Age of the Sääksjärvi impact structure, Finland: reconciling the timing of small impacts in crystalline basement with regional basin development

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We report a new age for the Sääksjärvi impact structure, Finland, a 6 km in diameter feature that formed in crystalline rocks of the Precambrian Baltic Shield. Two previous studies have reported $^{40}$Ar/$^{39}$Ar data for Sääksjärvi and suggested conflicting formation ages of $\leq 330$ Ma or approximately $560$ Ma, respectively. The former represents a possible complication for models which indicate that the region was covered by sediments of the Caledonian foreland basin throughout much of the Phanerozoic. We conducted a study combining imaging, microstructural analysis and U–Pb dating of shocked zircon from Sääksjärvi. The U–Pb dataset indicates a ca. 600 Ma impact into predominantly ca. 1850 Ma target rocks. A concordia age of $608 \pm 8$ Ma (2σ) confirms Sääksjärvi as the first known Ediacaran impact structure in the Baltic Shield and only the second worldwide. Our data indicate that the Sääksjärvi impact structure formed in exposed crystalline basement rocks of the Baltic Shield prior to the development of the Caledonian foreland basin. Given that most impact structures on Earth are relatively small features, radiometric dating of small impact structures in crystalline basement may place boundaries on the timing and spatial extent of palaeobasins that might be otherwise difficult to constrain.
1. INTRODUCTION

Small impact structures in crystalline basement have a unique ability to shed light on the
temporal and spatial extent of palaeobasins. Impact structures sometimes provide, in their impact
lithologies or down-faulted segments, a useful record of pre-impact bedrock units that have
otherwise been completely removed from around the structure; for example, the Lappajärvi
impact structure, Finland, preserves in its structural depression sedimentary units that have
facilitated reconstructions of Cambrian palaeogeography in the Baltic region (e.g., Slater and
Willman, 2019, and references therein). Similarly, the Siljan impact structure in Sweden, and the
Manicouagan impact structure in Canada, also preserve megablocks of early Phanerozoic
sedimentary units that are not well preserved in the surrounding regions (e.g., Grieve, 2006;
Grieve and Head, 1983; Lehnert et al., 2012, 2014, and references therein). At Paasselkä, and a
number of other impact structures in Finland and Sweden, impact melt breccias contain shocked
and melted fragments of Mesoproterozoic ‘Jotnian Sandstone’ that has been completely removed
by erosion elsewhere in the area (Buchner et al., 2009; Puura and Plado, 2005). Conversely, the
presence of small impact structures in crystalline basement can provide evidence that the
basement was not deeply covered by sediments at a given time if an accurate and precise age for
the structure can be attained. Such structures may therefore offer an opportunity to test, and even
place boundaries on, the size and lifetime of sedimentary basins which might otherwise be
difficult to constrain. To explore this possibility, we here revisit the age of a small impact
structure in crystalline basement (the Sääksjärvi impact structure, Finland) for which conflicting
$^{40}$Ar/$^{39}$Ar ages have been published (Bottomley et al., 1990; Müller et al., 1990), one of which
overlaps a proposed period of significant sedimentary cover in the region.
1.1. The Sääksjärvi impact structure, Finland

The Sääksjärvi impact structure is a deeply eroded, approximately 6 km in diameter feature submerged beneath an eponymous lake in southwest Finland (Fig. 1; e.g., Willman et al., 2010). Papunen (1969) suggested an impact origin for Sääksjärvi based on the observation of multiple sets of closely spaced planar structures in quartz within heavily brecciated and vesiculated rocks from the eastern shore of Lake Sääksjärvi and a glacial esker approximately 20 km to the southeast. To the best of our knowledge, there are no known outcrops of in situ impactites at Sääksjärvi (e.g., Papunen 1969, 1973; Pihlaja and Kujala, 2000). The structure has been targeted by six drill holes (totalling 860 m in length), including one into the centre of the gravity low which penetrated 180 m of suevite and other breccias (but not a coherent melt sheet) before terminating in deformed mica gneiss basement at a depth below surface of 242 m (Pihlaja and Kujala, 2000). Platinum group element patterns and Ni/Cr, Ni/Ir, and Cr/Ir ratios of impact melt lithologies suggest the Sääksjärvi impactor was likely a non-magmatic iron meteorite (Schmidt et al., 1997, Tagle et al. 2009).

Two studies have reported $^{40}$Ar/$^{39}$Ar data for impact melt rocks and impact melt-bearing breccias from Sääksjärvi. Bottomley et al. (1990) reported data from three samples described as fine-grained melt rocks with quartz and feldspar clasts that were relatively unrecrystallised. The samples displayed two distinct trends in their step-heating spectra: two samples gave progressively older apparent ages from Ar release steps as heating continued (and $^{39}$Ar was incrementally released), with ages rising from ca. 330 Ma and forming a plateau between 510 and 530 Ma, whereas aliquots from another sample gave a humped spectrum, with steps rising from ca. 400 Ma to a peak at ca. 650 Ma and then forming a plateau at ca. 600 Ma. The dataset
Figure 1. Map of impact structures in the Baltic region. Best estimate ages, structure diameters and target rock compositions from Schmieder and Kring (2020). When the age of an impact structure is given as a range in Schmieder and Kring (2020) we use the midrange value – for example, for the Iso-Naakkima impact structure, which is considered to have formed 1200–900 Ma, we use a value of 1050 Ma. Sääksjärvi is plotted using the new 608 ± 8 Ma age reported here. See Table 1 in Supplementary Appendix for full data used to create map.

