A large impact crater beneath Hiawatha Glacier in northwest Greenland

Kjær, Kurt H.; Larsen, Nicolaj K.; Binder, Tobias; Bjørk, Anders A.; Eisen, Olaf; Fahnestock, Mark A.; Funder, Svend; Garde, Adam A.; Haack, Henning; Helm, Veit; Houmark-Nielsen, Michael; Kjeldsen, Kristian K.; Khan, Shfaqat Abbas; Machguth, Horst; McDonald, Iain; Morlighem, Mathieu; Mouginot, Jérémie; Paden, John D.; Waight, Tod E.; Welkusat, Christian; Willerslev, Eske; MacGregor, Joseph A.

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We report the discovery of a large impact crater beneath Hiawatha Glacier in northwest Greenland. From airborne radar surveys, we identify a 31-kilometer-wide, circular bedrock depression beneath up to a kilometer of ice. This depression has an elevated rim that cross-cuts tributary subglacial channels and a subdued central uplift that appears to be actively eroding. From ground investigations of the deglaciated foreland, we identify overprinted structures within Precambrian bedrock along the ice margin that strike tangent to the subglacial rim. Glaciofluvial sediment from the largest river draining the crater contains shocked quartz and other impact-related grains. Geochemical analysis of this sediment indicates that the impactor was a fractionated iron asteroid, which must have been more than a kilometer wide to produce the identified crater. Radiotragraphy of the ice in the crater shows that the Holocene ice is continuous and conformable, but all deeper and older ice appears to be debris rich or heavily disturbed. The age of this impact crater is presently unknown, but from our geological and geophysical evidence, we conclude that it is unlikely to predate the Pleistocene inception of the Greenland Ice Sheet.
Geology of Hiawatha Glacier’s foreland

We visited the margin of Hiawatha Glacier in July 2016 to map tectonic structures in the glacier’s foreland and to sample its glaciofluvial sediment. The composition of ice-marginal erratic boulders derived from beneath Hiawatha Glacier indicates that the identified structure was formed within the same types of highly metamorphosed Paleoproterozoic terrain as mapped across most of Inglefield Land, which is part of the east-west–trending Inglefield mobile belt (fig. S1) (5). The complex tectonic foliation of these ancient rock formations has no clear relation to the present margin of the ice sheet. However, in a narrow zone along
the ice margin, brittle planar structures are superimposed on the bedrock foliation, striking tangentially to the semicircular ice margin around the subglacial circular structure, with moderate to steep outward dips and outward-plunging slickenside lineations (Fig. 1 and fig. S1).

Hiawatha Glacier terminates in a large river that eventually discharges into Nares Strait and is by far the most sediment-rich river discharging from a land-terminating glacier in northwestern Greenland (6). Photographic and satellite observations of this terminus over the past century show that distinct active proglacial sedimentation has led to grounding of the initially floating glacier tongue (fig. S2). In 2010, a proglacial outwash floodplain began forming at the terminus and has grown rapidly since (~0.65 km² as of 12 September 2016).

**Mineralogy and geochemistry of foreland glaciofluvial sediment**

Of the three glaciofluvial sediment samples we collected (table S1), only one sample was collected directly from the active floodplain (~2 kg of sand; HW21-2016). In this sample, we found angular quartz grains displaying shock-diagnostic planar deformation features (PDFs) (Fig. 2) (7). These PDFs are straight, generally penetrative, and spaced down to less than 2 μm. Only a few are decorated by small fluid inclusions, whereas toasting occurs in some grains (Fig. 3), i.e., a brown coloration due to intense post-shock hydrothermal alteration of the shock lamellae (8). The orientations of 37 PDF sets in 10 quartz grains were measured with a five-axis Leitz universal stage. Up to seven different orientations per grain were observed, with [1013] and [1012] predominating (Fig. 2) (9). This distribution is similar to the distribution observed in the central uplifts of large Canadian impact structures, where a threshold shock pressure of >16 GPa was inferred from the presence of [1012] PDFs (10).

This glaciofluvial sediment sample contains abundant intensely fractured and unweathered grains of detrital K-feldspar, mesoperthite, plagioclase, quartz, sillimanite, garnet, orthopyroxene, rutile, ilmenite, apatite, and other accessory minerals from the local bedrock. We also found a large variety of shock-metamorphosed and glassy grains, along with microbreccias, with sizes between 0.1 and 2 mm (Fig. 3). No larger cobbles or boulders were present at the sampling site of HW21-2016, and so far, none with diagnostic shock-metamorphic effects have been recovered from elsewhere in the foreland.

