South Greenland ice-sheet collapse during Marine Isotope Stage 11

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Varying levels of boreal summer insolation and associated Earth system feedbacks led to differing climate and ice-sheet states during late-Quaternary interglaciations. In particular, Marine Isotope Stage (MIS) 11 was an exceptionally long interglaciation and potentially had a global mean sea level 6 to 13 metres above the present level around 410,000 to 400,000 years ago, implying substantial mass loss from the Greenland ice sheet (GIS). There are, however, no model simulations and only limited proxy data to constrain the magnitude of the GIS response to climate change during this ‘super interglacial’, thus confounding efforts to assess climate/ice-sheet threshold behaviour and associated sea-level rise. Here we show that the south GIS was drastically smaller during MIS 11 than it is now, with only a small residual ice dome over southernmost Greenland. We use the strontium–neodymium–lead isotopic composition of proglacial sediment discharged from south Greenland to constrain the provenance of terrigenous silt deposited on the Eirik Drift, a sedimentary deposit off the south Greenland margin. We identify a major reduction in sediment input derived from south Greenland’s Precambrian bedrock terranes, probably reflecting the cessation of subglacial erosion and sediment transport as a result of near-complete deglaciation of south Greenland. Comparison with ice-sheet configurations from numerical models suggests that the GIS lost about 4.5 to 6 metres of sea-level-equivalent volume during MIS 11. This is evidence for late-Quaternary GIS collapse after it crossed a climate/ice-sheet threshold stability that may have been no more than several degrees above pre-industrial temperatures.

Little information is available on the magnitude of the retreat of the GIS or the Antarctic ice sheet (AIS) during MIS 11, thus hindering efforts to understand potentially nonlinear responses of Earth’s ice sheets to protracted warm intervals. AIS retreat could explain all of the proposed +6 to 13 m MIS 11 sea-level range. Alternatively, near-complete GIS deglaciation would account for the lower-end estimate of the sea-level highstand, with some AIS contribution required for a highstand greater than +7 m. Yet another possibility is that the GIS and AIS experienced minimal retreat during MIS 11, consistent with reconstructions suggesting that MIS 11 sea level may not have been appreciably different from today. Thus, constraints on the MIS 11 response of the GIS can shed considerable light on uncertain palaeo-sea-level records, sparse palaeoclimatic data and the possibility that the modelled temperature threshold for GIS collapse may have been exceeded during MIS 11. In the absence of direct geomorphic evidence for the magnitude of ice-sheet retreat during past interglaciations, we turn to geochemical proxy evidence to assess the south GIS response to MIS 11 climate change and, in turn, estimate the GIS contribution to MIS 11 sea level.

We use the sedimentary record of Eirik Drift core MD99-2227 (Figs 1 and 2) to infer GIS extent on south Greenland, where many models suggest interglacial ice-sheet mass loss will be most pronounced. The Eirik Drift receives terrigenous sediment from subglacial erosion of south Greenland’s Precambrian bedrock (the Ketilidian Mobile Belt (KMB), Archaean Block (AB) and Nagssugtoqidian Mobile Belt (NMB)) and Palaeogene volcanics that outcrop in east Greenland and Iceland (Fig. 1). These sediments are transported to the core site in the Western Boundary Undercurrent (WBUC) (Fig. 1 and Methods), and magnetic and geochemical properties of Holocene Eirik Drift sediments document the close coupling between GIS subglacial erosion, sediment transport and terrigenous silt deposition at MD99-2227. Other potential sources of terrigenous silt at Eirik Drift, including northeast Greenland, Scotland, Scandinavia and re-transported silt in Arctic sea ice, are likely to be negligible (Methods).

We estimate the provenance of the carbonate-free detrital silt fraction in Eirik Drift sediments using Sr–Nd–Pb isotope ratios, which trace terrestrial silt sources because the unique isotope compositions of south Greenland’s bedrock terranes reflect their differing ages and formation histories.