Approximate extent of the Baltic Shield (including Caledonian Orogenic Belt) and Phanerozoic sediments after Murrell and Andriessen (2004). The Caledonian foreland basin lay to the east of the Caledonian Orogenic Belt, over present day Sweden and Finland, but its precise extent is uncertain (see text).

lacked any statistically relevant plateaus that may have represented an impact age (see discussion of $^{40}$Ar/$^{39}$Ar dating of impact structures by Jourdan [2012]) and Bottomley et al. (1990) interpreted their data to indicate that a ≤330 Ma impact had incompletely degassed target rocks with K-Ar ages of between 500 and 600 Ma. Müller et al. (1990) reported $^{40}$Ar/$^{39}$Ar data for one
sample, which was described as a cryptocrystalline melt breccia with >15 % clasts (predominantly quartz and feldspar) and a matrix dominated by plagioclase and pyroxene. The sample gave a humped age spectrum with apparent age domains of ca. 550 and ca. 600 Ma. With no reason to prefer one age over the other, Müller et al. (1990) suggested that the ages should not be taken “too seriously”. Nevertheless, Müller et al. (1990) considered a weighted average age of 560 ± 16 Ma to be their best estimate for the age of the impact event. Similar to the dataset of Bottomley et al. (1990), the data presented by Müller et al. (1990) lack statistically robust plateaus and so none of the currently available $^{40}$Ar/$^{39}$Ar data from impact melt at Sääksjärvi are likely to record an accurate impact age.

1.2. Geological setting of the Sääksjärvi impact structure

The Sääksjärvi impact structure formed in crystalline basement of the Baltic Shield, in 1.9–1.8 Ga rocks related to the Svecofennian orogeny (Fig. 2). During the Phanerozoic these basement rocks were largely covered by sediments as a major foreland basin developed to the east of the Scandinavian Caledonides (Fig. 1) (e.g., Cederbom et al., 2000; Garfunkel and Greiling, 1998; Larson et al., 1999; Middleton et al., 1996; Murrell and Andriessen, 2004). However, the Caledonian foreland basin is not well preserved as rock exposures and estimates for its extent and, particularly, life span vary significantly.

Fission-track thermochronology and inverse modelling suggests that most of Finland was buried by approximately 1 km of Upper Paleozoic sediments that thickened to approximately 2.5 km towards the Caledonian border zone of western and southern Sweden (Cederbom et al., 2000; Larson et al., 1999). Cederbom et al. (2000) presented models indicating that the basin existed from the Devonian through to the early Mesozoic or even Cenozoic. Murrell and Andriessen (2004) interpreted apatite fission-track data for southern Finland to indicate that late Silurian
Figure 2. Simplified geological map of the Sääksjärvi impact structure, Finland, after the 1:200 000 bedrock map of the Geological Survey of Finland (GTK, 2017). White shaded area represents a lake (Sääksjärvi) and white lines denote rivers.

heating, associated with the proposed Caledonian foreland basin, was followed by Cenozoic cooling, representing exhumation and final exposure of the basement. Alternative models suggest that even the deepest portions of the basin, in Sweden, were largely eroded by the mid-Permian, with any Mesozoic sediment cover not exceeding 100 m (Söderlund et al., 2005).

1.3. Reconciling the Sääksjärvi impact event and the evolution of the Caledonian foreland basin

The suggestion that Sääksjärvi, a small impact structure in crystalline basement with no evidence for incorporation of supracrustal sedimentary rocks, formed at or after 330 Ma
is problematic for models that imply the region was covered with sediment for much of the Phanerozoic.

In light of the inconsistency between estimates for the timing of the Sääksjärvi impact event based on $^{40}\text{Ar}/^{39}\text{Ar}$ data (Bottomley et al., 1990; Müller et al., 1990) and evidence that the basement, which formed the target rock of the Sääksjärvi impact event, was in fact covered by up to 1.5 km of sediments of the Caledonian foreland basin during a long period comprising much of the Phanerozoic (e.g., Larson et al., 1999), we here revisit the age of the Sääksjärvi impact event with high spatial resolution U–Pb geochronology. Impact ages have long been obtained from U–Pb analysis of shocked accessory phases (e.g., Kamo and Krogh, 1995; Kamo et al., 2011; Krogh et al., 1984, 1993, 1996; Mänttäri and Koivisto, 2001) with recent advances offering the ability to better isolate impact-age domains of heterogeneous grains. These developments include decreasing analytical volumes in in situ geochronology. Another critical methodological advance is the ability to recognise impact-related microstructures that ultimately can be dated (e.g., Cavosie et al., 2015; Erickson et al., 2016, 2017, 2020; Kenny et al., 2017, 2019; Timms et al., 2017). Promisingly, microstructures in zircon that are suitable for dating (such as neoblasts in recrystallised grains) are not restricted to the largest impact structures but have been documented at structures as small as the 1.2 km in diameter Meteor Crater, USA (Cavosie et al., 2016).

Here we report on imaging, microstructural analysis and U–Pb dating of shocked zircon from the Sääksjärvi impact structure and present a new U–Pb age for the structure that is older than previously suggested ages and consistent with the presence of the Caledonian foreland basin.