Several grains consist predominantly or wholly of either glass or variably devitrified glass, as inferred from optical examination and Raman spectroscopy (Figs. 3 and 4 and Materials and Methods). Grain colors are highly variable, ranging from almost colorless to yellow, green, brown, and almost black; glasses with similar bulk compositions may have widely different colors. Major element compositions of glassy grains were determined by electron microprobe (EMP) (data file S1). Unlike typical crustal melts, these glasses generally have very low silica contents and commonly yield low analytical totals (~80%), which may be partly affected by poor sample polishing. However, Raman spectroscopy indicates that the glasses with low EMP totals are hydrous and carbon is commonly present. The presence of these elements likely contributes to the low EMP totals. The major element compositions are typically biotite-like (Fig. 3A), garnet-like (Fig. 3, B, G, and H), or feldspar-like (Fig. 3, C, D, L, and N). However, these glasses also include appreciable concentrations of elements that do not occur in the respective precursor minerals, such as 2 to 5 weight % (wt %) FeO and up to ~3 wt % MgO in glasses with overall feldspar-like compositions, up to ~0.6 wt % CaO in grains with biotite-like compositions, and 0.1 to 0.5 wt % K₂O in grains with garnet-like compositions. Euhedral magmatic microcroliths of plagioclase, ternary feldspar, orthopyroxene, zoned clinopyroxene, or ilmenite occur in some grains. The Raman spectrum of one glassy grain (Fig. 3A) has small mica bands on a glassy background, a carbon band at ~1600 cm⁻¹, a band indicating organic C–H bonds at ~2900 cm⁻¹, and a band at ~3700 cm⁻¹ from mica OH bonds (Fig. 4). Another elliptoidal grain has a garnet-like composition and a shrinkage crack in the middle and is interpreted to be an impact melt droplet (Fig. 3, G and H). Raman and optical spectroscopy of this grain shows that it consists mostly of glass, besides a broad carbon band at ~1600 cm⁻¹ (Fig. 4). Very slender radial microliths, recognized by their optical birefringence, are not detected in the Raman spectrum. Other glassy grains have darker rims ~10 μm thick along one or two sides and may be fragments of larger free-falling particles. The carbon bands in the three spectra of Fig. 4 partly or wholly stem from carbon coating, but similar carbon bands also occur in glasses in uncoated mounts.

These glassy grains are interpreted to be derived from impact melting of individual biotite, garnet, and feldspar grains in the metasedimentary bedrock. Their imperfect compositional overlaps with assumed precursor minerals show that the grains do not represent diaplectic glass but instead are variably contaminated mineral melts. Only one grain might approach a bulk rock melt composition (Fig. 3, I and J), as it is siliceous, is highly aluminous (data file S1), and has crystallized Mg–Fe–zoned cordierite microliths besides orthopyroxene and skeletal plagioclase. A Raman spectrum from the matrix displays glass, besides a carbon band at ~1600 cm⁻¹. Bands around ~2900 cm⁻¹ are organic C–H bonds, while the band at ~3500 cm⁻¹ represents H₂O within the glass. Two other grains contain brown toaste quartz (11), with abundant PDFs set in a matrix of devitrified glass with a feldspar-like composition (Fig. 3K) and a structureless mass of carbonaceous material, respectively (Fig. 3M). Another grain displays a shocked quartz fragment with a ballen structure (12) set in a glassy matrix of feldspar-like composition with evenly distributed, micaceous crystals only a few micrometers long (Fig. 3, N and O). Microbreccias with matrices of glass, feldspathic microliths, or carbonaceous material are common. The grain shown in Fig. 3 (P and Q) contains fragments of K-feldspar, plagioclase, ilmenite, and quartz in a loosely packed matrix of feldspar microliths. Several quartz areas contain elongate, cusped voids lined with very fine grained clayey material, which might either belong to the sample or be remnants from polishing; the voids themselves are readily distinguished from artifact holes and are interpreted as an original feature, possibly derived from partial vaporization of quartz. Last, the ellipsoidal grain in Fig. 3 (R and S) is black, is soft, and consists of tiny mineral fragments, mainly quartz and feldspar, embedded in a carbonaceous matrix. Some of the mineral fragments outline imperfect ovoid shells that may have formed when the grain was aggregated.