Figure 1 | Map of Greenland and other features mentioned in the text. a, Bedrock terrane boundaries (black dashed lines) and sampling sites for Greenland stream sediments (filled circles; multiple sites per symbol); KMB, Ketilidian Mobile Belt (grey); AB, Archaean Block (red); NMB, Nagssugtoqidian Mobile Belt (blue); PV, Palaeogene volcanics. Yellow squares mark locations of marine sediment core MD99-2227 and Dye-3 and Summit (GISP2, GRIP) ice cores. Dashed white lines denote modern deep-water circulation features that are thought to have been active during past interglaciations; DSOW, Denmark Strait Overflow Water; WBUC, Western Boundary Undercurrent. The bathymetric contour interval is 500 m. b, Inset map. White polygons show the potential configuration of the MIS 11 Greenland ice sheet, which is similar to modelled ice limits representing −6 m of sea-level-equivalent mass loss (Methods). Yellow squares are ice-core sites shown in a.
silt. Silts derived from Palaeogene volcanic rocks have very low $^{87}\text{Sr}/^{86}\text{Sr}$, which limits their contribution to the sediment. Interglacial MISs are indicated.

3,990 cm, where it increases to 3.975 cm. $^{87}\text{Sr}/^{86}\text{Sr}$ follows a similar trend (Supplementary Table 1) and is not strongly correlated with $^{206}\text{Pb}/^{204}\text{Pb}$, $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$ values. The AB and NMB silts are more similar isotopically, although AB silts tend towards higher $^{87}\text{Sr}/^{86}\text{Sr}$ and lower $^{207}\text{Pb}/^{204}\text{Pb}$ and $^{208}\text{Pb}/^{204}\text{Pb}$, than do NMB silts. Silts derived from Palaeogene volcanic rocks have very low $^{87}\text{Sr}/^{86}\text{Sr}$ and high $^{18}\text{O}$.

Figure 2 | MD99-2227 records on depth scale. a, Full $^{18}\text{O}$ Neogloboquadrina pachyderma (sinistral) record; interglacial MISs are indicated. $^{18}\text{O}=1,000 \times \left(\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{sample}}/\left(\frac{^{18}\text{O}}{^{16}\text{O}}\right)_{\text{VPDB}} - 1\right)$; VPDB, Vienna PeeDee belemnite. b, Weight per cent silt and sand. Vertical yellow bars denote ice-free intervals. c, e, Isotopic composition, with analytical uncertainty smaller than symbol size: $^{87}\text{Sr}/^{86}\text{Sr}$(c); $^{207}\text{Pb}/^{204}\text{Pb}$(e). $^{206}\text{Pb}/^{204}\text{Pb}$ and $^{207}\text{Pb}/^{204}\text{Pb}$ follow a similar trend (Supplementary Table 1) and are not shown here. f, Median inferred silt provenance from isotope mixing model, expressed as percentage of total sediment. Provenance estimates do not sum to 100% because they do not include clay or sand size fractions. g, Estimated flux of CaCO$_3$-free silt from south Greenland Precambrian terranes (upper and lower uncertainty estimates in Extended Data Fig. 2).

Because south Greenland Precambrian terranes have distinctly high $^{87}\text{Sr}/^{86}\text{Sr}$ and low $^{18}\text{O}$, the Sr and Nd isotope data are consistent with an overall reduction in silt derived from south Greenland’s Precambrian bedrock. Direct interpretation of the Pb data is complicated by anomalous KMB Pb isotope compositions relative to the AB and NMB (Extended Data Fig. 1). We use an isotope mixing model to estimate the proportion and flux of silt derived from each south Greenland terrane, based on the median solution from 10,000 model runs (Fig. 2f, g and Methods). The Palaeogene volcanic silt fraction of the total sediment increases from ~10% during late MIS 12 to 15–30% during MIS 11 (Fig. 2f), which probably reflects intensification of the Western Boundary Undercurrent during interglaciations [15–21]. Precambrian silt is initially 10–15% of the total sediment during MIS 12, with an increase to ~40% at 4,135 cm early in MIS 11 that is mainly driven by increases in the AB and NMB fractions. Precambrian silt decreases to 4–8% of the total sediment for the middle of MIS 11 (4,090–4,020 cm), and then increases again, to ~20% at 3,980 cm, with a subsequent return to ~5% at the end of MIS 11. Because inferred KMB contributions remain relatively constant during this interval, at <4% of total sediment, the decrease in Precambrian silt sedimentation above 4,110 cm is driven mainly by changes in silt sourced from the AB and NMB terranes.