2. MATERIAL AND METHODS
Zircon grains were separated from five samples from the Sääksjärvi impact structure: three samples of impact melt rock (n1047_IMP-2, n1049_IMP-1, and n5947_MS-17-1) and two samples of impact melt-bearing breccia (n1048_IMP-3 and n1050_IMP-11b). Four of the samples were taken from drill cores reported on by Pihlaja and Kujala (2000) and n5947_MS-17-1 was a float sample. Unfortunately, the coordinates of the drill holes, as well as the intervals at which these samples were collected, are not known and the precise origin of the float sample is uncertain (although it was likely collected from the eastern or south-eastern shore of lake Sääksjärvi or in glacial drift southeast of the structure – see Willman et al. [2010] and Fig. 1 in Papunen [1969] for occurrences of impactites in the Sääksjärvi area).

The samples were disaggregated in a jaw crusher and ring-and-puck-style mill before their heavy mineral fractions were concentrated by magnetic separation (with a hand magnet and Frantz magnetic separator) and heavy liquid density separation (using methylene iodide with a density of approximately 3.3 g/cm$^3$). Zircon grains with a turbid, or cloudy, appearance were preferentially picked from the heavy mineral separates as it has been shown that these are more likely to be granular and contain age-reset domains than translucent grains (e.g., Schmieder et al., 2015). The selected grains were placed on double-sided sticky tape and cast in 2.5 cm-diameter epoxy mounts. The mounts were polished with a diamond suspension to expose grain interiors and a final polish with colloidal silica prepared the grains for microstructural analysis.

This study comprised three separate analytical periods, in 2001 (period #1; the results of which were presented by Mänttäri et al. [2004]), 2018 (period #2), and 2020 (period #3). In 2001 zircon grains from samples n1047_IMP-2, n1048_IMP-3, n1049_IMP-1, and n1050_IMP-11b were imaged in scanning electron microscopy (SEM) backscattered electron (BSE) mode and analysed for U–Pb isotopic composition and age by secondary ion mass spectrometry (SIMS) on
the Cameca IMS1270 ion microprobe at the NordSIMS Laboratory, Swedish Museum of Natural History, with an analytical pit diameter of approximately 30 μm (generated with a duoplasmatron O ion source). In 2018 zircon grains from sample n5947_MS-17-1 were imaged in BSE, secondary electron (SE), and cathodoluminescence (CL) mode before undergoing U–Pb analysis using the NordSIMS instrument upgraded to Cameca IMS1280, which employed an analytical pit approximately 15 μm in diameter (also generated with a duoplasmatron O ion source). In 2020 grains from the 2001 analytical session were revisited. The grains were repolished to remove the original analytical pits before being imaged in BSE, SE, and CL modes. Nine grains with granular and/or porous textures were then selected for microstructural characterisation by electron backscatter diffraction (EBSD) analysis (three of these had undergone U–Pb analysis in 2001 whereas the others had not been analysed previously). These grains then underwent U–Pb isotopic analysis in which the analytical pit was approximately 5 μm in diameter (using a Hyperion radio-frequency [RF] plasma ion source). Grain n1048_IMP-3_z5, which was analysed with two 30 μm diameter pits in 2001 and nine 5 μm diameter pits in 2020, was subsequently analysed with two 10 μm diameter analytical pits (also using the Hyperion RF plasma ion source).

In analytical period #1, the polished surfaces of the zircon grains were imaged in BSE mode. In periods #2-3, the grains were imaged in BSE, SE, and CL modes on an FEI Quanta FEG 650 SEM equipped with a Gatan ChromaCL2 system at the Swedish Museum of Natural History, Stockholm.

Electron backscatter diffraction analysis was performed with an Oxford Instruments Nordlys detector attached to the FEI Quanta FEG 650 SEM. Grains were indexed for zircon, reidite and monoclinic ZrO₂ using match units based on crystallographic data from Hazen and
Finger (1979), Farnan et al. (2003), and Howard et al. (1988), respectively. Analytical conditions and parameters include: accelerating voltage of 20 kV, working distance ~18 mm, stage tilt of 70°, electron backscatter pattern (EBSP) binning of 4x4, EBSP gain set to ‘High’, and background defined with collection of 128 frames, Hough resolution set to 60, band detection min/max of 6/8. Maps were collected with step sizes between 90 and 250 nm. Data collection was performed in Oxford Instruments AZtec software and post-acquisition processing in Oxford Instruments Channel 5 software v. 5.12. Data cleaning in Channel 5 comprised a wildspike correction and a level six nearest neighbor zero solution extrapolation for all grains. Maps of local misorientation represent the average misorientation between pixels in 5x5 (Fig. 3), 7x7 (Supplementary Figs 3-4), or 9x9 (Supplementary Fig. 5) grids. Grain boundaries, which are shown in some maps, are here defined by >2° misorientation between adjacent pixels.

