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SHORT COMMUNICATION

A ground-penetrating radar study of the Vaidasoo bog (Estonia): no crater structure exists

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Ground-penetrating radar (GPR) was used to analyse the circular Vaidasoo bog in northern Estonia. This was done to better understand its structure and origin, and to test the suggestion that Vaidasoo represents a meteorite impact structure. The combination of GPR with LIDAR data suggests that Vaidasoo bog is developed in a NW–SE oriented glacial tunnel valley where post-glacial hydrology is affected by glaciofluvial deposits. As no clear impact-modified bedrock features were identified and the circular bog does not mirror the topography of the bedrock, we conclude that the Vaidasoo structure does not represent a meteorite impact structure.

Key words: Vaidasoo structure, ground-penetrating radar, Estonia, peat.

INTRODUCTION

Presently, three structures (Kaali, Kärdla and Neugrund) of confirmed impact origin are known in Estonia (Plado, 2012). However, there are several other circular structures the origin of which has been unclear. One such structure, the 325-m-diameter Vaidasoo structure (centered at 59°16’5’’ N; 25°2’34’’ E; Fig. 1) is located in northern Estonia. A meteorite impact origin was suggested by the amateur archaeologist P. Böckler in 2004 (Terasmaa, 2006). The suggestion was based on an aerial photograph where a circular structure stands out (Fig. 1). To study the structure and to explain its origin, the Geological Survey of Estonia (GSE) drilled a 16 m deep hole into the centre (for location see Fig. 1) of the circular feature in March 2006. The borehole revealed that the limestone bedrock is fissured whereas the topmost 3 m is fragmented. On top of the bedrock lies a bluish-grey silt layer up to 1 m thick, which is covered by up to 0.5 m of whitish calcareous lake deposits, containing mollusc shells. The lake deposits are overlain by a 4.5 m thick succession of marsh and bog deposits. The drilling and geophysical results were reported by Suuroja et al. at the Lockne Meeting "Impact craters as indicators of planetary environmental evolution and astrobiology" in 2006.

A weak, 0.2 mGal negative anomaly was identified from two approximately 1 km long gravity profiles made by the GSE. Suuroja et al. in 2006 (at the Lockne Meeting) concluded that Vaidasoo may represent a deeply eroded meteorite impact structure but left the origin of the structure open to debate.

The Vaidasoo structure is located on the north Estonian Limestone Plateau where Ediacaran, Cambrian, and Ordovician sedimentary bedrock with a total thickness of ~200 m lies on the southern slope of the Precambrian Fennoscandian Shield (Suuroja et al., 2003). In the region, Upper Ordovician limestone (Kahula and Rägavere regional formations) appears at 40–45 m a.s.l. The uppermost surface of the limestone is dissected by old, presently buried, incisions of glacial origin. The Vaidasoo structure is located in a NW–SE trending buried valley that is about 1.5 km wide and 5–10 m deep, and becomes narrower and deeper towards the SE. The bedrock in general is overlain by Quaternary deposits:

- glacial till,
- glaciofluvial sands and gravel,
- marsh and bog peat deposits.

The glaciofluvial deposits occur mainly as NW–SE-oriented esker ridges, as revealed by a geological map of Quaternary deposits and modern topography (Fig. 2).

Topographic lows of the region are often filled with peat deposits (Suuroja et al., 2003). A sharp circular borderline (see Figs. 1 and 2) marks the boundary between the ~325 m diameter pinewood-covered raised bog and mixed forest-covered transitional mire. The circular structure is crossed by a W–E-trending high voltage power-line. A sand and gravel quarry is located just north of the Vaidasoo structure.

Below, we present results of a GPR study over the Vaidasoo structure. The study is applied to shed light on the origin and subsurface morphology of Vaidasoo.

