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Evidence for ca. 1 Ga hypervelocity impact event found in northwest Greenland

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ABSTRACT

There are likely many undiscovered impact structures on Earth, but several challenges prevent their detection, including possible concealment beneath large ice sheets. In recent years, geophysical, geochemical, and microphysical evidence has mounted for a ca. 58 Ma impact structure under the Hiawatha Glacier, northwest Greenland. Here, we report evidence for a second, much older hypervelocity impact event in this region, recorded in an impact melt rock sample collected from a glaciofluvial deposit in Inglefield Land. Secondary ion mass spectrometry U-Pb analyses of shock metamorphosed zircon grains yielded a previously unrecorded, Proterozoic best estimate impact age of 1039 ± 16 Ma (mean square of weighted deviates = 2.9). Based on Archean–Proterozoic target rock U-Pb ages obtained from unshocked zircon grains and the location of the melt rock sample along the ice margin, we suggest this sample was derived from a hypervelocity impact structure farther inland, concealed by the Greenland Ice Sheet. This study demonstrates the ability to uncover new impact events in some of the most inaccessible areas on Earth and the possibility of sampling multiple impact structures from one location when examining *ex situ* material. Our results have implications for current and future Martian and lunar returned samples that demonstrably bear complex impact histories.

INTRODUCTION

There is diagnostic evidence for ~200 hypervelocity impact craters on Earth (Schmieder and Kring, 2020; Kenkmann, 2021). However, it is likely that many more undetected structures exist (Hergarten and Kenkmann, 2015), particularly beneath the Greenland and Antarctic ice sheets, which obscure ~10% of Earth's land surface. Identification of diagnostic indicators is required to confirm an impact origin for candidate structures (French and Koeberl, 2010), including either physical (e.g., planar deformation features [PDFs] in quartz) or geochemical evidence (e.g., elevated Ir concentrations).

Constraining precise ages of impacts allows for better understanding of the role impact cratering has played in the paleoclimate evolution of Earth (e.g., Schulte et al., 2010). Ideally, impactite lithologies are sampled *in situ*. When such access is not feasible, samples can be collected distally when topographic evidence links detrital samples to a structure with clear crater morphology (Osinski et al., 2022). This approach was recently used to demonstrate an impact origin for the Hiawatha structure located beneath the Greenland Ice Sheet (Kjer et al., 2018; Garde et al., 2022), which is likely a 57.99 ± 0.54 Ma impact structure based on shocked zircon and monazite U-Pb dating of two detrital impact melt rock samples (Kenny et al., 2022; Hyde et al., 2024). Many other impact structures have been confirmed using similar procedures (e.g., Dypvik et al., 1996; Alwmark et al., 2015).

Here, we investigated the sparse impact record of Greenland recorded by five detrital impact melt rock samples recently exhumed from the Greenland Ice Sheet, by combining electron backscatter diffraction (EBSD) and state-of-the-art U-Pb analysis by secondary ion mass spectrometry (SIMS) of variably shocked zircon.

SAMPLES AND METHODOLOGY

Five detrital, pebble-sized impact melt rock samples (HW19-02, HW19-04, HW19-17, HW19-31, and HW19-32) were selected from 40 samples collected proximal to the Hiawatha structure in Inglefield Land, northwest Greenland (Fig. 1A). Two of these samples were collected from a glaciofluvial channel, which is the main drainage channel of the structure, 4 km past the terminus of the protruding Hiawatha Glacier. Three other samples were collected from two locations along the ice margin that conceals the western rim of the structure. PDFs in quartz grains were indexed using a U-stage mounted on a petrographic microscope following Stöffler and Langenhorst (1994). Zircon grains were mechanically separated from each sample, mounted in epoxy, and polished. In total, 119 grains were imaged by backscattered electron (BSE) and cathodoluminescence (CL) imaging, and further microstructural characterization of 18 grains was conducted by EBSD, on an FEI Quanta FEG 650 scanning electron microscope at the Swedish Museum of Natural History. Grains displaying a variety of microtextures were then chosen for U-Pb isotopic composition and age analysis ($n = 185$) using a CAM-ECA IMS1280 ion microprobe at the NordSIMS Laboratory, Stockholm, Sweden. Metamict and fractured domains of grains were avoided for