In the 2001 and 2018 U–Pb sessions, the analytical procedure largely followed the routine of Whitehouse et al. (2001), with the duosplasmatron-generated primary beam yielding analysis pits approximately 30 and 15 μm across, respectively. In the 2020 analytical period the Hyperion-generated primary beam largely generated analysis pits approximately 5 μm across, with two additional analyses performed with a 10 μm pit. A routine correction for common Pb (Pb_c) was applied during post-acquisition processing of the U–Pb data. The percentage of non-radiogenic, i.e. common, 206Pb (f_{206}%) in the total measured 206Pb was estimated from measured 204Pb, assuming a modern-day Stacey and Kramers (1975) Pb composition, i.e. that Pb_c encountered in the analyses is likely to be modern and related to unavoidable sample contamination (in crevices) during polishing of the grain mount (Zeck and Whitehouse, 1999). If the Pb_c is not modern but is actually ancient, U–Pb ages for high-Pb_c analyses will be slightly over-corrected, i.e. slightly too young. This is unlikely to be significant and Kenny et al. (2019)
reported that their concordia age for relatively Pb\textsubscript{c}-rich ($f_{206}$% ranging from 0.15 to 3.08)
shocked zircon from the Lappajärvi impact structure would be less than 0.2 % older if the Pb\textsubscript{c}
encountered in those analyses was 1.9 Ga (a likely crystallisation age for those grains) and not
modern, as assumed. In all sessions 91500 standard zircon (ID-TIMS 206\textsuperscript{Pb}/238\textsuperscript{U} age = 1062.4 ±
0.8 Ma; Wiedenbeck et al., 1995) was used as the calibration reference material. Temora 2 (ID-
TIMS 206\textsuperscript{Pb}/238\textsuperscript{U} age = 416.78 ± 0.33 Ma; Black et al., 2004), which has consistently given ages
within ± 1% relative to the reference age when analysed at the NordSIMS laboratory (Jeon and
Whitehouse, 2015), was analysed as a secondary reference material during the 2018 session and
the 10 μm session in 2020, returning weighted average ages of 420.6 ± 3.0 Ma (MSWD = 0.93,
probability = 0.46, n = 6) and 420.6 ± 3.3 Ma (MSWD = 0.37, probability = 0.92, n = 8),
respectively. We used the decay constant values of Steiger and Jäger (1977) and all uncertainties
are presented at the 2σ level.

3. RESULTS

3.1. Imaging

Zircon grains from all five samples have diverse appearances with approximately half of the
deliberately picked cloudy grains exhibiting simple to complex internal zonation, with no
evidence for impact-related deformation, and half displaying granular and/or porous textures.

Of the apparently granular grains, some appear almost entirely recrystallised (e.g., Fig. 3) and
others retain conspicuous non-recrystallised domains (e.g., Fig. 4), whereas for others the degree
of the recrystallisation is not clear from imaging alone (e.g., Fig. 5). Individual neoblasts within
recrystallised grains range in size from less than 1 μm up to approximately 15 μm in dimension
and appear to take one of two forms: rounded granules 1-3 μm in size (e.g., Figs 3-4) or
Figure 3. Example of granular zircon from Sääksjärvi which preserves evidence for the former presence of reidite – grain n1048_IMP-3_z13. F-G: Pole figures and plots of high-angle misorientation axes provide microstructural evidence for the former presence of reidite in the form of: (i) domains of neoblasts systematically misoriented by 90°, (ii) coincidence among (001) and {110} poles, and (iii) high-angle misorientation axes coincident with poles to {110}. Ellipses show locations of SIMS U–Pb analyses. IPF – Inverse Pole Figure.
Figure 4. Example of granular zircon from Sääksjärvi which does not preserve evidence for the former presence of reidite–grain n1048_IMP-3_z4 (contrast with Fig. 3). Dashed ellipse A shows the approximate location of a 30 μm analytical pit (session #1, 2001) prior to repolishing for imaging and microstructural analysis shown here.
**Figure 5.** A zircon grain (n1049_IMP-1_z11) from Sääksjärvi which appears granular in backscattered electron and cathodoluminescence imaging but microstructural analysis reveals that apparent sub-domains share a single approximate orientation.
subhedral to euhedral crystallites which are generally larger (e.g., Fig. 6). Some grains display both small, rounded granules and larger, euhedral crystallites (e.g., Fig. 6).

Grains with pores generally also display some degree of recrystallisation elsewhere in the grain (e.g., Fig. 6 and Supplementary Figs 1-2). Pores are usually round and approximately 0.2 μm in diameter; in some grains they are quite homogeneously distributed (e.g., Fig. 6) whereas in others they occur in bands, suggestive of a possible relationship with pre-impact zoning within the zircon (e.g., Supplementary Figs 1-2).

3.2. Microstructural characterisation

Six of the nine grains selected for EBSD analysis indexed well, producing whole-grain microstructural maps (Figs. 3-5 and Supplementary Figs 3-5), whereas one grain only indexed on approximately 20% of the exposed surface (Fig. 6) and two did not produce electron backscatter diffraction patterns and so were not mapped (see imaging in Supplementary Figs 1-2).

In all grains zircon was the only phase to index. No evidence was encountered for ZrO$_2$ (a product of zircon dissociation at high temperature, which commonly accompanied granular textures in impact-related zircon; e.g., Timms et al., 2017; Cavosie et al., 2018) or the current presence of the high-pressure ZrSiO$_4$ polymorph, reidite (e.g., Glass et al., 2002).

Microstructural characterisation reveals that many grains are almost entirely composed of low-strain, newly crystallised domains, neoblasts (Fig. 3), whereas others retain non-recrystallised domains defined by high degrees of strain apparent in maps of local misorientation (e.g., Supplementary Figs 3,5). Of the seven grains which displayed at least some degree of recrystallisation and were analysed by EBSD, four preserve crystallographic evidence for the former presence of reidite in the form of: (i) domains of neoblasts systematically misoriented by
Figure 6. Shocked zircon that most accurately and precisely records the age of the Sääksjärvi impact event – grain n1048_IMP-3_z5. The grain displays both granular (B) and porous (C) textures. Dashed ellipses A and B show the approximate location of 30 μm analytical pits (session #1, 2001) prior to repolishing for imaging and microstructural analysis shown here. Of the other analysis pits, C to K are approximately 5 μm in diameter and L and M are approximately 10 μm in diameter. The 608 ± 8 Ma concordia age was obtained from data from analytical pits C, D, G, and K, which are shown in red.
90°, (ii) coincidence among (001) and {110} poles, and (iii) high-angle misorientation axes coincident with poles to {110} (Fig. 3, Supplementary Figs 3-5), which are indicative of the transformation sequence zircon → reidite → zircon (Cavosie et al., 2016, 2018, Timms et al., 2017). Of the three remaining granular grains, one displays a non-recrystallised core (with up to 5° internal misorientation) that is surrounded by granules with apparently random orientations (Fig. 4), one appears granular in BSE and CL images but microstructural analysis shows that sub-domains share a single approximate orientation (and deformation occurs in the form of misorientation up to approximately 10° across the grain; Fig. 5), and the third is partly granular and partly porous, with neoblasts not displaying any systematic relationships (Fig. 6).