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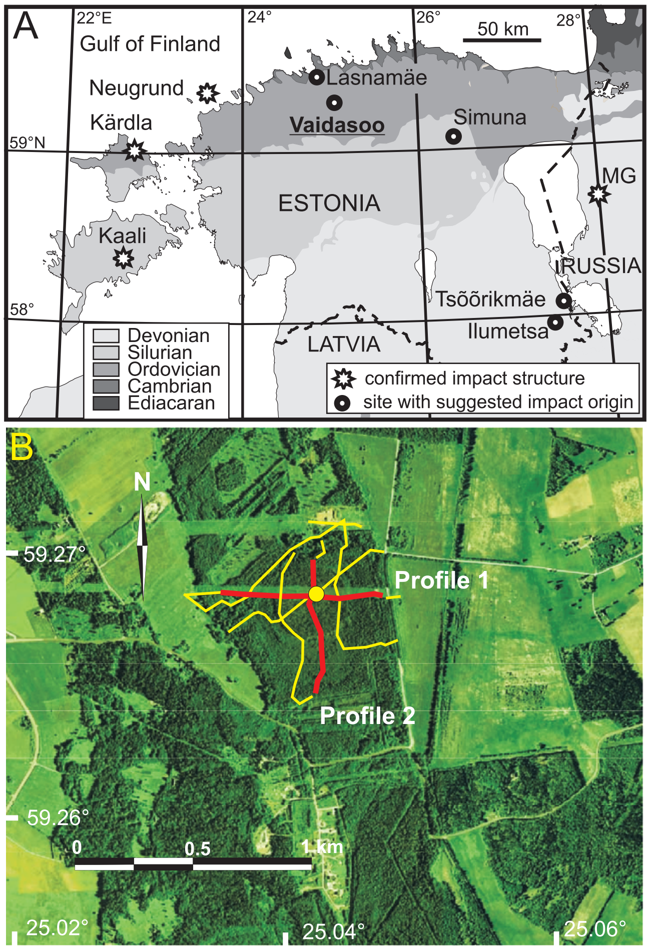

Fig. 1A – geological sketch map of the Estonian sedimentary basement showing the locations of proven and suggested impact structures, including Vaidasoo (MG – Mishina Gora meteorite impact crater, in Russia); B – Vaidasoo structure on an aerial photograph (Estonian Land Board); the red and yellow lines indicate locations of the ground-penetrating radar paths; images along the red ones are illustrated by Figure 3; a yellow dot marks the location of the borehole cored by the Geological Survey of Estonia

METHODS

The GPR method is widely used as a non-destructive geophysical tool to investigate shallow subsurface structures. Ground-penetrating radar emits electromagnetic waves (EMW) in frequencies ranging from tens of MHz to a couple of GHz into the ground and registers signals reflected back from subsurface discontinuities and interfaces of layers of different dielectric properties. The present GPR field work was performed in July 2010. The profiles were recorded with a *Zond 12-e* system by Radar System Inc. (Latvia) using 300 MHz frequency. The distances were measured by odometer wheel, which was also used to trigger the measurements at constant spacing (set to 10 cm). A GPS device connected to the radar system was used for positioning. The positional accuracy is estimated to be ~5 m in open view and about 10–15 m in forested areas. The topographic corrections were calculated at about 10 m spacing on profiles using an inverse to distance weighing algorithm by combining positional data and LIDAR measurements of the Estonian Land Board. Despite relatively large positional inaccuracy in lateral direction, the accuracy in vertical direction is estimated to be only a few decimetres, because the landscape is relatively flat. To improve the signal-to-noise ratio, stacking of 4 measurements was applied. *Prism2* software was used for data processing, which included (i) a bandpass filter with the aim to remove occasional low-frequency interference and (ii) time-dependent gain. To convert two-way travel time measured by radar device to a depth-scale, velocities of 0.036 m ns^{-1} for peat-covered areas (Plado et al., 2011) and 0.106 m ns^{-1} for ar-