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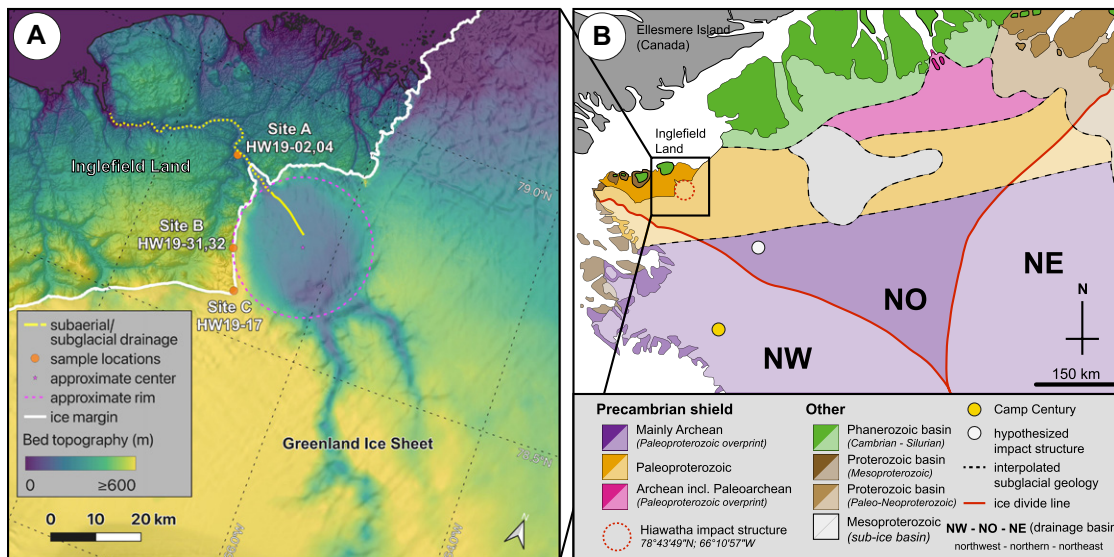


Figure 1. (A) Map of Hiawatha structure in Ingfield Land, northwestern Greenland. Individual impact melt rock sample locations—Site A: 78.841°N, 67.294°W; Site B: 78.667°N, 66.979°W; Site C: 78.589°N, 66.815°W. (B) Simplified geologic map of northern Greenland. Interpolated subglacial geology is from Dawes (2009). Lighter colors represent ice cover. See Supplemental Material for details of map generation and references (see text footnote 1).

U-Pb analysis. To acquire impact ages, granular areas were targeted where Pb loss is more likely complete (e.g., Schmieder et al., 2015b). Grains were repolished to acquire additional data. Further details of laboratory techniques used are given in the Supplemental Material¹.

RESULTS

Sample Descriptions

All five samples are clast-rich impact melt rocks (Stöffler et al., 2018); samples HW19-02, HW19-04, and HW19-17 comprise a hypocrySTALLINE melt matrix (Fig. 2), whereas HW19-31 and HW19-32 comprise a perlitic and spherulitic glassy matrix, respectively (Fig. S1). All samples contain quartz grains with PDFs. Four of the samples (HW19-02, HW19-04, HW19-31, and HW19-32) and their shock features were described in Hyde et al. (2023), whereas sample HW19-17 is presented here for the first time. Sample HW19-17 is a pebble-sized, orange-gray impact melt rock containing an aphanitic matrix composed of plagioclase microlites, siliceous mesostasis, and secondary smectites (Fig. 2; Fig. S1). The clast load is dominated by quartz clasts, which are commonly recrystallized or partially digested (Fig. S1). PDFs in quartz are heavily decorated with large fluid inclusions (Fig. 2C). Indexing of quartz PDF orientations revealed that {1013} is the most common orientation (28%), followed by {1012} and {1014} (22% and 17%, respectively; Fig. S2D). All samples contain zircon grains; those within polycrystalline clasts commonly appear pristine, whereas those within the melt matrix are often deformed (Fig. 2D).

