 5000–6400 y BP, is provided by the age of paleosols buried underneath the impact ejecta layer (Szczuciński et al., 2016).

3. Methodology

The present study was performed using digital terrain modelling, starting with processing the digital elevation model (DEM) through