SMALL IMPACT CRATER-LIKE FEATURES: THE TOR CRATER, SWEDEN, AS A REFERENCE STRUCTURE IN EVALUATING ALTERNATIVE CAUSES OF FORMATION IN NON-VOLCANIC SETTINGS ON EARTH AND MARS.

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Introduction: Although many Earth processes cause crater-shaped features, most of them can be discriminated based on their past and/or present geological setting. For instance, craters in non-volcanic settings are suspected of having an impact origin. Small impact craters may be challenging to confirm, mainly if restricted to remote-sensing. Currently, only ~200 confirmed terrestrial impact craters are known, but despite the relatively high formation rate of small impacts, only 17 of them are smaller than ~200 m [1,2]. Every year numerous new impact sites are proposed, often based solely on the remote sensing / geophysical data [3,4]. To be accepted as impact craters, they need to be evaluated against common shock indicators [5] related to the detection of impact metamorphism (*e.g.*, presence of PDFs [6]) or geochemical signatures of extraterrestrial material (pieces of meteorites or their geochemical or/and isotopic tracers). The evaluation is time-consuming and requires expensive equipment by researchers experienced in the impact cratering process; thus, hundreds of suspected impact structures wait for an assessment based on the accepted conditions [7].

Here we present a multi-technique analysis to evaluate a potential impact origin against other plausible causes of formation of the Tor structure in central Sweden (62.501613°N, 12.631767° E).

Geological settings: Tor is a slightly irregular, 40 m in D, rimmed structure located in Sweden (62.50161°N, 12.63177° E) within the NW-SE-trending Ljusnan river valley that is mainly covered by boulder-rich silty till. The direction of the Weichselian ice sheet movement in the valley was from the SE or ESE. As the local ice margin retreated eastwards during the last deglaciation, the Ljusnan glacial lakes were dammed in the valley [8,9]. The area was deglaciated ~10.2 cal. ka BP [10].

Tor was proposed to be of impact origin by [8,11] partly based on morphological similarity to other Holocene impact craters such as Kaali [12] and Morasko [13]. Tor is widely advertised in the region as an impact crater. Recent work by [14] shows that Tor-like features are common in the area and that their location correlates with shallow-water areas of a past ice-dammed lake. They concluded that Tor is most likely an iceberg pit, forming when icebergs make forceful, vertical contact with the seafloor [15].

The Tor structure's well-preserved morphology allows detailed analysis of its formation and data for comparison with similar structures in areas potentially affected by both impact cratering and iceberg-scouring on Earth and Mars, e.g. [16, 17].

Methods and results: A local digital elevation model was created using photogrammetry (Fig. 1). According to the ground-penetrating radar (GPR) survey, the thickness of sediments varies between 4 and 8 m. Sediment cover is thinnest under the central pond and thickest at the rim-like feature. Based on the reflector that originates from the basement's top surface, the Tor structure includes no depression within the basement. Electro-resistivity tomography (ERT) shows a layered sequence that can be interpreted as glacial till overlying resistant crystalline (Fig. 2). The top of crystalline bedrock is flat and is situated at about 624-625 m asl that is in good agreement with GPR data.

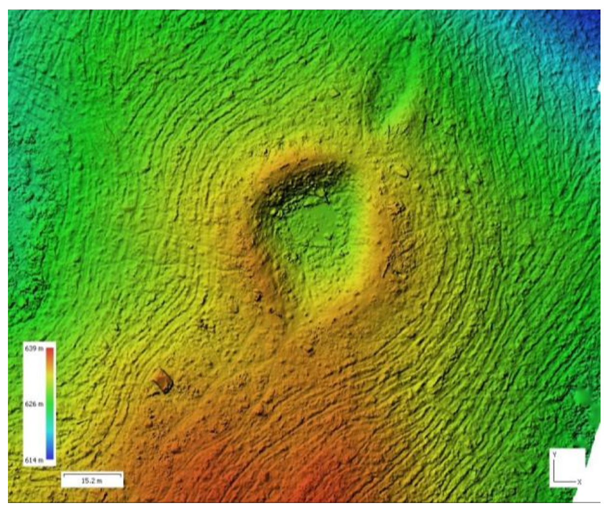

Fig. 1. DroneDEM. Tor is located on the local hillside and is accompanied by the groove in NNE. The area around the structure has been ploughed to enhance reforesting.