¹Supplemental Material. Figures S1–S5, U-Pb data, and materials and methods. Please visit <https://doi.org/10.1130/GEOL.S.25460953> to access the supplemental material; contact editing@geosociety.org with any questions.

Zircon Microstructures

Separated zircon grains from all samples range from undeformed to displaying one or more shock deformation microstructure (Fig. 3; Figs. S3–S4). Unshocked grains showed a variety of textures in CL images (i.e., oscillatory zoning). EBSD imaging of deformed grains revealed planar deformation bands, planar fractures, crystal-plastic lattice strain, and porosity (Fig. 3A; Fig. S4). Additionally, some grains displayed shock recrystallization and shock microtwins (Fig. 3B), and rarely dissociation of zircon to ZrO₂ (Figs. S3–S4; Timms et al.,

2017). The high-pressure zircon polymorph reidite was not detected in any grain. At least one partially recrystallized grain displayed systematic crystallographic relationships (90° misorientation), indicating former reidite in granular neoblastic (FRIGN) zircon (Fig. S4G; Cavosie et al., 2016, 2018; Timms et al., 2017).

U-Pb Geochronology

The U-Pb data for four of the five samples (excluding HW19-17) individually yielded discordant arrays, trending from the Paleoproterozoic to the Late Paleocene (Fig. 4A; Fig. S5;

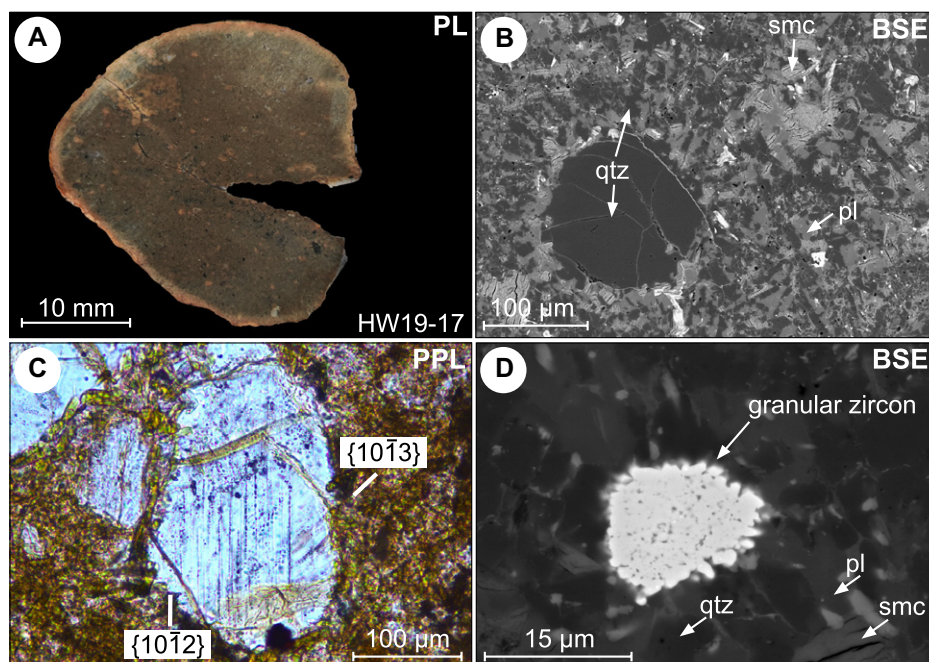


Figure 2. (A) Cut surface of detrital impact melt rock sample HW19-17; plane light (PL). (B) Backscattered electron (BSE) image of partially digested quartz clast in microlitic matrix. (C) Quartz grain with two sets of planar deformation features (PDFs) oriented about {1013} and {1012}. (D) Granular zircon grain within impact melt matrix. Abbreviations: pl—plagioclase; qtz—quartz; smc—smectite/clay; PPL—plane-polarized light; XPL—cross-polarized light.

