PROBLEMATIC VERY SMALL IMPACT CRATERS

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The danger from very small asteroids: Impacts of even very small asteroids can detectably influence our society. In 2013, a 20 m in diameter body exploded over Chelyabinsk, seriously injuring >1500 people [1]. In 1947, formation of a strewn field in Sikhote-Alin caused the USSR army to go on alert [2]. An explosion of an extraterrestrial body over Tunguska river flattened 2000 km^2 of Siberian forest [3]. Humankind can only prepare for this natural hazard if the historical frequency and environmental influence is understood. Based on the extrapolation of the currently measured impact rate of small bodies at the top of the atmosphere, >20 craters ~100 m in diameter are expected in the Holocene alone [4], yet only six are known [5].

Identification of small impact craters (<200 m in diameter) is problematic, because the methodologies for identification of impact craters have been developed for large impact structures. The most unequivocal criteria are the presence of shock metamorphic indicators (like planar deformation features in quartz or shatter cones) and, to lesser extent, detection of geochemical traces of extraterrestrial matter [6]. However, in the case of small impact craters in unconsolidated target rocks, such signatures are detectable only within a small volume of target material which have subsequently been distributed as ejecta over 10's of km^2, diluting the measurable shock metamorphic signal [7]. As a result, out of 14 confirmed small impact craters, planar deformation features and high-pressure phases have been reported only from two recent impact craters developed in desert areas: Kamil [8] and Wabar [9]. A small number of potential shatter cones are reported from Kaali [10] and the suspected crater Sobolev [11], where the target rock consists of a couple of meters of unconsolidated sediments overlying lithified rocks from which the shatter cones were formed. Fragments of melted rocks have been reported from only 4 out of 14 cases. In practice, the only widely used impact indicator of confirmed non-witnessed (excluding Carancas [12]) impact craters <200 m in diameter is the association with iron meteorite fragments (13 out of 13 cases).

Dating very small **impact craters**. The formation of some features was witnessed in modern times, such as Carancas [12] or Sikhote Alin [2]. In the case of Wabar, there are some historical records pointing to the moment of impact [13]. Establishing a crater age is straightforward if there is ^{14}C datable (<50 ka) organic material associated with the impact structure, e.g., in the form of a paleosol (e.g., Morasko [14]), charcoals of organisms killed during the impact event (e.g., [15,16,17]) or dating of the oldest materials in a crater lake (Morasko: [18]). If no material for ^{14}C dating is available, the age can be estimated based on palynology (Morasko: [19]), cosmogenic nuclides within meteorites associated with the craters, e.g., Haviland [20] or Henbury [21]. Exposure cosmogenic nuclide dating of the ejecta is only possible if craters are more than a couple tens of thousands years old and target rocks were at least partially consolidated [22]. Luminescence dating, such as at Odessa [23] or Wabar [24], may in many cases not yield precise or accurate results due to not complete resetting during impact event, such as at Kamil [25] or Morasko [26]. Often, different methods give drastically different age estimations, e.g., Kaali [17]. And sometimes, the only method is guestimate based on the level of crater preservation: Veevers, Dalgaranga [5].

Studies, including field work in very small impact craters especially those developed **in unconsolidated materials** should be designed specifically for those features by understanding both the impact cratering process and Quaternary geology techniques. This allows not only to describe and recognize new impact sites [27], but also to use those well preserved craters to better understand the impact process itself. For example, by mapping the ejecta blanket [14], and interaction of paleosol with ejecta we can learn about the stages of ejecta deposition [28] and better understand complexities of the double crater formation [29]. Additionally, even though a presence of features characteristic for ejecta blankets of young very small impact craters can not be treated as a proof of an impact origin of a specific circular structure, a lack of them is suggestive that an impact origin can be excluded, and other processes are more likely [30].

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