# The Structure of the Kaali Impact Crater (Estonia) based on 3D Laser Scanning, Electro-resistivity Tomography, and iSale Hydrocode Modelling.

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**Introduction:** The Kaali crater-strewn-field located on the island of Saaremaa, Estonia (58.37°N, 22.67°E), consists of nine well-preserved craters, ranging in size from 110m diameter (Kaali Main) to a few meters in diameter [1, 2]. The Kaali Main crater is an important feature to study the effects of small asteroidal impacts on terrestrial planets, as it lies near the transition between strength and gravity dominated crater morphologies [e.g. 3]. Despite having been identified as an impact crater since the 1920's [1, 2], documentation of the crater's structure has been limited to topographic observations and few reported strike and dip measurements [4]. In August, 2014, we made a scientific expedition to map the crater in unprecedented detail using 3D laser scanning tools and detailed strike and dip measurements of all outcrops to describe the crater in more detail. Additional measurements using ground-penetrating radar and electro-resistivity tomography (ERT) were also conducted to further refine the subsurface crater morphology. Field observations have been used to constrain preliminary iSale hydrocode modelling for the Kaali Main crater.

Our results include the highest resolution topographic map of the crater to date, previously unreported observations of overturned ejecta blocks and strata, and refined morphometric estimates of the crater. Additionally, research conducted as part of the expedition from a trench transect of the ejecta blanket has provided a new, best-estimate for the formation of the crater (3200a +/- 30 BP) based on $^{14}$C AMS dating of charcoal from within the ejecta blanket [5].

**Background:** The strewn field is the result of the breakup during atmospheric entry of a type IAB iron meteorite [6] previously estimated between 400 and 10,000 tons [7]. The target rocks consist of Silurian dolomite covered by 1-3m of glacial till [8]. Despite anthropomorphic changes to the crater (an observation platform was built inside the crater's southern rim, and a path was constructed from the floor to the north rim), the stratigraphy of most of the outcrops is preserved.

**Structural Mapping and Topographic Models:** Although the Kaali Main crater has been the subject of previous investigation (e.g. [1, 2, 4, 6-11]), most of the structural descriptions of the crater pre-date modern crater investigations. The impacted dolostones are homogenous; however they show identifiable marker horizons with distinct bedding features and way-up features that could be correlated across outcropping strata and adjacent ejecta blocks. 377 strike and dip measurements were made of 43 outcrops around the crater, with dipping angles from 15 to 85°. In general, almost vertical dipping blocks are observed in the upper parts of the inner slopes of the crater wall, with flattening dips lower on the walls. In areas of the southern slope where trenching was conducted in the 1960's, dip angles from 36° to 54° have been noted [10]. Even though strongly inclined blocks were noted (dip-angles as high as 88° [11]), blocks rotated above 50° or even overturned were considered being affected by erosion and slope processes and not identified as intrinsic to the crater formation process. Our new observations show that most high dip-angle features fit well with overall dip-angle systematics, and contiguous blocks of dolostone that were overturned as part of the overturned flap of ejecta can be demonstrated in at least four areas around the crater [e.g. Fig.1].

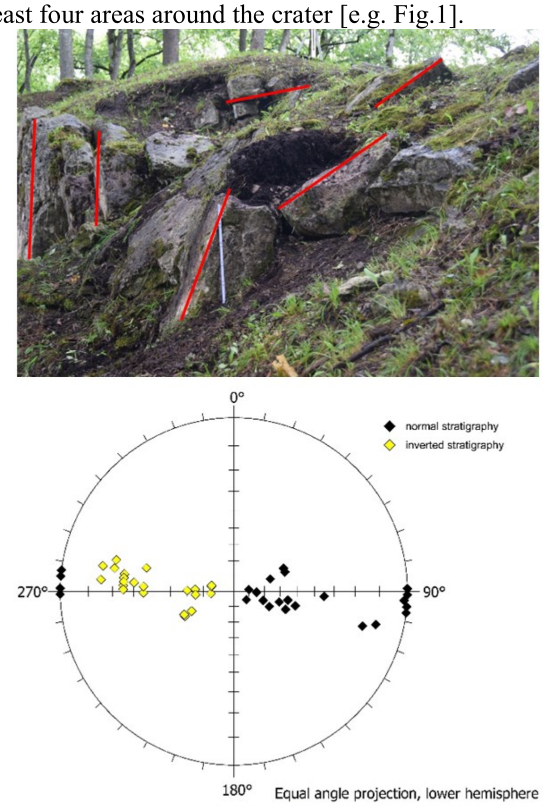


**Figure 1:** Example stereogram plot of strike and dip data from an outcrop of overturned strata in the eastern rim. Red lines are bedding surfaces used for measurements. Overturned strata is observed in at least 4 outcrops around the rim.

