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Holocene impact craters on Earth

Abstract

Impact craters are formed by collisions of cosmic bodies moving with hypervelocity. The formation of these features is not restricted to the distant geological past; new structures are constantly being created and at least 13 confirmed impact craters and crater fields have formed during the Holocene alone. This short review paper: (1) introduces the basics of the impact cratering process to physical geographers and Quaternary geologists; (2) provides a short description of representative examples of such features (Morasko, Kaali, Kamil, Ilumetsa); and (3) discusses the similarities and differences among very small craters, and contrasts these with larger impact structures. This manuscript may be useful to researchers planning to test whether a small Quaternary depression in the ground may be of impact origin.

Keywords

Impact crater • asteroid • planetary protection • Morasko, Kaali • Holocene

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Introduction

Impact craters are formed by collisions of cosmic bodies moving with hypervelocity. Their formation is one of the most crucial geological processes that shapes surfaces of all solid planetary bodies in our Solar System and beyond (Melosh 1989), but the importance of this started to be recognized only within the last 70 years. Suggestions of the extraterrestrial origin of some of the round, rimmed structures on the surface of the Earth were first proposed at the beginning of the 20th century (e.g., Barringer crater in the USA recognized by Barringer in 1909, Kaali in Estonia recognized by Reinvaldt in 1933), usually due to spatial association with iron meteorites. However, most geologists either did not pay much attention to this process, or clearly misunderstood the impact mechanism (Barringer 1909). Only after World War II did this start to change. First, the similarities between atomic bomb craters and the Barringer crater in Arizona were discovered (Chao et al. 1960). Then, thanks to the data collected during Apollo missions, it was commonly recognized that most craters on the surface of the Moon were formed by cosmic collisions. As a result, the geological specialty of impact cratering was born. Over the following decades, it remained a rather obscure topic until it was shown that the last great extinction was caused by the impact of a large asteroid and resulted in the formation of Chicxulub crater and the end of the dinosaur era (Alvarez et al. 1980, Hildebrand et al. 1991). Another rejuvenation of the impact cratering research community came from the collision of the ~4-km-in-diameter Shoemaker Levy 9 comet with Jupiter in July 1994, which was observed live on TV by astronomers and the public. This event not only resulted in two major Hollywood movies about asteroids hitting Earth being released in 1998 (Armageddon and Deep Impact), but also in the large-scale development of planetary protection programs such as CNEOS by NASA (CNEOS 2023).

Currently, those projects efficiently trace asteroids larger than 1 km in diameter that may bring a global or at least regional disaster (CNEOS 2023). While there is currently no known asteroid that could cause such catastrophic damage, it is probable that a populated area will be hit by a significant asteroid impact within the lifespan of our species, based on the current impact flux on Earth (Bland & Artemieva 2006). In the next few hundred years, the most likely hazard comes from small bodies with diameters ranging from 20 to 50 meters, which are large enough to form an impact crater several hundred meters in diameter upon reaching Earth's surface.

Potentially dangerous events caused by collisions with small asteroids happen every couple of decades. The explosion over Podkamennaya Tunguska River in 1908 flattened thousands of square kilometers of Siberian forest (Florenskiy 1963). In 1947 the formation of Sikhote Alin crater field (Krinov 1971) supposedly caused a nuclear-war scare. A couple of recent collisions with asteroids were not predicted by planetary protection programs: Carancas crater in 2007 (Tancredi et al. 2009), Chelyabinsk meteor in 2013 (Popowa et al. 2013), and the Kamchatka event in 2018 (Gordeev et al. 2019). Encounters with even relatively small objects can have serious consequences; for example, the explosion of the Chelyabinsk asteroid, which was initially 20 m in diameter, over a Siberian city in 2013 injured more than 1,500 people (Popowa et al. 2013).

The aim of this paper is to review the relevance of the formation of impact craters in Quaternary geology, to describe examples of very small Holocene impact craters on Earth, and to contrast very small craters with much larger structures.