The association of shocked quartz grains mantled by carbonaceous material, microbreccias with amorphous carbonaceous matrix, and glasses with a range of mineral-like compositions is highly unusual for confirmed impact structures, and we are unaware of any directly comparable grain assemblages from these structures. The large morphological and compositional variety of the HW21-2016 grains is unlikely to stem from a homogenized melt sheet on a crater floor. Rather, it probably represents components of the uppermost, un lithified part of an impact structure, and at least a few grains are considered likely to be ejecta (e.g., Fig. 3, G and H).

Subsamples of all three glaciofluvial sediment samples were crushed in an agate mill and analyzed for major and trace elements, platinum-group elements (PGEs), and Au (Materials and Methods and data file S2). Two samples (HW12-2016 and HW13-2016) contain low
concentrations of PGE, Au, and other siderophile elements that are consistent with bulk upper continental crust, so those two samples are believed to derive from local bedrock unaffected by the impact (figs. S1 and S3 and Supplementary Materials and Methods). In contrast, every tested subsample of the same sample that contained shocked quartz (HW21-2016) also contains elevated concentrations of Ni, Co, Cr, PGE, and Au, indicating a relatively rare iron meteorite. PGE data for HW21-2016 produce prominent and consistent chondrite-normalized positive Rh and negative Pt anomalies (fig. S3), and metal ratios are unlike most typical terrestrial rocks that could potentially be local sources for these elevated PGE concentrations (e.g., komatiites, picrites, or high-Mg basalts). Rare sulfide-rich chromitites from the Bushveld Complex have similarly distinctive positive Rh anomalies, but even addition of this material cannot reproduce the observed Rh anomaly. Furthermore, weathering and dispersal of similar rocks would be expected to produce an abundance of Mg-rich and Ti-poor chromite, which is not observed concentrations of PGE, Au, and other siderophile elements that are consistent with bulk upper continental crust, so those two samples are believed to derive from local bedrock unaffected by the impact (figs. S1 and S3 and Supplementary Materials and Methods). In contrast, every tested subsample of the same sample that contained shocked quartz (HW21-2016) also contains elevated concentrations of Ni, Co, Cr, PGE, and Au, indicative of a relatively rare iron meteorite. PGE data for HW21-2016 produce prominent and consistent chondrite-normalized positive Rh and negative Pt anomalies (fig. S3), and metal ratios are unlike most typical terrestrial rocks that could potentially be local sources for these elevated PGE concentrations (e.g., komatiites, picrites, or high-Mg basalts). Rare sulfide-rich chromitites from the Bushveld Complex have similarly distinctive positive Rh anomalies, but even addition of this material cannot reproduce the observed Rh anomaly. Furthermore, weathering and dispersal of similar rocks would be expected to produce an abundance of Mg-rich and Ti-poor chromite, which is not observed concentrations of PGE, Au, and other siderophile elements that are consistent with bulk upper continental crust, so those two samples are believed to derive from local bedrock unaffected by the impact (figs. S1 and S3 and Supplementary Materials and Methods). In contrast, every tested subsample of the same sample that contained shocked quartz (HW21-2016) also contains elevated concentrations of Ni, Co, Cr, PGE, and Au, indicative of a relatively rare iron meteorite. PGE data for HW21-2016 produce prominent and consistent chondrite-normalized positive Rh and negative Pt anomalies (fig. S3), and metal ratios are unlike most typical terrestrial rocks that could potentially be local sources for these elevated PGE concentrations (e.g., komatiites, picrites, or high-Mg basalts). Rare sulfide-rich chromitites from the Bushveld Complex have similarly distinctive positive Rh anomalies, but even addition of this material cannot reproduce the observed Rh anomaly. Furthermore, weathering and dispersal of similar rocks would be expected to produce an abundance of Mg-rich and Ti-poor chromite, which is not observed.