Sediment flux estimates (Fig. 2g, Methods and Extended Data Fig. 2) corroborate the provenance interpretations based on the percentage of total sediment. Silt flux from south Greenland’s Precambrian bedrock is 1.7–3.5 g cm$^{-2}$ kyr$^{-1}$ during late MIS 12 and into MIS 11, but decreases by an order of magnitude to ~0.3 g cm$^{-2}$ kyr$^{-1}$ during MIS 11. Flux from the KMB during MIS 11 is low, but does not decrease as precipitously as flux from the AB or NMB, both of which decrease to a flux of less than ~0.1 g cm$^{-2}$ kyr$^{-1}$.

Comparing our terrane provenance record with similar estimates for the last interglaciation (LIG; 128–116 kyr ago) and the Holocene epoch, we find that the Precambrian silt contribution at the end of MIS 12 is similar to sedimentation during the penultimate and last deglaciations (Fig. 3b, c). Precambrian silt early in MIS 11 is largely derived from the NMB and AB, and probably reflects increased ablation and attendant discharge of silt from the south GIS, similar to early LIG and Holocene silt pulses [16]. The low in Precambrian silt during the MIS 11 $^{18}\text{O}$ minimum (Fig. 3a) is unprecedented with respect to these later interglaciations (Fig. 3b). The near-complete loss of NMB- and AB-derived silt drives this minimum, with individual terrane contributions decreasing to <1% of total sediment. For comparison, the minimum NMB + AB fraction is 10–15% of the total sediment during the Holocene and LIG (Fig. 3b). Although it is not appropriate to compare sediment flux during the Holocene and Termination I owing to stretching in the upper part of MD99-2227 [15] (Methods), terrigenous silt flux from south Greenland’s Precambrian bedrock was over an order of magnitude higher in the LIG than during MIS 11 (Fig. 3c).

One explanation for the near absence of NMB and AB silt during the MIS 11 $^{18}\text{O}$ minimum is that a change in ocean circulation reduced or stopped transport of NMB and AB sediment to Eirik Drift. However, the continued input of KMB and Palaeogene volcanic silt suggests that sediment transport pathways to Eirik Drift during MIS 11 were similar to other interglaciations [15,16,21]. Alternatively, ablation, meltwater production and subglacial erosion are high during ice-sheet retreat [4], but complete ice loss from a given terrace would lead to the cessation of subglacial erosion and meltwater transport of silt and, in turn, to decreased sediment flux to the ocean. We therefore interpret the near absence of NMB and AB silt during the MIS 11 $^{18}\text{O}$ minimum as indicating the loss of ice from these terranes. Deglaciated terranes may supply minor amounts of silt even during periods of minimal or absent GIS coverage, owing to paraglacial processes that entrain and transport glacial sediment in recently deglaciated areas [12,23]. The relatively consistent MIS 11 KMB silt flux may suggest persistent valley glaciers or local ice caps, or both, on that terrace, perhaps due to regionally high snow accumulation [12]. The NMB and AB silt increase at the end of MIS 11 implies south GIS regrowth, and an associated increase in subglacial erosion [4].
North Atlantic, suggests the presence of marine-terminating ice on east-central and northeast Greenland during MIS 11\textsuperscript{26,27}.

We compare these constraints on MIS 11 GIS extent (see, for example, Fig. 1b) with ice-sheet models that simulate GIS response to past and future climate warming, to qualitatively assess potential GIS contribution to MIS 11 sea level. Models with ice absence on the NMB and AB terranes simulate a GIS contribution to sea-level rise of >4.5 m (refs 9–12), whereas the maximum modelled GIS retreat consistent with our interpretation of an ice-free AB and NMB and other geological constraints\textsuperscript{25–27} yields ~6 m of GIS sea-level contribution\textsuperscript{2}. South GIS retreat could therefore account for all, or most, of the minimum estimated MIS 11 sea-level highstand of ~6 m (ref. 1) and is within the 1σ uncertainty envelope of the Red Sea sea-level record\textsuperscript{2}, implying a relatively stable AIS. Alternatively, the upper end of MIS 11 sea-level estimates implies complete collapse of the West AIS and at least some mass loss from the East AB\textsuperscript{2}, in addition to 4.5–6 m of GIS sea-level contribution.