Basics of the impact cratering process

An impact crater is formed when the surface of a rigid planetary body is hit by another body with a relative velocity greater than the speed of sound in the target rock (Melosh 1989, French & Koeberl 2010, Osinski et al. 2022). During collision, the kinetic energy of the moving object is transformed into a shock wave (an almost discontinuous change in characteristic of the medium). As a result, the impactor and a portion of target rocks are transformed in a high pressure and temperature regime (melted, vaporized, shock metamorphosed, fragmented) and later moved to create an impact crater. Normally, the diameter of the resulting crater is 15 to 20 times larger than the asteroid that made it. The minimal velocity required to form a crater within unconsolidated sediments is >1 km/s (Schmalen et al. 2022). If a meteoroid slows down from its initial velocity in space (for Earth, on average ~20 km/s) to the terminal velocity (300–600 m/s) due to its interaction with an atmosphere, no craters are formed, and a meteorite may be found within a small terminal pit. If a single asteroid is fragmented during the atmospheric passage, but some of the individual fragments preserve enough velocity, numerous impact craters are formed at the same time – this is called a strewn field (e.g., Morasko in Poland: Szokaluk et al. 2019, Figure 1).

Holocene craters catalog

Currently, about 200 impact sites on the surface of Earth are known (Osinski et al. 2022), about 30 of them were most probably formed during Quaternary, and 11 of them are of confirmed Holocene age (Beauford 2015, Schmieder & Kring 2020), including two cases that were witnessed: Carancas in 2007 (Tancredi et al. 2009) and Sikhote Alin in 1947 (Krinov 1971). Holocene craters vary in size between 15 meters in diameter for Carancas in Peru (Tancredi et al. 2009), and up to 157 meters in diameter for the largest crater in Henbury (Milton 1968). Out of 11 confirmed Holocene craters, five are single crater structures (e.g., Kamil in Egypt), and six are strewn fields (e.g., Kaali in Estonia). In addition to the confirmed Holocene craters, Table 1 also includes two structures (Dalgaranga and Veevers, both in Australia: Shoemaker et al. 2005) whose dates have not been properly determined; their age, based on morphological freshness, is estimated to be no older than late Pleistocene. Additionally, there are two structures (Ilumetsa in Estonia: Plado 2012, Losiak et al. 2020 and Sobolev in Russia: Khryanina 1981) that have not been confirmed as impact craters because of the lack of meteorites associated with them but were likely formed by an asteroid impact. Below we present a more detailed description of four very small impact craters, which are representative.

Morasko, Poland

Morasko is a strewn field located in central Poland (Szokaluk et al. 2019). It consists of seven recognized impact craters. The largest is 96 meters in diameter and about 12 meters in depth, and the smallest is about 30 meters in diameter (Wlodarski et al. 2017). Before entering the Earth's atmosphere, the impactor weighed between 600 and 1100 tons (which corresponds to an asteroid of up to ~6 m in diameter); it moved with a velocity of 16–18 km/s and hit at an angle of 30–40° (Bronikowska et al. 2017). The Morasko meteorite associated with the craters belongs to the iron IAB group (Muszynski et al. 2012). The asteroid hit an edge of glaci-tectonically deformed terminal moraine from the Poznan phase (~18,500 years ago, the Frankfurt phase) of the last glaciation. The target rocks consist of Neogene clays in the base, and a couple of meters of glacial till overlaid by glacial and fluvioglacial sands; however, the distribution and thickness of those constituents is variable and patchy. The continuous ejecta

Figure 1. Distribution of ~200 impact craters on Earth. Black circles indicate the location of Holocene structures: black circles with a small white circle inside show the location of craters whose formation was witnessed (Carancas and Sikhote Alin). Black circles with a white rectangle inside show the location of craters where shock metamorphic features were found (Kamil and Wabar). Fully black circles show the location of structures whose impact origin was confirmed solely by an association with meteorites. Black circles with a gray circle inside show the location of probable, but not confirmed, impact craters – ones that are not associated with known meteorites (Ilumetsa and Sobolev). The location of all other impact craters is shown using white circles
Source: own study based on Schmieder & Kring 2020, and articles listed in Table 1.

Table 1. A list of Holocene impact craters sorted by the diameter of the largest structure. The list does not include features: (1) older than 10 ka (e.g., Douglas: Kenkmann et al. 2018); (2) terminal pits (e.g., Sterlitamak: Petaev 1992); (3) not confirmed yet by commonly accepted recognition criteria, described by French & Koeberl (2010). The list includes two structures (Ilumetsa and Sobolev) that are not associated with any identified meteorite fragments (so they are not officially confirmed) but circumstantial evidence suggests they were formed by an impact. The list also contains two confirmed craters (Dalgaranga and Veevers) whose age has only been estimated to be a couple of thousand years based on their morphology. Source: own study based on literature research – especially sources listed in the table.