Fig. 3. Impact-related sediment grains from glaciofluvial sediment sample HW21-2016. (A) Grain 21C-v32: Pale yellow glass grain of biotite (Bt)–like composition with possibly inherited prismatic sillimanite (Sil) crystals and beginning devitrification in its lower part. (B) 21D-u28: Pale green glass grain of garnet (Grt)–like composition with dark rim and beginning devitrification around small trapped mineral fragments. (C) 21C-t26: Black glass grain of felsic-like composition with new microperthitic clinopyroxene (Cpx) and ilmenite (Ilm). (D to F) 21B-12a: Microperthitic K-feldspar (Kfs) (D) and brown glass of K-feldspar–like composition (E). Inclusions of quartz (Qtz) have acted as nucleation centers for devitrification (F). (G and H) 21C-z08: Dark brown, ellipsoidal glass particle of garnet-like composition with a central contraction crack and beginning crystallization of slender prismatic, radial crystallites. (I and J) 21C-x20: Pale glass grain of aluminous felsic composition with new microperthitic orthopyroxene (Opx), zoned cordierite (Crd), and skeletal plagioclase (Pl). (K) 21C-u05: Devitrified glass of felsic-like composition with four quartz fragments with PDFs. Arrows indicate prominent PDF orientations. (L) 21C-w29: Pale brown glass of K-feldspar–like composition; quartz inclusion with PDFs (top left) and two round inclusions lined with pale micaceous material, possibly former vesicles in the impact mineral melt. (M) 21C-z22: Lozenge-shaped, toasted quartz fragment with PDFs throughout, rimmed by black amorphous carbonaceous material. (N and O) 21D-r06: Quartz fragment with ballen structure (O), set in a matrix of feldspar-like composition with tiny micaceous crystallites. (P and Q) 21E-p08: Microbreccia with matrix of minute ternary feldspar grains and numerous tiny voids (Q) and inclusions of quartz, K-feldspar, plagioclase, garnet, and ilmenite, and larger elongate, cuspatate voids, and channels in quartz (black arrows) with interior linings of clayey material. White arrow in enlargement pointing at a hole from sample preparation, clearly distinguishable from the neighboring original void. (R) 21D-u01: Black ellipsoidal grain comprising numerous target mineral fragments and dust in a carbonaceous matrix identified with scanning electron microscopy–energy-dispersive spectrometry and indicated by microprobe totals of only 40 to 70 wt %. (S) The entire 21D-u01 grain with hole from polishing.
in HW21-2016. The only two recovered spinels are one Cr-poor magnetite and one ilmenite, which have significantly lower MgO, Cr$_2$O$_3$, and NiO than spinels found in impact ejecta (13). Combinations of PGE ratios in HW21-2016 [e.g., (Rh/Pt)$_N$ > 1.2, (Rh/Ru)$_N$ < 0.3, and (Pd/Pt)$_N$ > 2.5] effectively rule out terrestrial rocks and carbonaceous, ordinary, or enstatite chondrites as likely sources, whereas some iron meteorites contain high Rh and Pd concentrations. Modeling indicates that the best fit for the siderophile element data is a mixture between ordinary, or enstatite chondrites as likely sources, whereas some iron meteorites contain high Rh and Pd concentrations. Our examination of the HW21-2016 glaciofluvial sediment sample allows us to conclude three things about its source. First, the shocked quartz grains with multiple PDF orientations very likely originate from a large impact crater upstream from the sampling site. Second, the glassy particles, microbreccias, carbonaceous materials associated with shocked quartz and microbreccias, and grains that are likely ejecta that allows us to conclude three things about its source. First, the shocked quartz grains with multiple PDF orientations very likely originate from a large impact crater upstream from the sampling site. Second, the glassy particles, microbreccias, carbonaceous materials associated with shocked quartz and microbreccias, and grains that are likely ejecta that requires a rapidly cooled surficial environment can only be derived from an intact or largely intact crater. Third, the PGE anomalies suggest that these metals derive from a highly fractionated iron asteroid.