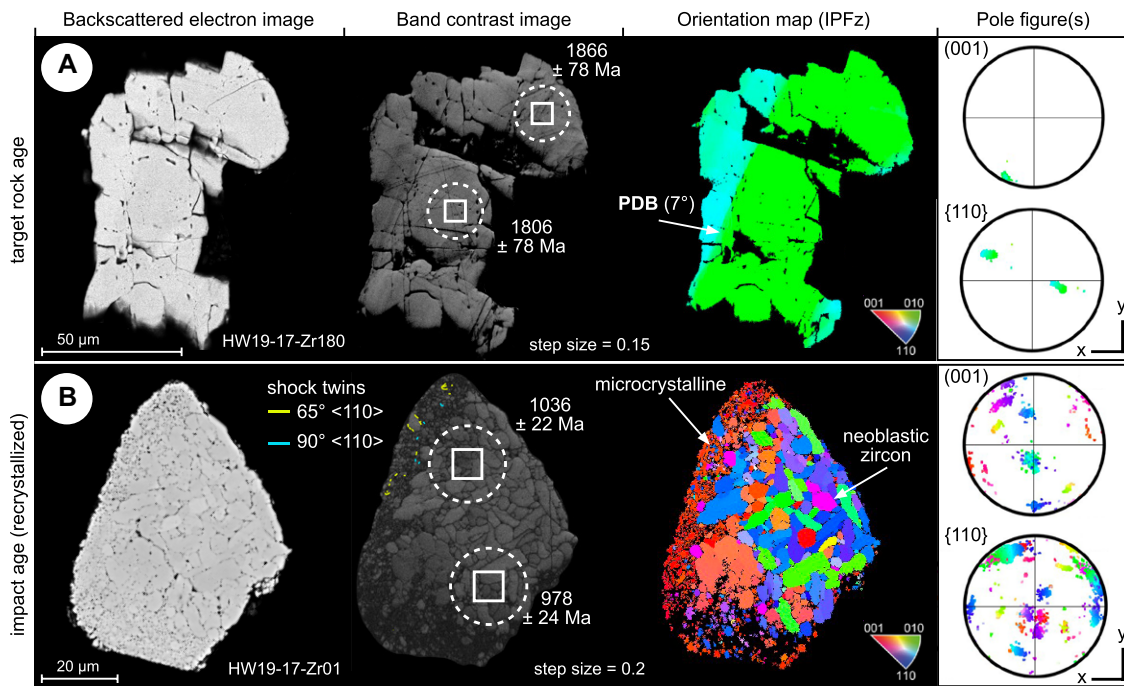


Figure 3. (A) Deformed zircon grain that records target rock ages, with likely impact-related planar deformation band (PDB), although not diagnostic (Kovaleva et al., 2015). **(B)** Shock-recrystallized zircon grain that records an impact age. Subdomains in inverse pole figure image reflect distinct crystallographic orientations between large neoblasts (e.g., Kenny et al., 2017). Dashed circles—U-Pb analysis pits (~16 μm across); solid squares—5 μm \times 5 μm area of sampled material (Supplemental Material [see text footnote 1]). U-Pb ages older than 1200 Ma are $^{207}\text{Pb}/^{206}\text{Pb}$ ages; those younger than 1200 Ma are $^{206}\text{Pb}/^{238}\text{U}$ ages. Uncertainties are 2σ .

