Impact structures as indicators of cratonic denudation

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Meteorite impact structures can provide important information on long-term denudation on the Earth's cratons. Impact structures in the Fennoscandian Shield contain rocks (i.e., impactites), that have developed during the collision, and, possibly, remnants of the pre-impact sedimentary rocks. The crater depressions may also be filled with post-impact sediments. Sedimentary deposits in impact structures have not been much utilized before in studying the erosion-burial history of the Fennoscandian craton. Here, we use published data on meteorite impact structures to reconstruct the depth of erosion in southern Finland and neighboring platform areas. Post-impact erosion depths were estimated using an empirical relationship derived from well-preserved impact structures. Results support ultra-slow erosion of the basement and sedimentary cover continuing over hundreds of millions of years.

Keywords: Fennoscandian Shield, unconformity, meteorite impact structure, erosion, sedimentary rocks, denudation.

1. Introduction

Terrestrial meteorite impact cratering is an important geological process. Around ~200 impact structures (IMPs) are proven globally (Schmieder and Kring, 2020). The Fennoscandian Shield hosts ~17% of them whereas in Finland 12 structures are proven. The remarkable concentration of IMPs in Finland is mainly a result of the re-exposure of an extensive bedrock denudation surface, the Cambrian unconformity, and temporary burial of IMPs under the protective cover of sedimentary rocks.

Meteorite impact structures always contain breccias, but some of the structures include sedimentary rocks as well. Several small craters in Fennoscandia (Sääksjärvi, Lumparn, Karikkoselkä, Söderfjärden, Iso-Naakkima, Saarijärvi, Suvasvesi N, Neugrund, Kärdla, Lockne, Mishina Gora, and Jänisjärvi) hold remnants of post-impact sedimentary rocks or traces of pre-impact sedimentary cover. Most of the IMPs in Fennoscandia are <10 kilometers in diameter with Neoproterozoic to Upper Palaeozoic ages. In many cases, the inner structure has been studied by drilling and/or geophysical studies. Impact craters have suffered erosion of various intensity depending much on their size and age. We use this dataset to estimate erosion depths across southern Finland and its surroundings through the Neoproterozoic and Phanerozoic.

2. Study methods

We calculated erosion depths based on geometries and ages of proven IMPs in the region. Altogether, we used data on 21 simple and complex IMPs in Finland, Sweden, Estonia, and Russia (Figure 1). We applied the method of Degeai and Peulvast (2006) that is based on the empirical relationship between the original diameter (D) and original depth (dt) derived from well-preserved IMPs on Earth (Figure 2). Original depth is derived from values of maximum and minimum depth, taking into account the uncertainties (>30%) that exist in estimating depth in the global dataset due to differences between terrestrial and marine target settings, target material, and impact trajectories. The total post-impact erosion depth (*ed*) since the impact is derived by subtraction of breccia base elevation below present (*dp)* from *dt*. If *dp* is unknown, the maximum depth of the rock sequence lost to erosion is constrained by *dt* only (Figure 2). The rate of erosion is averaged for the time since impact.

3. Results

The large Keurusselkä IMP in south-central Finland has a $^{40}Ar/^{39}Ar$ date of 1150 ± 10 Ma (Schmieder et al. 2016). The original diameter has been between 14 and 36 km (Hietala and Moilanen, 2007; Osinski and Ferriére, 2016; Raiskila et al. 2011). Today, the crater is eroded close to the base of its former breccia layer (Raiskila et al. 2013), indicating a post-impact erosion depth of 0.80–1.23 km. Thus, the long-time erosion rate is, considering the age, very low (<1 m/Ma).

The absence of small Mesoproterozoic IMPs likely reflects the protection of the basement beneath the sedimentary cover. Iso-Naakkima, only 130 km E of Keurusselkä (Figure 1), has a palaeomagnetic age of 1200–900 Ma (Pesonen et al. 1996). Considering the above erosion rate, the survival of this small (*D* = 2.5 km) crater is incompatible with erosion and the palaeomagnetic age is most likely overestimated. Microfossil evidence from the sediment sequence prefers rather the early Ediacaran age (Elo et al., 1993), and erosion depth can be explained if the youngest sediment is of post-impact age. Existence of this small crater can be accounted for by slow erosion in the Ediacaran and later burial. Also, the survival of the small (*D* = 3.8 km) IMP at Suvasvesi North dated to >710 Ma (Schmieder et al. 2016b) implies limited basement erosion during or since the Neoproterozoic.

Jänisjärvi is dated to 687 ± 5 Ma and it retains fragments of Neoproterozoic siltstone in breccias (Jourdan et al. 2012). Its *dp* is uncertain, but *dt* provides a maximum depth of erosion of 650 m. Söderfjärden (550–520 Ma) and Kärdla (455 Ma) have been buried since the formation and preserve original crater forms (Puura and Plado, 2005). Söderfjärden (*D* = 6.6 km) provides an estimate for *dt* of 390 m that compares to a drilled depth of 320 m (Lehtovaara, 1982; Öhman and Preeden, 2013) and recent seismic studies between 330–410 m of depth (Fennvik, 2018). At Kärdla (*D* = 4 km), the estimated *dt* is 290 m and the drilled depth of impact breccias is 220 m (Suuroja et al., 2002). At Söderfjärden the fine state of preservation of the crater rim indicates that this crater has been exhumed recently.