Crater Parameters							**References**
Crater	**Country**	**Coordinates**	**Diameter of the largest crater [m]**	**Age**	**Impactor type**	**No. craters**	
Carancas	Peru	16° 39’ 52” S; 69° 2’ 39” W	14	2007 AD	H4-5	1	Tancredi et al. 2009
Haviland	USA	37° 34’ 57” N; 99° 9’ 50” W	15	0.2 ka	Pallasite	1	Honda et al. 2002
Dalgaranga *	Australia	27° 38’ 6” S; 117° 17’ 20” E	24	?	M.siderite	1	Hamacher et al. 2013
Sikhote Alin	Russia	46° 9’ 36” N; 134° 39’ 12” E	27	1947 AD	IIAB	5 +n	Krinov 1971
Whitecourt	Canada	53° 59’ 56” N; 115° 35’ 51” W	36	1.1 ka	IIIAB	1	Herd et al. 2008
Kamil	Egypt	22° 1’ 6” N; 26° 5’ 16” E	45	2000 BC–500 AD	Iron, ungr.	1	Sighinolfi et al. 2015
Sobolev **	Russia	46° 18′ 0″ N; 137° 52′ 0″ E	53	? / <1 ka	?	1	Khryanina 1981
Campo d. Cielo	Argentina	27° 36’ 35” S; 61° 40’ 53” W	65x105	4 ka	IAB	4 +n	Cassidy et al. 1965
Ilumetsa **	Estonia	57°57’36″N; 27°24’11″E	80	7 ka	?	2	Losiak et al. 2020
Veevers *	Australia	22° 58’ 12” S; 125° 22’ 21” E	80	?	IIAB	1	Shoemaker et al. 2005
Morasko	Poland	52° 29’ 25” N; 16° 53’ 48” E	100	5 ka	IAB-MG	7	Szokaluk et al. 2019
Kaali	Estonia	58° 22’ 22” N; 22° 40’ 10” E	110	3.5 ka	IAB	8	Losiak et al. 2016
Wabar	Saudi Arabia	21° 29’ 58” N; 50° 28’ 7” E	116	~19th century	IIIA	5	Gnos et al. 2013
Henbury	Australia	24° 34’ 19” S; 133° 8’ 53” E	157	4.2 ka	IIIAB	13	Shoemaker et al. 2005
Boxhole	Australia	22° 36’ 46” S; 135° 11’ 43” E	170	3 ka	IIAB	1	Shoemaker et al. 2005

** not dated properly*
*** probable but unconfirmed structures*

blanket extends to about one crater-radius distance from the rim (Szokaluk et al. 2019). The age of the structures is estimated to be 3–6 ka, with the most probable age assumed to be about 5 ka (Szczuciński et al. 2016). Charcoal formed during the impact was found within the proximal ejecta (Losiak et al. 2022).

Kaali, Estonia

Kaali is a strewn field in western Estonia, on Saaremaa Island (Losiak et al. 2016). At least nine impact structures have been recognized there. The largest structure is 110 m in diameter and around 17 m deep to the current level of lake deposits (Plado 2012). It was formed by the impact of an IAB iron meteoroid weighing between 400 and 10,000 tons. The target rocks consist of horizontally layered Silurian dolomites covered by up to a few meters of glacial till. The ejecta blanket consists of an overturned sequence of those two types of materials, lying up to about a half crater radius of the rim, which are not mixed but separated into two distinctive layers. The age of the crater, based on charcoals formed during the impact (Losiak et al. 2022) and emplaced within its proximal ejecta, was determined to be shortly after 1530–1450 BCE (3237 ± 10 14C yr BP) (Losiak et al. 2016).

Kamil

Kamil is a single impact crater, 45 m in diameter and 10 m deep, located in south-western Egypt (Folco et al. 2011). It is pristine: the satellite images show the ejecta rays that extend up to 300 m from the crater, a feature that is visible in only one other site among terrestrial impact craters. The continuous ejecta blanket extends up to 50 m from the rim. The crater was formed by the impact of an iron meteoroid: Ni-rich ataxite Kamil Gebel (D’Orazio et al. 2011). Target rocks are sub-horizontally layered sandstones overlaid by up to a few centimeters of loose unconsolidated aeolian sediments (Fazio et al. 2014). The crater has not been precisely and accurately dated; based on its excellent preservation and the paleoclimate in this area, its age is estimated to be 2000 BC–500 AD (Sighinolfi et al. 2015). It is