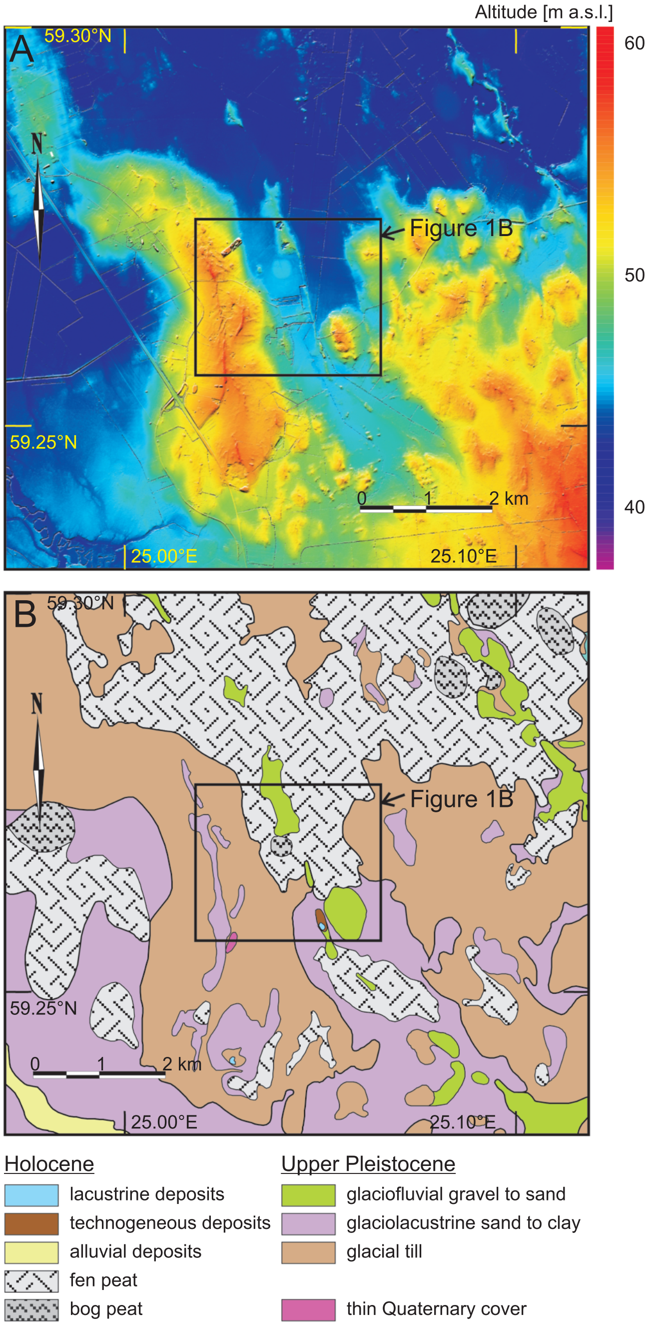

Fig. 2A – topographic data of the study site obtained by LIDAR measurements (Estonian Land Board); B – Geological map of Quaternary deposits (originally at a scale of 1:50 000; simplified after Suuroja et al., 2003)

eas covered by mineral soil (wet sand; Davis and Annan, 1989), were used. Interpretation of the GPR images is supported by the drilling data.

RESULTS

The maximum thickness of peat reaches 4.8 m in the central part of the circular raised bog and decreases smoothly in the directions of the transitional mire (Fig. 3). The reflection pattern of GPR images reveals two distinctive parts: (i) the upper part, which corresponds to peat with a smaller degree of decomposition (bog peat), characterized by more numerous and higher intensity reflectors compared to (ii) underlying peat with a higher degree of decomposition (fen peat) and lake sediments that appear as a layer with no or little internal reflectivity. The interface between the organic/lake deposits and underlying silt or gravel is unambiguously detectable across the whole area. This enabled the identification of the underlying relief and morphology of the depression. The characteristics of the reflection patterns of silty glaciolimnic sediments and sandy gravel in the glaciofluvial esker are too similar to be distinguishable in the radar data.