Supplemental Material). Combined, these data ($n = 77$) produced a lower concordia intercept age of 50.5 ± 8.6 Ma (Figs. S5I–S5J). Concordant ages from unshocked grains from these same four samples yielded a concordia age at 1928 ± 13 Ma (Fig. 4A; Fig. S5O). In contrast, HW19-17 revealed vastly different U-Pb results: All data from that sample ($n = 108$) recorded a discordant array trending from the Neoproterozoic–Paleoproterozoic to the Mesoproterozoic–Neoproterozoic boundary (Fig. 4A; Fig. S5A). A clear correlation between grain microtexture and apparent age was observed (Fig. S5B). Analyses from shock-recrystallized zircon grains gave concordant dates, collectively yielding a best estimate concordia age of 1039 ± 16 Ma (mean square of weighted deviates [MSWD] = 2.9; Figs. 3B and 4). This age was calculated from eight analyses from four neoblastic grains (Figs. S5G–S5H). Critically, none of these eight analyses gave $^{206}\text{Pb}/^{238}\text{U}$ ages younger than 976 ± 66 Ma (Fig. 4; Fig. S5A). Furthermore, unshocked zircon grains from HW19-17 recorded four concordia ages of 1.8, 1.9, 2.53, and 2.7 Ga, approximately (Fig. 4; Fig. S5).

DISCUSSION

Two Distinct Impact Events

An unambiguous impact origin for all five samples is demonstrated based on PDFs in quartz and shock recrystallization of zircon (Fig. 2; Fig. S4; Hyde et al., 2023). The hypervelocity impact event that formed the enigmatic HW19-17 sample occurred at 1039 ± 16 Ma, from SIMS U-Pb analysis of recrystallized domains of shocked zircon grains (Figs. 3B and 4). This procedure yields precise ages for ancient

impact events (e.g., Kenny et al., 2017; Erickson et al., 2020). This impact event, slightly older than the Stenian-Tonian boundary at 1000 Ma, is unknown in Earth's impact record and represents one of the oldest recorded impact events (e.g., Schmieder and Kring, 2020). A ca. 1 Ga impact event contrasts clearly with the other four melt rock samples from Inglefield Land (Fig. 1), which together yield a lower intercept age of 50.5 ± 8.6 Ma, within uncertainty of a 57.99 ± 0.54 Ma zircon U-Pb best estimate impact age based on two melt rock samples collected at the same location (Fig. 4; Fig. S5; Kenny et al., 2022). That ca. 58 Ma impact age is attributed to the Hiawatha impact structure (Fig. 4), so our discovery of a ca. 1 Ga impact event adds substantial complexity to the impact history of northwest Greenland.

Additional indirect evidence for two distinct impact events is provided by U-Pb analysis of unshocked zircon grains, interpreted to represent the crystallization ages of target protoliths (Fig. 3A). Within HW19-17, we observed the same 1.9 Ga target rock age that was dominant in the other four samples that recorded the previously identified late Paleocene impact event only (Fig. 4; Fig. S5; Kenny et al., 2022). This age corresponds with known lithologies in the deglaciated foreland of the Hiawatha structure, i.e., ca. 1.9 Ga Etah group paragneiss (Nutman et al., 2008), indicating local provenance of the samples (Kenny et al., 2022). However, U-Pb data from HW19-17 yielded additional target rock ages that are sparse or absent in all our other samples (e.g., two Neoproterozoic U-Pb ages, ca. 2.53 and ca. 2.7 Ga; Fig. 4C), representing rock ages that are not found at the surface in Inglefield Land (Nutman et al., 2008).

Location of New Impact Structure

Any physical parameters of this new impact event and crater, if still preserved, are as-of-yet undetermined. Impact melt (60–70 GPa; Stöfler et al., 2018) is observed in sub-kilometer-scale structures on Earth (e.g., Kamil crater, Egypt: $\varnothing = 45$ m; Fazio et al., 2014). However, Kenkmann (2021) demonstrated a paucity of craters older than 100,000 yr old that are <3 km in diameter. Given the Proterozoic age of this new impact event, the structure likely had an original diameter of several kilometers.