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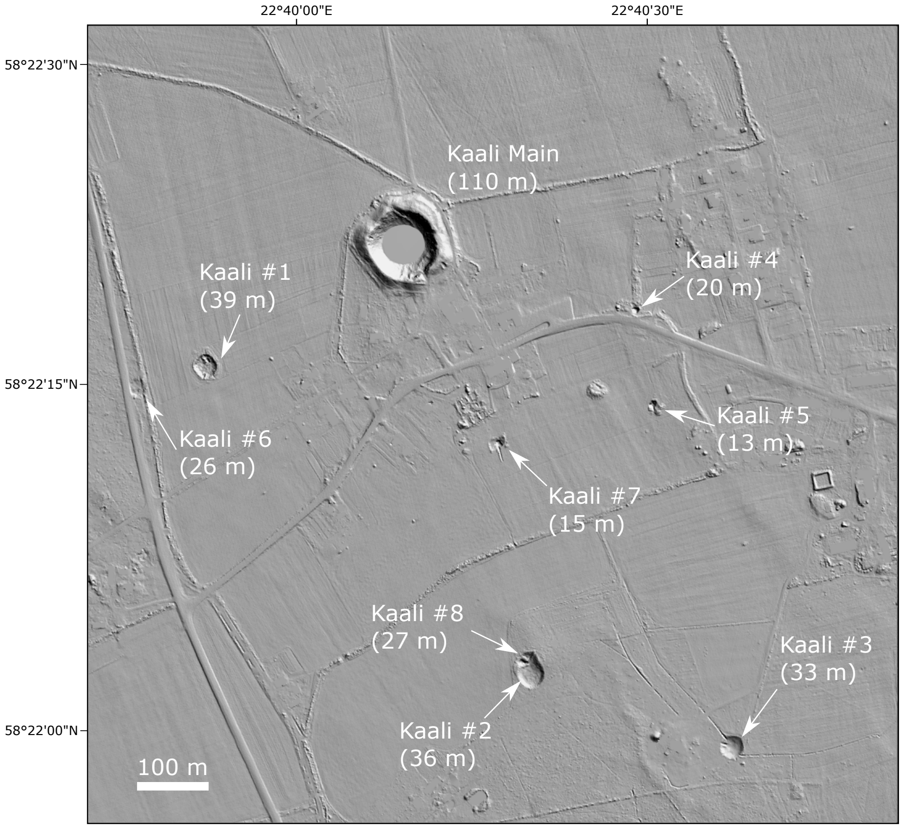

Figure 2. Kaali crater strewn field
Source: own work based on LIDAR data from the Estonian Land Board 2023

unique among very small impact craters because it is associated with signs of shock metamorphism such as planar deformation features, shatter cones, and high-pressure polymorphs of SiO_2 (coesite and stishovite) as well as a significant number of different types of impact melt (Fazio et al. 2014). Interestingly, it was discovered thanks to the analysis of satellite images available through Google Earth.

Ilumetsa (probable crater), Estonia

Ilumetsa is a set of two rimmed crater structures in south-east Estonia (Plado 2012). The larger structure is 80 m in diameter and 8 m deep, while the smaller one is 50 m wide and 3.5 m deep; they are located 725 m from each other. The geology of this area consists of a couple of meters of Quaternary sedimentary cover (glacial tills and sands) overlaying unconsolidated Middle Devonian sandstones (Losiak et al. 2020). Ilumetsa is not considered a confirmed impact site because neither remnant of the projectile nor other identification criteria, such as planar deformation features (PDFs), have yet been found. Only circumstantial evidence exists to support the extraterrestrial origin of these structures: (1) the presence of sedimentary beds deformed in a way consistent with being part of proximal ejecta (Aaloe 1963, Losiak et al. 2020); (2) a small thickness of the glacial sediments around the craters; (3) the presence of charcoal (Losiak et al. 2020), within what can be interpreted as a proximal ejecta blanket in a geomorphic setting, which is similar to charcoals found in other impact structures (Losiak et al. 2022); (4) 14C dating of those charcoals, showing that both craters formed simultaneously between 7170 and 7000 cal. years BP, about 7 ka after deglaciation of this area (Losiak et al. 2020). Further research is needed to test the impact origin hypothesis of Ilumetsa and numerous similar features because most of the roundish depressions in the ground are not impact craters, especially in a young glacial landscape (Plado et al. 2022).