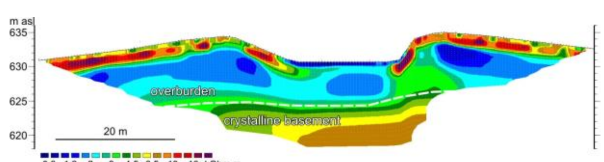

Fig. 2. ERT profile. It shows a layered sequence with ~6 m of overburden on top of the crystalline basement.

Magnetic anomaly correlates positively with topography due to highly magnetic overburden compared to the magnetization of the basement. Modeled relief of the top surface of crystalline rocks is smooth compared to topography. It does not show any short wavelength undulations that may suggest magnetic material such as meteorites. Metal detector search revealed no metallic meteoritic fragments in an area of ~28,000 m^2 surrounding Tor. ^{10}Be exposure dates of four boulders located on the N-E edge of the structure vary between 9970±417 and 9478±319 years, i.e the time directly after the disappearance of the ice-dammed lake [18]. We dug two 2-m long radially oriented trenches in the NW and NE sections of the feature. The trenches revealed a podzol developed on a glacial till. No signs of an overturned structure (or paleosol), like ones observed in other small impact craters formed in unconsolidated materials [12,19], were found.

Charcoals were previously identified in specific locations within proximal ejecta blankets of small impact craters developed in unconsolidated materials [12,19,20]. Measuring charcoal reflectance allows to determine the level of ordering within the char that correlates to the environment in which it was formed; this allows distinguishing between wildfire and impact charcoal that can be found in proximal ejecta blankets of confirmed impact craters [12,19]. Charcoals were present in the eluvial soil zone lenses, with multiple particles present next to each other. The samples come from within the soil layer: between 10-40 cm below the ground. A couple of charcoal samples from the present ground surface in the surrounding area was collected for reference. The reflectance of charcoals is characterized by numerous grains with >1.3% and a high standard deviation within a particle. We ^{14}C dated four charcoal particles. The ages of two samples overlap (Tor1_25: 7059-6710 BC, Tor2_21: 7038-6696 BC), while two other samples fall outside of this time range (Tor1_14: 6570-6427 BC and Tor2_9: 3351-3094 BC). Thus, the age distribution demonstrates three separate charcoal-producing events. The oldest one took place soon after deglaciation and removal of the ice-dammed lake from this area.

Discussion: The Tor feature's shape is only broadly consistent with morphological ratios expected of an impact crater but is similar to iceberg pits in the area [14] and similar settings in Norway [22]. There is no sign of overturned flap sequence neither in the geophysical data nor within the trenches. No signs of metal-containing extraterrestrial impactor were detected. ^{10}Be exposure ages from boulders are consistent with the timing of deglaciation/ice-dammed lake drainage in the area, supporting glacial transport. The distribution of charcoals found within trenches follows the surface and is different from previously identified impact charcoals [12,19]; it suggests that these were introduced into the subsurface as part of the typical soil processes (animal burrowing and/or trees uprooting). ^{14}C shows that charcoals were formed in at least three separate events, not correlating with the boulders' ^{10}Be exposure age. Charcoal reflectance is characteristic for a low-energy forest fire [21].

Conclusions and implications: No evidence supports the impact origin of Tor, and our observations fit better with the iceberg theory. Iceberg plow-marks in the form of linear ridges and grooves are known from locations on Mars where proglacial lakes may have formed [23]. However, to our knowledge, no crater-like features in these areas have been suggested to have formed by icebergs. This study suggests an approach towards small crater evaluation on Earth and Mars.

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