3.3. U–Pb geochronology

The first U–Pb analyses, with analytical pit diameters of approximately 30 μm, were performed in 2001 and target sites for the 43 analyses (on 34 zircon grains from four samples) were based on BSE images. The data define two discordant trends in U–Pb space: one between ca. 1.85 Ga and ca. 600 Ma and the other between ca. 600 Ma and present (Fig. 7A). The ca. 1.85 Ga ages are consistent with the Svecofennian ages of the target rocks at Sääksjärvi (Fig. 2) whereas the ca. 600 Ma lower intercept age is not known from any rocks in the area. Most analyses which plot to the right of the ca. 1.85 Ga to ca. 600 Ma discordant array in Tera-Wasserburg (TW) space (Fig. 7A) have $^{207}\text{Pb}/^{206}\text{Pb}$ ages of ca. 600 Ma, consistent with later Pb loss superimposed on grains which were fully age reset at ca. 600 Ma. However, a few grains that lie off the ca. 1850–600 Ma trend have $^{207}\text{Pb}/^{206}\text{Pb}$ ages >600 Ma, indicating later Pb loss superimposed on grains which were only partially reset at ca. 600 Ma.

The second batch of U–Pb analyses, with analytical pit diameters of approximately 15 μm, was undertaken in 2018 and, for this analytical session, target sites for 22 analyses (on 17 zircon
Figure 7. Concordia diagrams displaying all secondary ion mass spectrometry (SIMS) U–Pb data gathered in this study. A: Data generated with 30 and 15 μm analytical spots (using duoplasmatron ion source during SIMS analyses). B: Data generated with 10 and 5 μm analytical spots (using Hyperion RF plasma ion source during SIMS analyses). C: Data for grain n1048_IMP-3_z5 (see Fig. 5) – colours as in B. All data rendered at 2σ uncertainty.
grains from a previously unanalysed sample of impact melt rock, n5947_MS-17-1) were selected based on BSE, SE, and CL images of the grains. Four analyses plot on or close to the concordia curve at \( \text{ca.} 1850 \text{ Ma} \), consistent with the previously recognised Svecofennian ages; one analysis lies on the \( \text{ca.} 1850–600 \text{ Ma} \) discordia trend; and the remaining analyses plot to the right of the discordia trend, again consistent with later Pb loss superimposed on the original discordant array. Additionally, a single, almost concordant analysis gave a \( ^{207}\text{Pb}^{/206}\text{Pb} \) age of \( \text{ca.} 2.6 \text{ Ga} \) (Fig. 7A), highlighting an age not recognised in the earlier U–Pb dataset.

The third set of U–Pb analyses, most with analytical pit diameters of approximately 5 \( \mu \text{m} \) and two with pit diameters of 10 \( \mu \text{m} \), were performed in 2020. This time, target locations for 50 analyses (on nine zircon grains from three of the samples first analysed in 2001) were based on EBSD maps and complementary BSE, SE, and CL images (except for the two grains which did not index well and were targeted on the basis of traditional images alone; Supplementary Figs 1-2). On the basis of microstructural characterisation, we targeted (i) individual neoblasts and domains of neoblasts (with the aim to date recrystallisation), as well as (ii) non-recrystallised, high-strain domains, and (iii) porous, non-indexing regions in three grains. Similar to earlier analyses, the new dataset defines a trend between \( \text{ca.} 1.85 \text{ Ga} \) and \( \text{ca.} 600 \text{ Ma} \) with approximately 15 analyses plotting to the right of the array in TW space, indicative of later Pb loss superimposed on the original discordant array (Fig. 7B). However, many isotopic ratios and ages from this session have significantly larger uncertainties than encountered previously – a result of a higher proportion of analyses incorporating significant amounts of \( \text{Pb}_c \) (40% of analyses had \( f_{206}\% >1 \) compared to 14% of analyses in the 2001 session), likely due to targeting of granular grains. One grain was particularly rich in \( \text{Pb}_c \), with calculated \( f_{206}\% \) values ranging between 4.7 and 9.3 (grain n1050_IMP-11b_z18; Supplementary Fig. 4). The application of a
Pb correction to the seven data points from this grain result in over-correction with six of the Pb-corrected data points lying below the concordia curve in TW space.

