THE ORIGIN AND TECTONIC MODIFICATION OF THE SAARIJÄRVI IMPACT STRUCTURE, NORTHERN FINLAND. T. Öhman[1,2], [1]Department of Geosciences, Division of Geology, and [2]Department of Physical Sciences, P.O. Box 3000, FI-90014 University of Oulu, Finland, (teemu.ohman@oulu.fi).

Background: The Saarijärvi structure in Taivalkoski, northern Finland (65°17.4'N, 28°23.3'E) is the northernmost generally accepted impact structure in Europe currently located on dry land, and the only one in the Fennoscandian Shield formed in Archean basement complex. The target consists of Archean gneissose granitic and tonalitic rocks, and three generations of Early Proterozoic metadolerite dykes. Saarijärvi is reasonably well studied, especially given its small size (current D=1.5–2 km) and inconspicuous lake- and bog-filled appearance. This is due the substantial economic interest that was shown to Saarijärvi from the 1800's up to present day. The main economic incentive was the kaolin-bearing Ediacaran and Early Cambrian claystone deposited in the structure. In the late 1990's the structure was also considered a possible kimberlite pipe. As a result, seven drill-cores – three of which extend through the sedimentary rocks to the basement – and a great amount of geophysical data now exist on Saarijärvi. Despite the wealth of data, several aspects of the origin and evolution of the structure are still very poorly constrained.

Indications of impact: The impact origin of Saarijärvi structure was confirmed in 1997, when weakly developed planar deformation features (PDFs) in three orientations in quartz grains from the depth of ~156 m, i.e. from the bottom of the sedimentary sequence, were discovered [1]. In addition, quartz grains display planar fractures (PFs) in multiple orientations, and occasional mosaicism. Later, shatter cones in granitoids and metadolerites were discovered as well. However, the PDFs described so far [1] have been of the "incipient" type [2], and not of the well-documented and totally undisputable type [e.g. 3]. Nevertheless, they are notably different from tectonic deformation lamellae also present in Saarijärvi rocks, and the few measured Miller indices are typical for shocked quartz. Overall, the "big picture" of the Saarijärvi structure leaves very little doubt of the impact origin.

Pre- or post-impact sedimentary sequence? Finnish impact research has recently been slightly enlivened by discussion regarding the pre- or post-impact origin of the mainly Phanerozoic sedimentary rocks currently filling many of the structures [4]. In Saarijärvi, the sedimentary rocks have been interpreted to be post-impact, thus yielding a minimum age of about 600 Ma for the structure [1]. However, there is no real evidence for the post-impact origin. In all of the drill-cores, the sedimentary rocks display variable stratigraphic order, chaotically varying dips of the bedding, as well as slump features. Boulders of basement rocks are present in the middle of the sedimentary sequence in one of the drill cores, as well as in one small outcrop. These observations hint towards a pre-impact origin of the sedimentary rocks, not post-impact. In addition, indications of shock metamorphism, like poorly developed "incipient" PDFs and PFs in quartz grains, are present throughout the sequence. These could be explained as detrital grains deposited long after the impact, but they could also have been deposited immediately after the projectile impacted the sedimentary rocks that were still unconsolidated.

Tectonic modification: The Oulujärvi shear zone is one of the major crustal-scale tectonic features in northern Finland. The Auho fault, which is the main fault in this shear- and fault zone, passes Saarijärvi only about seven kilometers northwest from the structure. More importantly, also on a local scale notable tectonic features are present. The north–south oriented Ölkky lake is situated in a beautiful small gorge immediately north of Saarijärvi. Other similarly oriented fracture valleys are present southwest from Saarijärvi.

One of the curiosities in Saarijärvi is the presence of a central island in such a small and thus presumably simple impact structure. The island is notably elongated in N–S-direction, which is further emphasized by its continuations visible in e.g. apparent resistivity data. The orientation of the island parallels that of the Ölkky lake. Brecciated outcrops in the island consist of metadolerites and granitoids, which display evidence of tectonic deformation (cataclastic veins, slickensides, kink-banded sheet silicates) and hydrothermal alteration, but no signs of shock metamorphism. Also the presence of narrow clinochlore veinlets in the heavily brecciated contact of metadolerite and granitoid implies tectonic deformation. Hence, the island apparently is merely a tectonic block, uplifted well after the impact. Possible other similar but smaller blocks laying somewhat beneath the surface of the sediments may be indicated by minor anomalies in gravity and magnetic data.

The side profile of the Saarijärvi structure, revealed e.g. by the gravity and apparent resistivity data, is notably non-symmetric. The southern side of the structure is deeper, and also the slope of the basin's wall is steeper in the south. Unless an idea of a highly oblique impact is provoked, the whole structure must have been tilted towards south, leading to more severe erosion on the northern side of the structure. Six existing gravity profiles, three of which cross the whole structure including the central island, would make a detailed 3D-gravity modeling of the structure possible, enabling also more robust interpretations of the tectonic modification in Saarijärvi.