**3D Laser Scanning:** A point cloud containing 18 million data points was created using 43 individual scans from a tripod mounted Faro 3D 330x laser scanner, and backpack mounted PLS scans [12]. Scans were processed using Trimble Realworks software and a DEM, Hillshade, Slope Map and Contour Map were created in ESRI ArcScene software. Mean positional displacement of the combined TLS and PLS point clouds are better than 12 cm in elevation and 20 cm in horizontal positioning. Fig 2 shows a preliminary 3D representation of the DEM created from the point clouds, and a contour map derived from the DEM.

**Electro-Resistivity Tomography:** ERT measurements show the subsurface stratigraphy of the ejecta blanket along a ~35 m transect of the south-western crater rim. Ejecta thickness varies from ~4m thick at the rim to ~.75 m in the distal regions. A relatively uniform 1m thick layer of glacial till is also observed overlying the dolomite bedrock target. ERT measurements match well the stratigraphy and unit thicknesses of a 5 m long trench dug in the same area.

**Photogrammetry:** Photogrammetric techniques from images of key outcrops were used to create textured, photorealistic 3D representations using Agisoft PhotoScan software. Various 3D models can be seen at (http://tinyurl.com/ KaaliCrater3d)

**iSale Hydrocode Modelling:** Strike and dip measurements and ERT ejecta thickness estimates are being used to constrain high-resolution iSale hydrocode models of the Kaali Main crater formation and to learn more about terrestrial strength/gravity regime transition craters. Modelling is currently in progress using the DEM shape model for comparison and with emphasis on determining impact velocity (constrained by the atmospheric breakup of a 1AB iron meteorite), projectile size, and ejecta blanket thickness.

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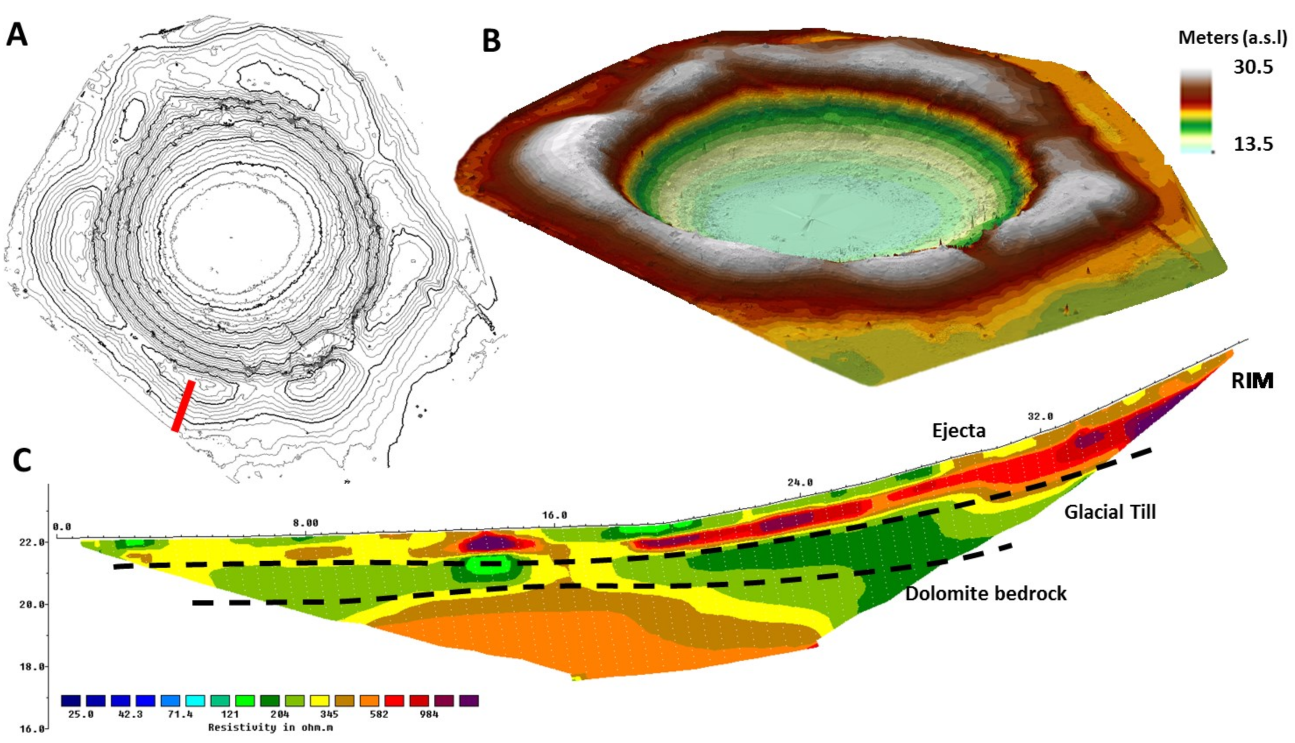


**Figure 2: A)** Contour map (25cm contours) created from 3D laser scan point cloud. **B)** Digital Elevation Model (DEM) oblique view of Kaali Main Crater viewed from the Southwest. Lowest points on the crater floor are the surface of the Kaalijärv pond. **C)** ERT transect of southwestern ejecta blanket (red line in Fig2a). Ejecta is clearly discernable over the underlying units.