Radiostratigraphy of Hiawatha Glacier
In addition to mapping bed topography, the 2016 radar survey also revealed the internal structure of the ice itself. Three major radiostratigraphic units were mapped within and near Hiawatha Glacier (Fig. 5 and movie S1). The upper unit is reflection rich and typically constitutes the up to six thirds of the ice column, with stratigraphic layering that is continuous and conformable across the structure and is observed throughout the Greenland Ice Sheet (movies S2 and S3). Where dated in Greenland ice cores, this radiostratigraphic unit unambiguously represents a complete sequence of Holocene ice (11.7 to 0 thousand years (ka) ago) (fig. S5) (4). Where the base of this radar-identified unit outcrops at the ice surface along the margin of Hiawatha Glacier, it corresponds to the top of a distinct, visually dark, and debris-rich band previously identified isotopically as representing the Younger Dryas cold period (12.8 to 11.7 ka ago) at multiple sites across the northern Greenland ice-sheet margin (figs. S2H and S6) (14). Above this band, cleaner ice at the surface represents the beginning of the Holocene epoch.

This Holocene ice overlies the second radiostratigraphic unit, which has either poorly expressed or absent stratigraphic layering in the radar data. This reflection-poor unit constitutes the remainder of the ice column outside of the circular bedrock structure and the middle part of the column within it (Fig. 5). This unit must include ice from the Last Glacial Period (LGP; ~115 to 11.7 ka ago). In radar profiles in the northeast corner of the study area, outside the crater, this unit corresponds to late LGP ice exposed at the surface (fig. S6). To the northeast of and within the structure, this unit sits conformably below the Holocene unit, but within the structure, it does not contain any reflection-rich Bolling-Allerød ice (14.7 to 12.8 ka ago), from the period immediately before the Younger Dryas, or the trio of distinct LGP reflections observed throughout the northern Greenland Ice Sheet, the youngest of which is ~38 ka old (fig. S5) (4). Instead, those LGP reflections fade and dip noticeably toward Hiawatha Glacier and are absent within ~100 km of it (movies S2 and S3). This second unit does not conform uniformly to the overlying Holocene unit across the entire survey area. In the southern portion of the survey area, its upper interface is exceptionally rough and undulating (movie S1 and fig. S6, C and F to H).

The third unit is basal ice that is thickest in the western half of the survey area, downstream of the center of the structure. This unit contains numerous point scatterers and contiguous bed-originating reflections that tend to initiate at the protruding central peaks within the structure and along its rim (Fig. 5, A, B, E, and F, and movie S1). Radar sounding of the northern Greenland Ice Sheet sometimes detects strong deep reflections that are unlikely to contain significant concentrations of non-ice debris (4). However, we interpret the present observations to indicate unusually thick and debris-laden basal ice due to active subglacial erosion and englacial entrainment of mechanically weak subglacial sediment. In support of this interpretation, we note that this unit is mostly detected above the structure itself, and that debris-rich ice outcrops at the front of Hiawatha Glacier, indicating active erosion beneath at least part of the glacier (fig. S2H). We cannot yet directly connect the radar-interpreted top of the basal ice (Fig. 5I) with ground observations of the glacier margin itself (fig. S2H), because this basal ice typically thins substantially as it flows toward the structure’s rim (movie S1). The combination of these features, along with the increased small-scale roughness of the bed within the circular structure itself, has not been previously reported by any other radar-sounding survey of an ice sheet.

The ice overlying the downstream half of the structure displays full-column folding of Holocene layering. This folding includes shallow (<100 m depth) and thus recent near-surface layering, and the fold amplitudes are nearly uniform with depth, indicating that active basal processes drive this ice deformation (Fig. 5 and movie S1). Deep synclines in this internal layering (up to ~150 m drawdown relative to adjacent ice) indicate either active and localized basal melting (15) or lateral changes in basal drag, but deformation caused by spatial change in basal drag would generate a strain field whose effect upon internal layering would likely decrease in amplitude toward the ice surface (16). These full-column synclines correspond to fold patterns at the surface visible where seasonal melting exposes bare ice. These surface patterns show that the hinge line of the most prominent englacial syncline is oriented along ice flow, beginning roughly above the center of the structure and continuing to within a few kilometers of the glacier terminus (Figs. 1B and 5).

Southwest and downstream of the central synclines, an unusual subglacial reflection is observed beneath Hiawatha Glacier that is
Fig. 5. Radiostratigraphy of Hiawatha Glacier. (A and B) Example radargrams across Hiawatha Glacier. See movie S1 for all radargrams. The radargram in (A) passes through the subglacial troughs that enter the crater, so the rim there has been fully eroded. (C) Map of study area showing location of (A) and (B) overlain on local bed topography. (D to G) Examples of mapped radiostratigraphic units within Hiawatha Glacier with key features labeled. (H to J) Thickness of Holocene, LGP, and basal ice within and near Hiawatha Glacier. Background is a natural-color composite Landsat-8 scene from 11 August 2015. Black lines are survey tracks. Units are mapped only where identification is unambiguous. Holocene ice thins as ice flows toward the glacier and is extensively exposed at the ice margin. The incomplete LGP ice sequence thins significantly downstream of the center of the Hiawatha impact crater. Conversely, the apparently debris-rich basal ice thickens significantly downstream of the structure's center. Inset panels show mean, SD, and distribution of the absolute value of crossover thickness differences.
remotely flat, specular, and clearly not an off-nadir reflection (Fig. 5E and movie S1). This reflection, typically ~15 m beneath the uppermost debris that generates the ice-bed reflection and previously unobserved beneath an ice sheet, is most simply interpreted as the local groundwater table, indicating that the structure’s subglacial sediment is water saturated below this level and sufficiently dry above it to permit radar penetration. From examination of high-resolution satellite imagery, most supraglacial rivers that drain into meltwater channels close (3 to 8 km) to the Hiawatha Glacier terminus (Fig. S7), indicating limited supraglacial meltwater input into the subglacial hydrologic system across most of the structure. On the basis of the above observations and the likely subglacial drainage basin for our survey area (Fig. 1), we conclude that the area beneath Hiawatha Glacier and within the circular structure very likely constitutes the primary sediment source region for the floodplain, where we retrieved the glaciofluvial sediment sample HW21-2016.