The location of this ca. 1 Ga impact event is currently unknown, but it is probable that impact melt rock sample HW19-17 was transported from an impact structure hidden inland beneath the Greenland Ice Sheet (Fig. 1B). Assuming that the sample has been eroded relatively recently, i.e., since the Neogene onset of glaciation in Greenland (Bierman et al., 2016), modern ice-flow directions (Rignot and Mouginot, 2012) suggest that the structure is likely situated beneath the northern ice-drainage basin of the Greenland Ice Sheet (Fig. 1B). Interpolated subglacial geology in northern Greenland (Dawes, 2009) indicates that Neoproterozoic–Paleoproterozoic bedrock dominates the southern portion of this drainage basin. Further, zircon U-Pb ages in subglacial detrital sediment from the nearby Camp Century ice core are similar to those found in HW19-17 (Figs. 1B and 4; Christ et al., 2023). In sum, these considerations suggest that HW19-17 originated from an impact farther inland than the Hiawatha structure and not in the immediate vicinity of Inglefield Land (Fig. 1).

In agreement with these tentative location constraints, we note the earlier discovery of a circular ice-surface expression overlying a grav-

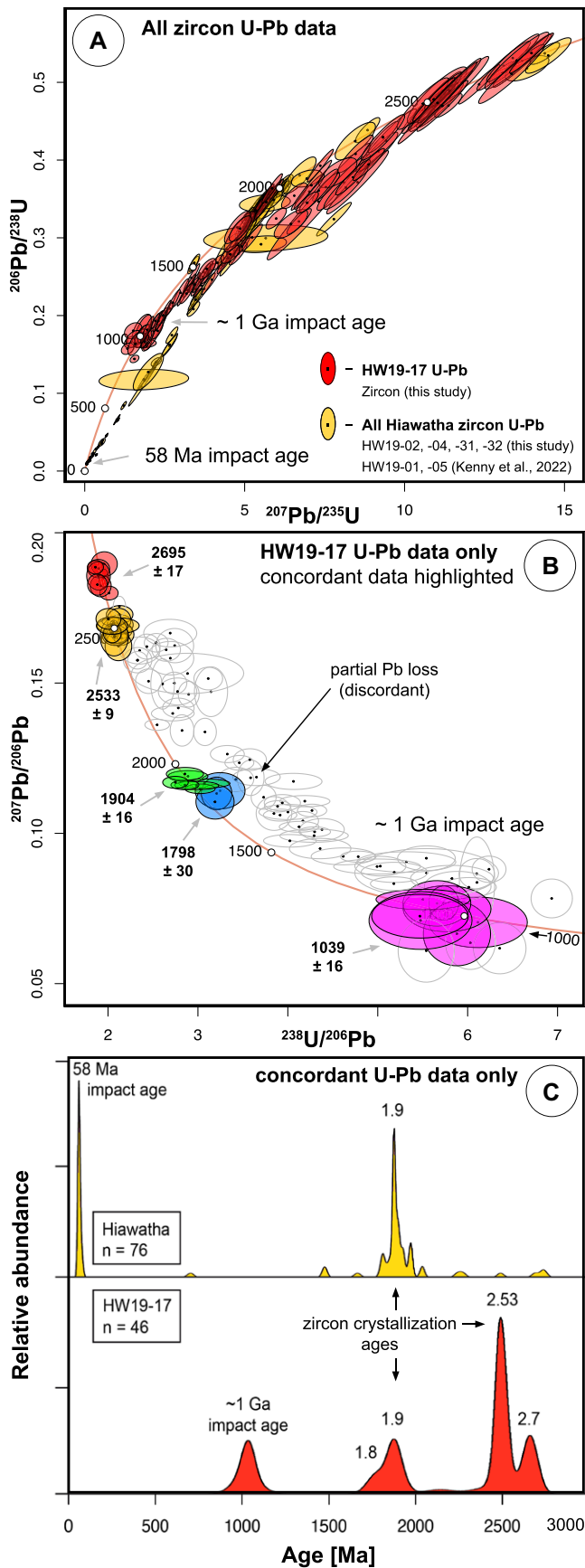


Figure 4. Secondary ion mass spectrometry (SIMS) zircon U-Pb data. (A) HW19-17 data and data from six other melt rock samples. Data yield two overlapping, but distinguishable, linear discordia trends with distinct lower-intercept ages. HW19-17 yielded a ca. 1 Ga impact age, whereas all other samples analyzed here align with previous work, yielding a Late Paleocene (ca. 58 Ma; Kenny et al., 2022) impact age. (B) Tera-Wasserberg diagram showing four distinguishable concordant target rock ages from HW19-17, as well as best estimate impact age at 1039 ± 16 Ma. (C) Kernel density estimates for concordant U-Pb data from all samples recording 58 Ma impact (yellow) and HW19-17 (red).

structure, due to its lower depth-to-diameter ratio (MacGregor et al., 2019). However, further investigation is required to test an impact hypothesis for its origin.

The absence of well-dated impact craters or deposits dating to 1039 ± 16 Ma (e.g., Schmieder and Kring, 2020) precludes a connection to a specific event and rules out all known Mesoproterozoic impact structures, i.e., the Keurusselkä impact structure (1151 ± 10 Ma; Schmieder et al., 2016) and the Stac Fada impact deposit (1177 ± 5 Ma; Parnell et al., 2011). It is possible that the sample originated from a poorly dated impact structure in Canada (e.g., the Presqu'île impact structure: <2729 Ma; Higgins and Tait, 1990), which at ca. 1 Ga was assembled with Greenland in Rodinia (Pesonen et al., 2012). This is unlikely, however, as it would require HW19-17 to have remained at the surface in northwestern Greenland for an unusually long time, given that there is no plausible ongoing mechanism to transport the sample to Inglefield Land.