Differences between very small Holocene impact craters on Earth and larger craters

Although all impact features are formed by a shock wave induced by a collision with an extraterrestrial body, there are three important differences between very small impact craters (<200 m in diameter), characteristic for Holocene, and larger impact structures on Earth.

Rarity of high pressure and temperature phases

The largest known impact crater on Earth, Vredefort in South Africa, which has a diameter of over 200 km, released two magnitudes more energy (~1E+23 Jules) in a nearly single point in space and time (couple of minutes) than the entire Earth releases over a year – as heat flow, seismic and volcanic energy (~1E+21 Jules table 2.1, French 1998). No other geological process on Earth's surface induces such high temperatures (>> 1000°C) and pressures (>>5 GPa), and those atypical conditions leave characteristic signs within rocks, called shock metamorphism. Finding characteristic features formed as a result of a shock wave passage allows us to unequivocally identify the site of an asteroid impact. Those features include shatter cones, planar deformation features, high-pressure (diaplectic) mineral glasses, high-temperature, whole-rock impact melts, and various high-pressure mineral phases such as coesite; these are commonly found in large impact sites (recent reviews in French & Koeberl 2010 and Osinski et al. 2022).

The smallest known impact craters are formed by more than ten magnitudes of energy less than the largest ones; for example, a crater of about 100 m in diameter such as the largest Morasko in Poland (Szokaluk et al. 2019) was formed with a similar amount of energy as that released during the explosion of the atomic bomb in Hiroshima (~1E+13 Jules: French 1998). As a result, during their formation, only a limited volume of target rocks experience high enough pressures and temperatures to be recognizably shock metamorphosed. Additionally, because very small impact craters tend to develop in unconsolidated Quaternary materials, the shock wave passage affects material differently than in consolidated rocks and distributes modified material over a large area. For instance, in the Morasko strewn field in Poland, the volume of sediment shocked to pressures greater than 10 GPa (the minimal pressure necessary for producing planar deformation features in a portion of quartz grains experiencing those conditions) is very small – around 200 m^3 compared with >7000 m^3 total volume of ejected material – that is, less than 3% (Bronikowska et al. 2017). As a result, the search for shocked grains and impact melt has been unsuccessful. Within the 15 known recent craters (Table 1), planar deformation features and coesite (high pressure polymorph of quartz) were found only in Kamil and Wabar, while impact melt particles are also present in the Henbury crater field. Therefore, the primary criterion used to identify small impact craters in unconsolidated sedimentary materials is not the shock wave passage indicators but the discovery of meteorite fragments.

Intensive interaction with the atmosphere

Impactors that are one kilometer in diameter or larger are usually not substantially influenced by the atmosphere during their transition. However, smaller bodies, especially those within the size range of up to 50 m in diameter, as is the case for all known Holocene craters (<160 m in diameter; Table 1), interact considerably with the atmosphere (Artemieva & Shuvalov 2019). Air compression and friction induced during the atmospheric passage heats up an asteroid, which leads to its ablation, fragmentation, and deceleration. The most important parameters that influence the way an asteroid interacts with the atmosphere are: (1) the meteoroid's physical properties (size, density, strength, pre-existing zones of weakness); (2) its entry velocity and angle; and (3) the properties of the atmosphere (particularly important when considering different planets such as Mars or Venus).

A significant portion of the initial kinetic energy of an asteroid of less than 100 m in diameter is deposited within the atmosphere (Artemieva & Shuvalov 2019). On the one hand, this slows down the impactors, limiting the amount of energy delivered to the surface that might produce an impact crater; on the other hand, shock waves formed in the air can be strong enough to cause significant damage to the environment without forming an impact crater (e.g., Chelyabinsk bolide: Popova et al. 2013; Tunguska: Florenskiy 1963). However, they are unrecognizable in the geologic record after just a few decades, so their frequency can only be estimated.

If at least one fragment of an asteroid survives the atmospheric passage with a velocity above about 1 km/s, an impact crater can be formed within unconsolidated sediments (Schmalen et al. 2022). Depending on the altitude and degree of meteoroid fragmentation, different patterns of craters can be formed. If just a single particle with sufficient velocity survives, a single small impact crater is formed; for example, Whitecourt in Canada (Herd et al. 2008). If an asteroid is separated into multiple particles that preserve a sufficient portion of their kinetic energy, then a strewn field is formed; for example, Kaali in Estonia (Losiak et al. 2016). Based on the spatial and size distribution of the craters within the group, it is possible to estimate the direction and impact angle of an asteroid (Bronikowska et al. 2017).