The depression that is filled by peat and lake sediments, has a gently (~1 m) undulating topography. It is surrounded by side margins, but these are not located symmetrically with respect to the circular feature. The sides are steepest in the eastern part of the study area, where the maximum dip of the slope reaches 6°. In the western and northern part of the depression the dip of the slopes is in the range between 0.6 and 2.2°. The radar data do not reveal the side margin of the depression on the southern side of the structure (Fig. 3). Thus, the circular raised bog (suggested impact structure) does not coincide with the depression. Also, we note that the depression is not circular and its slopes do not reveal any signs of dislocation. The profiles conducted over the eastern slope of the bedrock depression reveal glaciofluvial sediments as an esker. No deformed bedrock in the proposed crater rim area was found.

The hump in the bottom of the depression (marked with upwards pointing white arrows in Fig. 3) may consist of clay-rich deposits because the GPR signal is not able to penetrate into the hump and it is instead reflected from the top of the structure. As indicated on the crossing GPR profiles, the dimensions of the hump (80 m in the west-east and 25 m in north-south directions, and 0.8 m in height) resemble those humps to the south and south-west of Vaidasoo bog (Fig. 2), which are all interpreted to be recessional moraines.

DISCUSSION

Ground-penetrating radar is a widely used and effective tool to measure the thickness of the peat and identify the base morphology of peatlands. Good penetration depth within peat and