**DISCUSSION**

**Identification of the Hiawatha impact crater**

We conclude that Hiawatha Glacier is underlain by an impact crater based on the characteristic complex crater morphology beneath the ice (including a subdued central uplift), the rim-tangent structures superimposed on bedrock foliations next to the ice margin, and the fresh, recently deposited glaciofluvial sediment that contains shocked quartz, other impact-related grains, and elevated siderophile element concentrations that our observations strongly suggest originates from beneath Hiawatha Glacier. Other diagnostic impact features, such as shatter cones, are expected to be subglacial in this case; we also have not yet performed a gravity survey across Hiawatha Glacier. Beyond the grains in the sediment sample that we interpret to be possible ejecta, no ejecta layer associated with this structure has yet been identified. Despite the absence of such additional evidence, an impact origin for the structure beneath Hiawatha Glacier is the simplest interpretation of our observations, which we explicitly accept for the remainder of this discussion. This crater is potentially one of the 25 largest impact structures on Earth, and it is the only one of this size that still has a significant portion of its original surface topographic expression.

**Preliminary estimates of impactor and ejecta properties**

The diameter of an impact crater constrains the kinetic energy of the impactor. The formation of a 31-km-wide impact crater in crystalline target rock requires ~3 × 10²¹ J of energy (17). Assuming that the Hiawatha impactor was iron with a density of 8000 kg m⁻³ and its mass, 1.5 km (17). The impact would initially produce a bowl-shaped cavity ~20 km in diameter and ~7 km deep, which would quickly collapse (within ~1 min) to form a complex crater more than 31 km in diameter and ~800 m deep with a central uplift (17). This impact scenario would have melted and vaporized up to ~20 km³ of target rock, approximately half of which would have remained within the crater, forming a melt sheet up to ~50 m deep.

No ejecta layer that might be associated with the Hiawatha impact crater has yet been identified in either Greenland’s rock or ice records. If no ice was present at the time of a high-angle (>45°) impact, then the symmetric ejecta layer would be ~200 m thick at the rim, thinning to less than 20 m at a radial distance of 30 km from the rim (17). However, during most of the Pleistocene, an ice sheet covered the impact area (18). If ice was present and its thickness was comparable to the impactor’s diameter, then a more energetic projectile is required to produce a crater of the observed size, and the fraction of non-ice debris in the ejecta would be smaller than if the impact hit ice-free land (19). Furthermore, regionally extensive ice cover at the time of impact could have resulted in a significant fraction of the ejecta landing on the ice-sheet surface of the Greenland or Innuittian ice sheets, rather than on bare ground. As the crater is situated very close to the present ice margin, the site has almost certainly been ice free during one or several short (~15 ka) interglacial periods during the Pleistocene, such as predicted for the Eemian ~125 ka ago (20). On the basis of present ice-flow speeds (Fig. 1B), most impact ejecta deposited onto the ice sheet would have been transported to the ice margin within ~10 ka. Similarly, based on Holocene vertical strain rates (21), any such ejecta would be less than half of its original thickness within 10 ka.

If the Greenland Ice Sheet was present at the time of impact and a high-angle impact occurred during the late Pleistocene (LGP), then ejecta ought to be present in the four deep ice cores from central and northern Greenland that span the majority of the LGP (fig. S5), but none has yet been identified. At two of the ice cores (GISP2 and GRIP) located farthest (>1000 km) from the crater (fig. S5), the expected initial thickness of a symmetric ejecta layer for a Hiawatha-sized impact on rock is ~0.7 mm with an average particle diameter of ~0.4 mm (17). In the closer ice cores (fig. S5), this thickness increases roughly twofold. If ice were present at the impact site, then a significant fraction of the ejecta would also be ice (19), but the presence of any rock ejecta should be unambiguous in an ice core. A possible complicating factor to interpreting the absence of ejecta in ice cores south of the structure is the presently unknown angle of impact. Modeling indicates that oblique impacts (<45°) produce asymmetric ejecta predominantly downrange of the crater with an ejecta-free shadow zone up range and that this effect becomes more pronounced as the impact angle decreases (22). The Hiawatha impact crater is located farther north (78.722°N) than any other known impact crater, a position that increases the probability of a northward-directed oblique impact given the majority of Earth-crossing asteroids that move in or near the ecliptic plane. Such a scenario might be analogous to the late-Jurassic Mjølnir crater, which is also large (40 km diameter), is high latitude (73.8°N), and produced an asymmetric (northward focused) ejecta layer (23).