Plotting a regression through 56 of the 115 analyses from all analytical sessions (excluding analyses which clearly lie off the ca 1.85 Ga to ca. 600 Ma trend, i.e., those with ages >2.0 Ga, those which experienced significant later Pb loss, and those with substantial Pb-c components) yields a discordia line with a 1856 ± 15 Ma upper intercept and a 597 ± 7 Ma lower intercept (mean square of weighted deviates [MSWD] = 2.1) (Supplementary Fig. 7). The relatively high MSWD indicates some scatter in the data, which is likely related to subtle post-impact Pb loss even in this screened population, and perhaps also heterogeneous pre-impact ages of the zircon grains. Calculating a weighting mean ²⁰⁷Pb/²⁰⁶Pb age from the 21 analyses defining the horizontal array between ca. 600 Ma and present day gives an age of 679 ± 18 Ma (MSWD = 3.4) (Supplementary Fig. 7). The relatively high MSWD on this age again indicates scatter in the data, which, in this instance, can be attributed to variable degrees of Pb loss during the ca. 600 Ma event.

One grain in the 2020 dataset gave concordant data points at the ca. 600 Ma lower intercept of the discordant array which lack significant Pb contamination and therefore have small uncertainties (Fig. 7B-C). Four concordant, low Pb (f₂⁰⁶% values of 0.01, 0.01, 0.02, and 0.06) analyses on grain n1048_IMP-3_z5 give a concordia age (Ludwig, 1998) of 608 ± 8 Ma (2σ; MSWD of concordance and equivalence = 1.06; probability of concordance and equivalence = 0.39) (Fig. 7C). Given the low Pb values of these four analyses, whether the Pb is modern, as assumed in the Pb-c correction, or ancient will not affect the age at this level of precision. Significantly, the concordant data points with low Pb were from the porous portion of this mixed porous-granular grain (Fig. 6A,E and Supplementary Fig. 6; see also Supplementary Fig.
8 for a concordia diagram coloured according to zircon texture). Following the nine analyses with 5 μm diameter analytical pits, this grain was targeted with two 10 μm diameter analytical pits. However, neither of these two analyses were concordant, with one (targeting the porous domain) plotting back along the discordia array and the other (targeting a large neoblast) having experienced later Pb loss (Fig. 7B-C).

4. DISCUSSION

4.1. Age of the Sääksjärvi impact event

We interpret the ca. 1.85 Ga to ca. 600 Ma array of U–Pb data presented here to indicate partial Pb loss during an Ediacaran impact into Palaeoproterozoic Svecofennian rocks of the Baltic Shield. This was first suggested by Mänttäri et al. (2004) on the basis of the data acquired in the 2001 analytical period. Within the context of the 115 analyses on 57 zircon grains from five suevite and impact melt rock samples (over three analytical periods) the 608 ± 8 Ma concordia age (Fig. 7C) from a porous zircon grain represents the best age estimate for the Sääksjärvi impact event. We prefer the 608 ± 8 Ma age over the 597 ± 7 Ma lower intercept age calculated from 56 analyses as the high MSWD of the latter indicates some scatter, which is likely related to post-impact Pb loss in even that screened population. The 608 ± 8 Ma age is also favourable to the weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age calculated from the horizontal array as the older age of the latter can be attributed to variable degrees of incomplete impact-induced Pb loss (as reflected by its high MSWD value).

Our new age for the Sääksjärvi impact event is older than previous estimates of ≤330 Ma and ca. 560 Ma, which were based on $^{40}\text{Ar}/^{39}\text{Ar}$ data, and makes Sääksjärvi the first confirmed Ediacaran impact structure in Finland and the wider Baltic Shield (given that the 546 ± 5 Ma for the Gardnos impact structure, Norway [Kalleson et al., 2009] is based on ambiguous U–Pb data).
Furthermore, Sääksjärvi becomes only the second confirmed Ediacaran impact structure worldwide, with the Acraman impact structure, Australia, constrained to this time by the recognition of an associated ejecta layer in the Ediacaran Bunyeroo Formation (Williams and Gostin, 2005; Schmieder et al., 2015, and references therein).

### 4.2. Implications for the Caledonian foreland basin

As originally proposed by Mänttäri et al. (2004), the new Ediacaran age for the Sääksjärvi impact event reconciles the presence of this impact structure in crystalline basement with regional sedimentary cover of the Caledonian foreland basin persisting from its Siluro-Devonian onset through much of the Phanerozoic, and eliminates complications raised by a previously proposed age of ≤330 Ma (Fig. 8). Furthermore, the ca. 330 Ma component in the \(^{40}\text{Ar}/^{39}\text{Ar}\) data of Bottomley et al. (1990) may have resulted from heating caused by burial related to Caledonian sediment loading. The spread of \(^{40}\text{Ar}/^{39}\text{Ar}\) data between ca. 330 Ma and ca. 650 Ma (Bottomley et al., 1990) may now be reinterpreted as partial resetting of the \(^{40}\text{Ar}/^{39}\text{Ar}\) system as a result of burial and heating that is recognised in apatite fission-track datasets throughout the Baltic Shield (e.g., Cederbom et al., 2000; Murrell and Andriessen, 2004; Larson et al., 1999). However, it is not possible to ascertain whether the partial resetting related to burial and heating (caused by the overburden of sediment) was superimposed on almost complete resetting of the \(^{40}\text{Ar}/^{39}\text{Ar}\) system at the 608 ± 8 Ma impact or if it simply represents partial resetting from predominantly Palaeoproterozoic target rock ages. The interpretation that the \(^{40}\text{Ar}/^{39}\text{Ar}\) data is recording Paleozoic burial is also consistent with late Paleozoic lower-intercept ages of zircon across the Baltic Shield, considered a result of Pb having been leached from the grains by hydrothermal solutions related to the Caledonian Orogeny and foreland basin (Larson and Tullborg, 1998).