The tectonic modification is apparently a relatively late feature in the evolution of the Saarijärvi structure. This is indicated by the fact that especially the clayey part of the sedimentary sequence is strongly fractured obliquely to bedding, often with "polished" slickenside surfaces. Therefore, it seems probable that the major tectonic deformation of the structure took place after the consolidation of the sedimentary sequence, and thus could not have been the main cause for the observed chaotic nature of the sediments now filling the structure. This further implies that the sediments could well have been deposited before the impact. Thus, the probable age for Saarijärvi structure is less than ~520–600 Ma, and not 600–1980 Ma as previously believed.

The breccia problem: A highly interesting aspect in the discussion of pre- or post-impact sedimentation in Finnish impact structures is the question of impact breccias. Even in simple craters a small amount of suevite should be present, with larger quantities of lithic breccia. None can be found in Saarijärvi. The sedimentary rocks lie directly on the basement in all three drill cores that reach the basement. The basement itself is somewhat fractured and weathered, but not brecciated. Hence, it is apparent that no major amounts of breccia are currently present in the northern or central parts of the Saarijärvi structure.

If the justified idea that Saarijärvi is an impact structure is accepted, then a means to dispose of impact breccias is needed. It ought to be kept in mind, that the structure is currently filled with sedimentary rocks that are generally quite soft and easily disintegrated. Yet they have been retained in the depression for the past 600 Ma, surviving e.g. several glaciations, whereas the usually somewhat more coherent impact breccias seem to be totally absent.

Shatter cones and concentric craters: The minimum pressure where shatter cones can be formed is ~2 GPa. Such pressures can be found in the rocks of the crater floor and the central uplift. No true shatter cones have been found in the crater rim or beyond it, because the shock pressure on the rim is about a magnitude lower than required for shatter cone formation. However, in Saarijärvi, shatter cones are found in an area beyond the current depression. The majority of these are in local granitoid boulders that have not moved substantially. Even if they had moved, glacial transport direction indicates that they would have moved towards the center of the structure.

If impact occurs on a stratified target with a weak layer on top of a more rigid one, a concentric crater should form [e.g. 5, 6]. If it is accepted that Saarijärvi area was covered by unconsolidated sedimentary rocks when the impact occurred, Saarijärvi could be a concentric crater. In this model, the current depression filled with sedimentary rocks represents the inner crater, whereas the shatter cones were formed on the floor of the outer crater. If this was the case, then very little erosion has occurred. However, until numerical modeling of a Saarijärvi-sized concentric crater formation is performed, it remains rather speculative if shock pressure in the floor of the outer crater can reach the ~2 GPa required for the shatter cone formation.

Other open questions: Geochemistry of dark cataclastic veinlets in the central island is another problematic issue. The veinlets have elevated nickel contents up to 270 ppm, and Ni/Cr-ratios are several times higher than in typical granites. In fact, they are even slightly higher than chondritic ratios. Although meteoritic contamination is an appealing explanation, hydrothermal leaching and precipitation from the metadolerites, probably occurring in conjunction with the tectonic modification of the structure and the uplift of the central island, is a more plausible one. However, further studies including e.g. platinum group elements of the veinlets, breccias and host rocks should be made before any firm conclusions can be drawn.

Summary and conclusions: The Saarijärvi impact structure is filled with Ediacaran and Early Cambrian sedimentary rocks, now interpreted to be of pre-impact origin. Although the shatter cones are rather crude and in the "wrong" place, PDFs are of the "incipient" type, high Ni/Cr-ratios of cataclastic veinlets inconclusive, and impact breccias lacking, the structure most likely was caused by an impact <520–600 Ma ago. Saarijärvi could have originated as a concentric crater, with the shatter cones now marking the floor of the outer crater. However, modeling of shock pressures in small impacts to layered targets is required to estimate how realistic such a scenario in Saarijärvi actually is.

Acknowledgements: Thanks to the following people for providing data, samples, thought-provoking conversations, and good company on field trips to Saarijärvi: A. Abels, D. Badjukov, S. Elo, J. Kohonen, M. Lehtinen, J. Moilanen, L. J. Pesonen, J. Plado, J. Raitala, P. Tuisku, A. Uutela and S. Vishnevsky. Magnus Ehrnrooth Foundation is thanked for financial support.

References: [1] Pesonen L. J. et al. (1998) *LPS XXIX*, Abstract #1262. [2] French B. M. et al. (2004) *GSA Bull., 116,* 200–218. [3] Stöffler D. and Langenhorst F. (1994) *Meteoritics, 29,* 155–181. [4] Kohonen J. and Vaarma M. (2001) *Geologi, 53,* 111–118. [5] Quaide W. L. and Oberbeck V. R. (1968) *JGR, 73,* 5247–5270. [6] Ormö J. and Lindström M. (2000) *Geol. Mag., 137,* 67–80.