Two IMPs of the Triassic age, Karikkoselkä (Schmieder et al. 2010; Schwarz et al. 2015) and Paasselkä (Schwarz et al. 2015), show that the original depths of these structures constrain the maximum remaining depths of Palaeozoic sedimentary rock at the time of impact to 170–490 m. Lappajärvi 170 m of the sedimentary cover has been removed since 78 Ma, providing an average erosion rate of 2.2 m/Ma since impact. Results show also that Cenozoic erosion rates remained low.

4. Discussion and conclusions

Meteorite impact structures provide important evidence of burial and post-impact erosional histories (e.g., Masaitis, 2005; Puura and Plado, 2005) potentially spanning a prolonged period of time since they are not an immediate consequence of plate tectonic movements and subsequent thickening or thinning of the crust. In Finland, the sedimentary rocks preserved in IMPs indicate that (i) W and S Finland retained Early Palaeozoic cover through the Mesozoic, whereas (ii) in E Finland, Early Palaeozoic cover persisted in the Triassic, but the basement was re-exposed by the Late Cretaceous.

The absence of IMPs dated between 1150 and 710 Ma supports the former existence of protective sedimentary cover(s); perhaps including transient sedimentary cover derived from the Sveconorwegian orogenic belt. However, this cover may not have been thick: thickness of ≥640 m has been sufficient to protect the basement from any crater with $D \geq 10$ km. We note that the survival of small IMPs ($D \leq 5$ km) permits only limited depths of erosion ($dt \leq 300$ m). Altogether, the IMPs show that the Fennoscandian Shield has suffered ultra-slow erosion in the basement and sedimentary cover with rates to <2.5 m/Ma. This value is one of the lowest reported on Earth (see Hall et al. 2020).

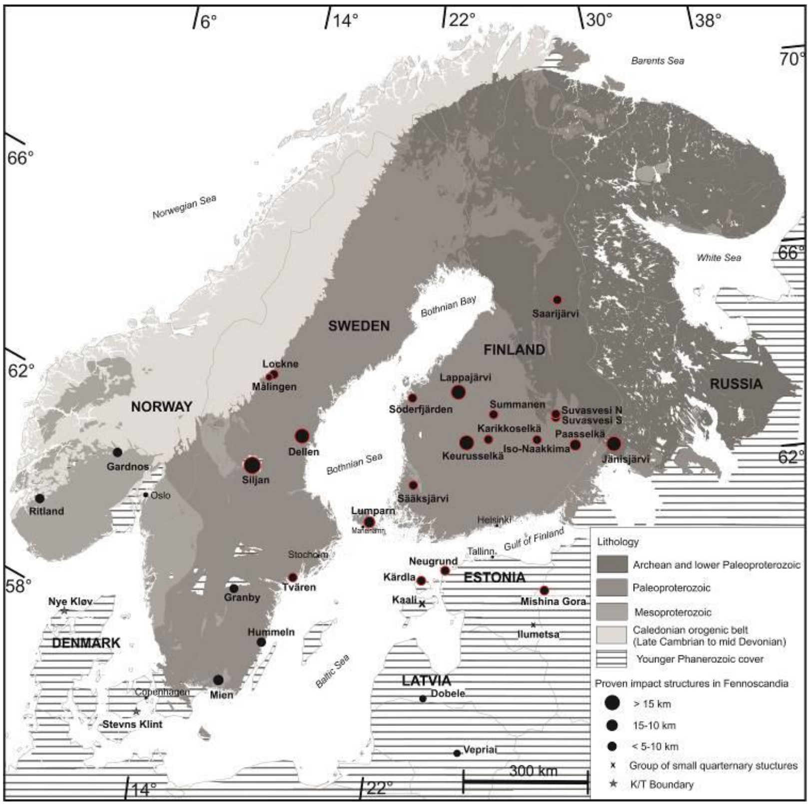

Figure 1. Bedrock map of the Fennoscandian Shield and proven impact structures. The studied impact structures are surrounded by red circles. Modified after Koistinen et al. (2001) and Plado & Pesonen (2002).

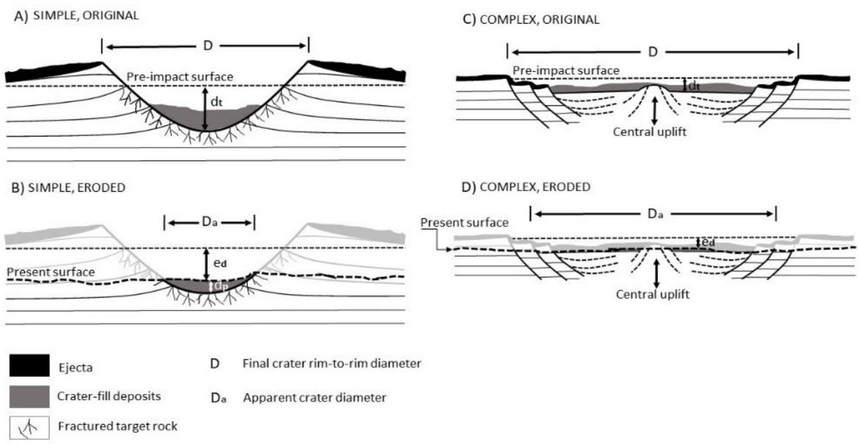

Figure 2. Models for simple and complex impact structures used to estimate post-impact erosion depths. Adapted from Degeai & Peulvast (2006), Osinski et al. (2018), Peulvast et al. (2009), and Turtle et al. (2005).

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