Similarly, a ca. 385 Ma age obtained from \(^{40}\text{Ar}/^{39}\text{Ar}\) analysis of impact melt lithologies from the
Figure 8. Age distribution of impact structures in the Baltic region. A: Previous interpretations of $^{40}\text{Ar}^{39}\text{Ar}$ data for Sääksjärvi (shown in red) overlying the distribution of other impact structures formed in crystalline basement. B: New U–Pb age from this study (shown in green) and distribution which includes the new age for Sääksjärvi. C: Age data for all impact structures of the Baltic region considered in this study (see Fig. 1). Histogram coloured according to scheme of Fig. 1. Five impact structures have poor age constraints and are not represented (see Table 1 in Supplementary Appendix).
Gardnos impact structure, Norway, has been interpreted to represent thermal overprinting of the Caledonian Orogeny and not the impact event itself (Grier et al., 1999), although this conclusion has been contested (Jaret et al., 2016).

### 4.3. Implications for dating impact events with shocked zircon

It is striking that the four precise, concordant data points used to calculate the new age for the Sääksjärvi impact event were from porous, non-indexing (i.e., poorly crystalline) domains of a zircon grain and not from the many recrystallised, or granular, domains analysed.

A number of recent studies have, in addition to analysing recrystallised (neoblastic) accessory phases such as zircon and apatite, also obtained impact ages from non-granular, but pore-rich grains (e.g., McGregor et al., 2018, 2019; Schmieder et al., 2019; Schwarz et al., 2020). However, most studies which have incorporated microstructural analysis have focused on targeting recrystallised (neoblastic) domains of shocked minerals (e.g., Erickson et al., 2017, 2020; Kenny et al., 2017). An advantage of recrystallised grains is that, in addition to potentially recording an impact age, they may also provide diagnostic evidence of shock if they record crystallographic evidence for the former presence of reidite (Cavosie et al., 2016, 2018; Timms et al., 2017). Porous textures, on the other hand, are not uniquely impact-related and, therefore, an age determined from this texture in *ex situ* grains (for example, in a detrital sample) cannot be considered a definitive impact age. We suggest that our findings at Sääksjärvi highlight a potential pitfall of restricting analyses to a single textural type and that studies incorporating microstructural analysis should not limit U–Pb analyses to recrystallised domains alone but should also include porous textures if they are present.
Our data suggest that the use of an approximately 5 μm diameter analytical spot (enabled by the recent installation of a Hyperion RF ion source at the NordSIMS laboratory) to isolate fully age-reset domains within heterogeneous zircon grains is likely to significantly aid U–Pb dating of impact events. Four of the nine 5 μm analytical spots on grain n1048_IMP-3_z5 gave concordant, low-Pbc data points that enabled calculation of the 608 ± 8 Ma concordia age. In contrast, none of the two 30 μm spots or two 10 μm spots on the same grain gave concordant data. It therefore seems likely that if analyses were restricted to ≥ 10 μm, concordant data may not have been obtained. We note that a number of recent studies have isolated impact-aged domains with a 10 μm analytical spot (e.g., Erickson et al., 2017, 2020; Kenny et al., 2017, 2019; Schwarz et al., 2020) but suggest that the advent of 5 μm spot analyses will aid targeting of specific domains in complex grains, increase the likelihood of fully isolating impact-age regions, and lead to more concordant data points (thereby improving uncertainties on impact ages).

Our new findings also reinforce the utility of U–Pb analysis of shocked accessory phases to complement ⁴⁰Ar/³⁹Ar dating for small impact structures. Interpretation of ⁴⁰Ar/³⁹Ar spectra is difficult for small impact structures, where the targets rock may not have been heated sufficiently to completely degas radiogenic argon, ⁴⁰Ar², previously accumulated in the rock (e.g., Jourdan et al., 2007; Pickersgill et al., 2020). Here, we show that complete resetting of the U–Pb system can be achieved at structures as small as Sääksjärvi and note that is likely possible at even smaller structures too, such as the 1.2 km-diameter Meteor Crater, Arizona, USA where recrystallised zircon were documented (Cavosie et al., 2016). Additionally, ⁴⁰Ar/³⁹Ar dating is difficult at structures for which there is a large time gap between target rock ages and the cratering event (meaning that even minor degrees of excess ⁴⁰Ar will significantly affect the calculated age; Jourdan et al., 2007), but this is optimal for the U–Pb system in zircon whereby a large age...
difference means that the impact-related discordant array intersects the concordia curve at a high angle, allowing one to distinguish impact-related Pb loss from later, e.g., modern, Pb loss (e.g., Fig. 7A). Conversely, \(^{40}\text{Ar}/^{39}\text{Ar}\) may be more applicable for craters for which there was a relatively limited time gap between the target rock crystallisation age and the impact event (e.g., impacts into Phanerozoic target rocks), where U–Pb data will be distributed along the concordia curve (as opposed to intersecting it), making it more complicated to reach unambiguous impact ages (e.g., Erickson et al., 2017; Tohver et al., 2012). Finally, the higher closure temperature of the U–Pb system in zircon relative to the \(^{40}\text{Ar}/^{39}\text{Ar}\) system means that it may be more likely to record the timing of the impact event and not later cooling of the impact structure (e.g., Kenny et al., 2019; Schmieder and Kring, 2020) and that once the structure has cooled, zircon may be less likely to be compromised by later heating, as appears to have affected the \(^{40}\text{Ar}/^{39}\text{Ar}\) system at Sääksjärvi.