Because it is not yet known whether the Greenland Ice Sheet covered this region at the time of impact, or its thickness at that time or the impact angle, our estimates of impactor size, initial crater size, impact melt volume, and ejecta thickness and extent should be considered preliminary.

**Age of the Hiawatha impact crater**

Impact craters on Earth are often dated using radiometric decay systems, but so far, no samples suitable for an absolute age determination have been recovered from the Hiawatha impact crater. We can confidently assume that the structure is younger than the 1.985 to 1.740 Ga old Paleoproterozoic bedrock that outcrops in the immediately adjacent foreland. Furthermore, multiple lines of indirect evidence derived mostly from our radar-sounding survey provide independent, albeit tentative, constraints on the crater’s age.

The crater’s depth (~320 ± 70 m) is muted compared to that predicted for a fresh, subaerial terrestrial crater of the same diameter (~800 m) (17, 24), which could result from either fast erosion over a short period or slower erosion over a longer period. Reported fluvial and subglacial erosion rates span a range of ~10⁻³ to 10⁻² m year⁻¹ (25–28). An erosion rate at the upper end of that range implies a minimum period of ~5 ka to
erode the rim and central uplift and partially fill the crater floor to form the present morphology, assuming that ice has covered the crater for nearly all of its existence. A lower-end erosion rate yields a loosely constrained maximum erosion period of ~50 Myr. Our radar evidence of active subglacial erosion at present (movie S1) and active sediment deposition at the glacier front (fig. S2) appear to favor a faster subglacial erosion rate and hence a younger age.

The structure’s rim cross-cuts and effectively terminates the northern channel east of the crater. The rim also redirects part of the southern channel to its southeast, so we infer that both channels predate the formation of this structure. These two channels are comparable to the paleoluvial channel networks of the neighboring Humboldt Glacier (29) and central Greenland’s mega-canyon (30), which are believed to predate the Pleistocene inception of the Greenland Ice Sheet (~2.6 Ma ago) (18). We note that this interpretation requires that the subsequently merged channels later breached the rim itself.

Radar evidence of active basal melting (full-column radiostratigraphic synclines) and subglacial water storage (groundwater table) within and beneath Hiawatha Glacier, respectively, appear to be anomalous as compared to grounded ice-marginal settings across northern Greenland. Possible basal melting could be due to an anomalous subglacial heat source and is consistent with, but not conclusive of, residual heat from the impact itself. Previous modeling of hydrothermal systems within martian subaerial impact craters suggests that such systems have a life span of ~100 ka for a 30-km-wide crater (31). For the terrestrial Hiawatha impact crater, the overlying ice sheet would have provided an ample supply of water for such a hydrothermal system during the Pleistocene and Holocene, but it would have also exported heat more efficiently from that system than for a subaerial crater, which suggests a shorter life span of any possible post-impact hydrothermal system than on Mars.

Last, Hiawatha Glacier’s radiostratigraphy is highly anomalous compared to the rest of the Greenland Ice Sheet (movies S1 to S3). LGP ice is neither complete nor conformable across the entire crater. Given modern surface velocities (~10 to 30 m year

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sign (37). It consists of three eight-element antenna arrays, operating in the frequency range of 150 to 520 MHz, with a 10-kHz pulse repetition frequency. One array is mounted under the fuselage, and the two others
under each wing. The center array both transmits and receives signals, while the wing arrays receive only. The total transmit power is 6 kW.

Three flights were performed out of Thule Air Base on 12, 16, and 17 May 2016 (movie S1) at a height of ~350 m over the ice sheet, corresponding to an elevation range of 1000 to 2000 m. Before the flights, the amplitude, time delay, and start phase of each element of the transmit array were adjusted to correct for system amplitude, time delay, and phase errors (37). The received return signals were filtered at radio frequencies before digitization at 1600 MHz. Each channel was digitally down-converted to complex baseband, decimated to 400 MHz, and then stacked in hardware. For this survey, each of the 24 channels recorded 19,612 complex samples at 294 Hz.