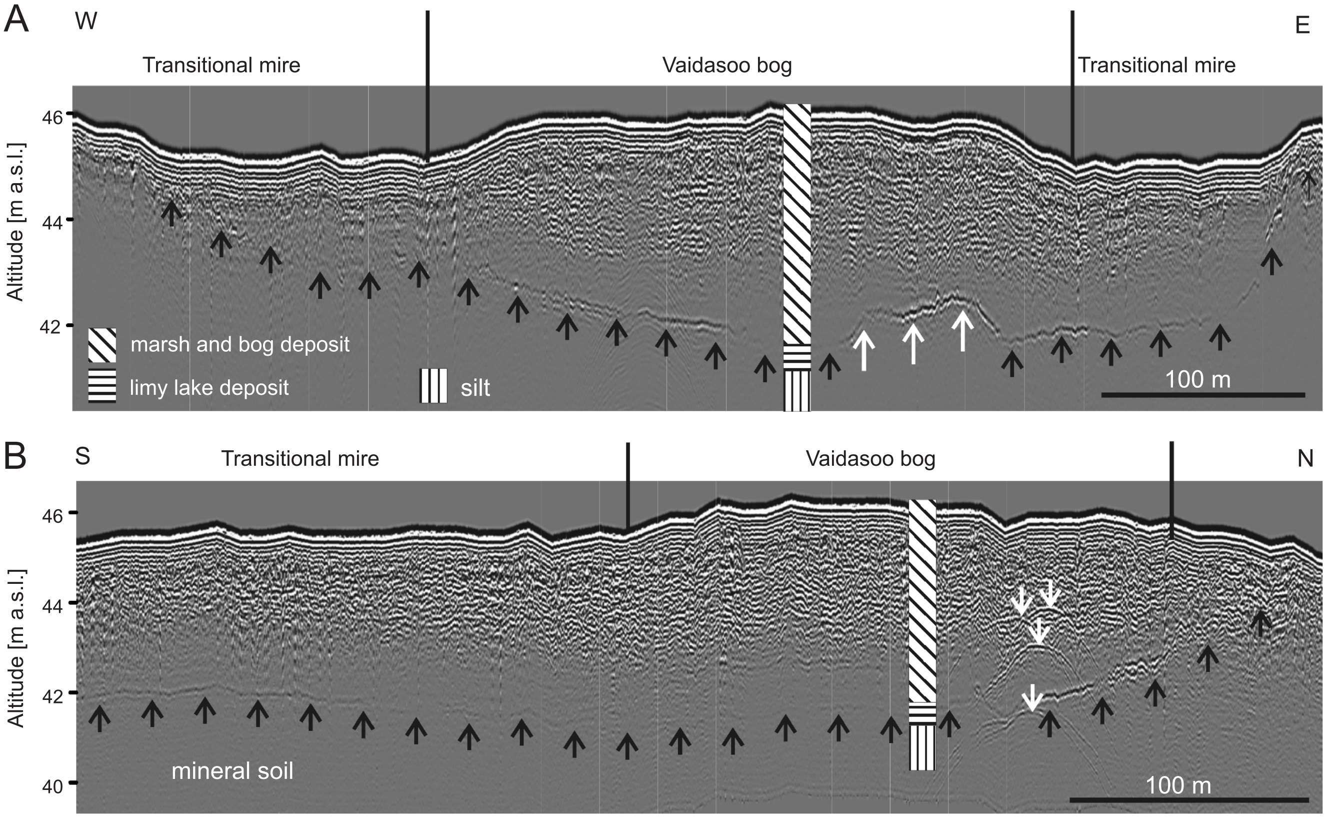

Fig. 3. Radar images along profile 1 (A) and profile 2 (B)

Topographic corrections for radar images are based on LIDAR data; see Figure 1 for locations of the profiles; black vertical arrows denote the peat-mineral soil interface; upwards pointing white arrows mark plausible recessional moraine ridge; downwards pointing white arrows mark the hyperbolae induced by high voltage power lines in the air; drilling results are shown on the profiles; note that the vertical scales are exaggerated (A – 26 times; B – 19 times) strong reflections from the peat-mineral soil interface afford clear-cut visualization of the underlying structures of the peat body (Slater and Reeve, 2002).

The circular peat bog body of Vaidasoo, which has superficial similarities to a meteorite impact structure, is not reflected in the shape of the depression below the peat. First, the size of depression is significantly larger than the circular structure outlined. Second, the depression has no margins in the southern and northwestern sides at distances that would be comparable to the diameter of Vaidasoo. Also, the existing slopes of mineral soil are at a low angle for an impact structure. Third, no hints of impact-generated dislocations or features that could resemble a rim structure were identified.

Drilling conducted in March 2006 by the Geological Survey of Estonia, revealed fragmented limestone in the centre of the structure, whereas the GPR profiles did not show any dislocated limestone blocks or traces of fragmented limestone in the area. The fragmented limestone in the bottom of the structure was probably not identified by GPR because the overlying silt attenuates the signal. In consideration of a meteorite impact hypothesis, the possibility exists that the original impact structure has been eroded. However, if this is the case, there exists no direct genetic relationship between the bedrock topography and the present circular bog. We suggest considering the possibilities that the top layers of limestone represent a layer of clay-poor local moraine.

The GPR and topographic data of the region suggest that development of the raised bog is connected with the glaciofluvial channel and general hydrology of the area. The eskers to the east of the structure are of type II (Brennand, 2000) i.e. a system of alternating glaciofluvial ridges and fans. One of the fan-like deposits exists a few hundred meters to the north of Vaidasoo bog and a few more can be observed every 1.5–2.0 km northwards along the esker system. Despite being formed of sand and gravel, glaciofluvial deposits hinder surface water flow in the consistently slightly northwards tilted topography. A similar effect was also observed by Laitinen et al. (2008) and The Proctor and Redfern Group Ltd. (1984). As constantly wet conditions were present, the growth of a peat-forming flora and the accumulation of a peat-started. After filling the large areas surrounding Vaidasoo with marsh and mire sediments, the conditions start to change from minerotrophic to ombrotrophic, and formation of a raised bog started. When geological obstacles preventing peatland expansion (positive landforms) are absent, the peatlands tend to form circular raised bog bodies whose margins do not coincide with the margins of the underlying depression.

CONCLUSIONS

The GPR study at Vaidasoo bog revealed that the circular pattern of vegetation is not mirrored in the shape and size of the bedrock depression. No dislocated or reoriented bedrock was identified. GPR and topographic/geological data from the area suggest that the development of the raised bog was connected with a glaciofluvial channel and the general hydrology of the area. In the latest stages of Vaidasoo formation, there were no geological obstacles to prevent peatland expansion and it formed a circular raised bog. Thus, we propose that the circular Vaidasoo structure represents a raised bog that formed in a peat-filled hollow in a NW–SE oriented bedrock depression, and is not related to an impact event.

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