4.4. Radiometric dating of small impact structures

Our new dataset highlights the potential of accurate and precise U–Pb dating of small impact structures in crystalline basement to test, and even place boundaries on, models for the timing and extent of palaeobasins that might otherwise be difficult to constrain. Although our new age for the Sääksjärvi impact structure does not place tighter constraints on the timing of the Caledonian foreland basin than were available from, for example, apatite fission-track studies, it demonstrates the possibility that future radiometric dating of impact structures may do so. For example, the Karikkoselkä impact structure, approximately 150 km northeast of Sääksjärvi, is a 1.5 km-diameter structure in crystalline basement that could provide new constraints, but its age is still ambiguous: Pesonen et al. (1999) suggested that palaeomagnetic data are consistent with
ages of 230-260 Ma, 530-560 Ma, and 1650-1760 Ma, whereas Schmieder et al. (2010) suggested a possible age as young as \textit{ca.} 9 Ma on the basis of (U–Th)/He analyses of zircon.

More broadly, radiometric dating of small impact structures in crystalline basement worldwide may provide constraints on sedimentary basins, the burial histories of palaeolandsapes, and associated tectonics in less well-studied regions. In practise, this potential utility will be hampered by the fact that most impact structures which formed on Earth have been removed by erosion (e.g., Hergarten and Kenkmann, 2015; Johnson and Bowling, 2014), with small impact structures more easily erased from the geological record than larger ones (which produced a deeper record in the lithosphere). Today there are only approximately 110 known impact structures on Earth that have diameters less than 6 km, the approximate size of Sääksjärvi (Schmieder and Kring, 2020). Of these, approximately 60 are between 1.2 and 6 km in diameter, meaning that at least this number are likely amenable to radiometric dating (given that datable microstructures in zircon were identified at the 1.2 km in diameter Meteor Crater, USA [Cavosie et al., 2016]). Encouragingly, most impact structures yet to be discovered on Earth’s surface are likely to be less than 6 km in diameter (with as many as 90 in the 1 to 6 km range; Hergarten and Kenkmann, 2015) and thus their radiometric ages may be of use in regional geological reconstructions.

5. CONCLUSIONS

New U–Pb data for shocked zircon indicates that the Sääksjärvi impact structure, southwest Finland, formed at 608 ± 8 Ma. This makes Sääksjärvi the first unambiguously dated Ediacaran impact structure in the Baltic Shield, and one of only two confirmed Ediacaran impact structures worldwide.
The 608 ± 8 Ma age for Sääksjärvi is older than previous estimates based on $^{40}\text{Ar}/^{39}\text{Ar}$ data and confirms that the impact into exposed crystalline basement occurred prior to the development of the Caledonian foreland basin. Apparently younger $^{40}\text{Ar}/^{39}\text{Ar}$ ages are likely a result of Caledonian sediment loading and burial.

The accurate and precise dating of Sääksjärvi reinforces the utility of shocked accessory phases in radiometric dating of small impact structures. Furthermore, the most accurate and precise age for Sääksjärvi was acquired from porous, poorly crystalline zircon, indicating that future studies should not focus on recrystallisation textures alone.

The use of a 5 μm diameter analytical spot (enabled by the Hyperion RF ion source) to isolate fully age-reset domains within heterogeneous zircon grains is likely to significantly aid U–Pb dating of impact events.

Dating of small impact structures (both those which are currently known and those yet to be discovered) may help constrain the lifetime and spatial extent of sedimentary basins worldwide.
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terrestrial mineral diagnostic of high-pressure and high-temperature shock deformation.
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Supplementary data

- **Supplementary Table 1** (Data used to produce map in Fig. 1 in main text)
- **Supplementary Figure 1** (Imaging of grain n1049_IMP-1_z4)
- **Supplementary Figure 2** (Imaging of grain n1049_IMP-1_z7)
- **Supplementary Figure 3** (Imaging and EBSD analysis of grain n1050_IMP-11b_z16)
- **Supplementary Figure 4** (Imaging and EBSD analysis of grain n1050_IMP-11b_z18)
- **Supplementary Figure 5** (Imaging and EBSD analysis of grain n1050_IMP-11b_z14)
- **Supplementary Figure 6** (Post-analysis imaging of grain n1048_IMP-3_z5)
- **Supplementary Figure 7** (Concordia diagram with regression through sub-population)
- **Supplementary Figure 8** (Concordia diagram coloured according to zircon texture)
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**Supplementary Table 1.** Data used to produce map in Fig. 1 in main text. Data from Schmieder and Kring (2020), except age for the Sääksjärvi impact structure which is from this study.
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Supplementary Figure 5. Imaging and EBSD analysis of grain n1050_IMP-11b_z14.
Supplementary Figure 6. Post-analysis backscattered electron imaging of grain n1048_IMP-3_z5. The bright material surrounding the grain and in some analytical pits and vesicles is gold remnant from the coating for ion microprobe analysis. Pits would have been free from gold after analysis but some was trapped in a number of the pits during brief polishing to remove the coating from the rest of the grain. No evidence for the presence of ZrO$_2$ was encountered. The 608 ± 8 Ma concordia age was calculated from data from analytical pits C, D, G, and K.
Supplementary Figure 7. Tera-Wasserburg concordia diagram with a regression through the sub-population defining the ca. 1850 to ca. 600 Ma trend and a weighted mean $^{207}\text{Pb}/^{206}\text{Pb}$ age of analyses which record later Pb loss. MSWD – mean square of weighted deviates.
Supplementary Figure 8. Tera-Wasserburg concordia diagram coloured according to zircon texture. Note that information on texture is not available for analytical period #1 (undertaken in 2001) and so these data are not presented.