More common preservation of meteorites

The older and larger the crater, the rarer the meteorite fragments associated with it (Melosh 1989). This is because, during the largest impacts, the asteroid experiences such high pressures and temperatures that it is fully melted or vaporized. However, even in this case, the geochemical and isotopic fingerprints of this extraterrestrial material may be detectable (e.g., Alvarez et al. 1980, Koeberl et al. 2007). In contrast with larger structures, all confirmed Holocene craters are associated with meteorite fragments because they are the only indicator widely applied, as other shock metamorphic indicators (French & Koeberl 2010) are usually missing or very hard to find.

There are two types of meteorites that are found around Holocene impact craters (e.g., for Whitecourt, see Newman & Herd 2015). The "primaries" are derived from the fragments of the initial body, that were caused to decelerate during the atmospheric passage, so that their velocity at impact was not sufficient to produce an impact crater. These can be recognized by signs of atmospheric ablation preserved on their surface in the form of a fusion crust (a thin layer of melted material). They are similar in properties to "normal" meteorites that fall in non-crater-forming events. A special sub-type of "primaries" are fragments that hit the Earth with a velocity below the ~1 km/s necessary for the formation of an impact crater, but above the terminal velocity of 300–600 m/s; as a result, they produce terminal funnels (Schmalen et al. 2022). These are typically holes of up to twenty to thirty meters in diameter with a large meteorite inside (e.g., multiple sites at the Campo del Cielo strewn field in Argentina: Vesconi et al. 2011). The second type of meteorites are called "shrapnels" and are derived from the disruption upon impact of the crater-forming asteroid fragment. They are characterized by angular and irregular edges and smoother, concave interior surfaces. The primary meteorites are usually larger and found farther away from the impact site than shrapnels (Newman & Herd 2015).

Interestingly, nearly all confirmed Holocene impact structures are associated with iron or stony-iron meteorites (12 out of 13 cases: Table 1), even though iron meteorites form only 5% of witnessed falls. This may be caused by the fact that the rocky impactors are not capable of surviving the atmospheric passage in large enough and fast enough pieces to produce craters (Bland & Artemieva 2006, Artemieva & Shuvalov 2019). However, the formation of Carancas crater by a stony meteorite (H4-5 ordinary chondrite) in 2007 (Tancredi et al. 2009) may suggest an alternative hypothesis. If this event had not been witnessed, it is very probable that Carancas would not be recognized as having been formed by an extraterrestrial collision because the impactor was very fragmented and hard to find even after only a year. This suggests that all confirmed Holocene small impact craters are associated with iron meteorites because fragments of iron meteorites are much easier to find than small fragments of stony meteorites, especially after a few thousand years of weathering. Two impact sites (Table 1), Ilumetsa in Estonia (Losiak et al. 2020) and Sobolev in Russia (Khryanina 1981) are considered probable, but not confirmed, impact sites because no meteorites were found nearby.

Conclusions

The formation of impact craters has shaped the geological history of Earth (e.g., the formation of the 180-km-wide Chicxulub crater that induced the Cretaceous–Paleogene (K–Pg) extinction event, which ended the era of the dinosaurs). However, this process is not restricted to the past. According to the extrapolation of the currently measured impact rate of small bodies at the top of the atmosphere, we would expect more than 20 craters of about 100 m in diameter in Holocene alone (Bland & Artemieva 2006), yet we know of only six (Schmieder & Kring 2000). A number of observed crater-forming events (Carancas in 2007: Tancredi et al. 2009; Sikhote Alin in 1947: Krinov 1971; or Tunguska in 1908: Florenskiy 1963) show that we should also expect similar events in the near future. The study of very small impact craters is useful to understand the environmental effects of such events, especially in terms of quantities and mechanisms of thermal energy release and deposition (Losiak et al. 2022) during impacts of small asteroids, such as the Tunguska event in Russia (Svetsov 2008) or the Kaali craters (Losiak et al. 2016). Additionally, these can be used to better understand the basic geological process of how surfaces of other planetary bodies are formed, such as the Moon (e.g., Suggs et al. 2014) and Mars (Daubar et al. 2013).

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