Post-flight processing included a matched filter algorithm for pulse compression in the vertical range direction, equalization to minimize sidelobes, focused synthetic aperture radar (SAR) processing in the along-track direction using an f-k migration adapted for radar sounding of ice (38), and array processing in the across-track direction after time, amplitude, and phase equalization of each SAR image (37). We assumed that the value for the real part of the relative permittivity of ice is 3.17 to convert englacial travel times to depth.

To detect the ice-bed interface and visualize coherent and incoherent backscatter, we used fully SAR and array-processed data from the central eight elements. This process results in a range resolution of 0.5 m and an azimuth resolution of 15 m. Bed topography was calculated by subtracting the ice thickness from the surface elevation available from the Greenland Ice Mapping Project (39). To improve the detection and visualization of coherent and incoherent internal backscatter, data from four segments were fully SAR and array processed using the center array, resulting in an improved range resolution (0.5 m) and azimuth resolution (~2.5 m) near the ice-bed interface.

**Raman spectroscopy of glaciofluvial sediment**

The Raman spectra were obtained with a WITec alpha300 R system, using a 488-nm laser, a UHTS300 spectrometer with a grating of 600 grooves mm⁻¹, a Peltier-cooled electron multiplying charge-coupled device detector, and a long working distance 50× microscope objective with a numerical aperture of 0.35. The instrument was calibrated using the Raman spectrum of a monocrystalline silicon wafer. Laser power was adjusted individually for each sample to prevent heat-induced damage. Acquisition times ranged between 5 and 30 s per spectrum, with 5 to 10 spectra combined for each spot, depending on the signal intensity.

**Geochemistry of glaciofluvial sediment**

Three glaciofluvial sediment samples were collected from the outwash plain in front of Hiawatha Glacier (HW12-2016, H13-2016, and HW21-2016). All three samples were geochemically analyzed for major elements, trace elements, PGEs, and Au using existing instrumentation and methods (40).

Three types of material were provided from the original HW21-2016 bulk sample. HW21-2016(1) was a subsample of ~60 g, which had already been processed for petrographic work, HW21-2016(2) was a subsample of ~30 g of the untreated sediment, and HW21-2016(3) was a subsample of 50 g of untreated sediment that had been sieved to between 63 and 200 μm. A fraction of this latter subsample was split into <125-μm and >125-μm sub-samples to determine the major and trace element chemistry of both the fine and coarse material separately. From samples HW12-2016 and HW13-2016, we took ~30 g of untreated subsamples of the original bulk sediment collected at these localities. Each subsample was crushed and homogenized to fine powder at Cardiff University in an agate planetary ball mill. Aliquots of 12 to 15 g of each crushed and homogenized sample were taken to determine PGE and Au concentrations. For each subsample, 0.1-g portions were analyzed for major and trace elements. Major and trace element data, PGE data, and Au data are all provided in data file S2. Subsample HW21-2016(1)B has significantly higher PGE concentrations than the other HW21-2016 subsamples, pointing to the heterogeneous nature of the siderophile-rich component in the sediment. Mean concentrations are calculated with and without this sample included in data file S2.

**SUPPLEMENTARY MATERIALS**

Supplementary material for this article is available at http://advances.sciencemag.org/cgi/content/full/4/11/eaar8173/DC1

Supplementary Text

Fig. S1. Bedrock type and lineations across Inglefield Land near Hiawatha Glacier.
Fig. S2. Terminus history of Hiawatha Glacier and its transition from a floating to a grounded tongue with a proglacial floodplain.
Fig. S3. CI-chondrite-normalized metal patterns for glaciofluvial sediment samples compared to upper continental crust.
Fig. S4. Model mixtures of crust with mass proportions of various meteorites.
Fig. S5. Radar reflectivity at the six deep Greenland ice core sites, as measured by predecessor radar systems to that used for the Hiawatha Glacier survey.
Fig. S6. Relationships between surface and radar layering.
Fig. S7. Supraglacial drainage of Hiawatha Glacier.
Table S1. Location and description of Hiawatha glaciofluvial sediment samples.
Movie S1. The 2016 AWI airborne radar survey over Hiawatha Glacier.
Movie S2. Operation IceBridge radar surveys across the Greenland Ice Sheet.
Movie S3. Operation IceBridge radar surveys toward Hiawatha Glacier.
Data file S1. EMP data for grains studied from HW21-2016 samples.
Data file S2. Major element, trace element, and PGE concentrations for subsamples and sub-subsamples of HW21-2016.

**REFERENCES AND NOTES**


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A large impact crater beneath Hiawatha Glacier in northwest Greenland


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