Implications of This New Impact Event

The most likely scenario is that four of the samples analyzed here are associated with the nearby Hiawatha structure and record the same Late Paleocene impact event (Figs. 1 and 4A; Kenny et al., 2022). The geomorphology of the Hiawatha structure (rim-to-floor depth of 320 ± 70 m; Kjær et al., 2018) is more consistent with a Late Paleocene impact than a ca. 1 Ga event, despite variable high-latitude erosion (Kenkmann, 2021). However, radiometric dating of impact materials collected in situ within the Hiawatha structure is still required to unequivocally confirm this scenario.

In contrast, detrital sample HW19-17 records a previously unknown ca. 1 Ga impact event (Fig. 4). This new discovery, alongside the other melt rock samples collected in Inglefield Land, demonstrates the rare occurrence of sampling multiple impact structures at a single location, which occurs infrequently on Earth (e.g., Schmieder et al., 2015a). These results demonstrate that it is imperative to combine isotopic characterization of zircon grains (e.g., U-Pb geochronology) with shock microstructures in detrital material to link them to a specific impact event, especially when working in regions of Earth with sparse impact records.

The procedures demonstrated in this study can be a useful analogue for future martian and lunar returned samples, as planetary regolith or surficial breccias demonstrably comprise shocked materials subjected to, or originating from, multiple impact events (e.g., Grange et al., 2013). Searches for detrital samples resembling impactites from known impact structures in moraine or glaciofluvial drainage channels can be used in the search for new impact structures likely hidden under large continental ice sheets (e.g., Hergarten and Kenkmann, 2015).

ositional and topographic low, 183 km south-east of the Hiawatha structure (Fig. 1B; MacGregor et al., 2019). This feature was proposed

to be a possible second subglacial impact crater ($\varnothing \geq 36$ km) based on remote sensing only and is presumed to be older than the Hiawatha

We have shed new light on the impact record of an otherwise inaccessible region and suggest more effort is warranted to search for detrital evidence of new impact events globally, which would help us to understand the succession of impact events that occurred throughout Earth's history.

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