Evidence for deglaciation of south Greenland consequently suggests that a climate/ice-stability threshold was crossed during MIS 11. Coupled climate–ice-sheet models simulate a threshold for complete GIS melting of 1.7–2.0 °C of warming relative to the preindustrial late Holocene if positive dynamic feedbacks are considered\textsuperscript{25}. They also simulate a long GIS response time for temperature increases approaching the 1.7–2.0 °C threshold. However, the GIS response is considerably more rapid under <4 °C warming scenarios, with complete collapse in <8 kyr. Unfortunately, available proxy records offer conflicting evidence for the Arctic palaeoclimate during MIS 11. The few existing temperature reconstructions from near-central south Greenland suggest that MIS 11 climate was no warmer than peak early Holocene or GIS climate\textsuperscript{28,29}. In contrast, Siberian pollen records\textsuperscript{30} suggest 4–5 °C of summer warming relative to the early Holocene and GIS (Fig. 3e). Limited field evidence indicates that continuous permafrost may have thawed during MIS 11 at a site in Siberia\textsuperscript{31}, although permafrost persisted locally through this interval in northern Canada\textsuperscript{29}. In the Arctic Ocean, faunal records\textsuperscript{32} imply that substantially warmer-than-present summer sea surface temperatures and seasonal—not perennial—sea-ice cover characterized MIS 11.

Our results therefore prompt us to ask why south Greenland deglaciated almost completely during MIS 11, when ice persisted through the LIG and the Holocene\textsuperscript{33}. Anomalous MIS 11 Arctic warmth\textsuperscript{3} and a seasonally ice-free ocean\textsuperscript{34} could have pushed the GIS past an ice-stability threshold that was not crossed during the LIG or early Holocene. Alternatively, protracted warmth during the long MIS 11 interglaciation may have allowed the GIS to respond fully to interglacial conditions that were similar to the early Holocene and LIG, with these later interglaciations being too short for comparable ice-sheet collapse. A more extensive network of Pleistocene climate and ice-extent records around Greenland is required to assess these alternative scenarios, which have important implications for predicting the long-term behaviour of the GIS in response to future climate change scenarios\textsuperscript{36,37}. In this context, our evidence for a late-Quaternary collapse of the south GIS provides an important example of geologically recent ice-sheet instability and retreat under climate conditions within the range of those anticipated by the end of this century.

**METHODS SUMMARY**

We supplemented an earlier compilation\textsuperscript{16} of Greenland stream sediment isotope geochemistry with an additional 31 samples of fine-grained glaciofluvial sediment collected from southwest Greenland (Extended Data Fig. 3). Chemical separation and isotopic analyses were conducted at the University of Wisconsin–Madison Radioisotope Laboratory. Subsamples of the 3–63 μm fraction of MIS 11 sediment from core MD99-2227 were twice leached with 0.1 M HCl to remove biogenic carbonate and authigenic Fe–Mn coatings. All samples were spiked with mixed Rb-Sr and rare-earth-element tracers, and then digested in Parr pressure vessels with hydrofluoric acid and HNO\textsubscript{3}. Pb, Rb–Sr and rare-earth-element separation was by sequential ion-exchange column chromatography. Isotope ratios were measured on a VG Sector 54 thermal ionization mass spectrometer, with Rb, Sr, Nd and
Sm concentrations determined by isotope dilution. Procedural blanks were negligible compared with sample size.

The isotope mixing model has four terrane components (KMB, AB, NMB and Palaeogene volcanics) and five endmembers (87Sr/86Sr, 86Sr/86Sr, 206Pb/238U, 238U/235U and 208Pb/204Pb). The model was run 10,000 times, with endmember composition and concentration randomly selected within the 16.5–83.5% quantile range of the stream sediment data sets for each terrane. Mixing model results are corrected for CaCO3 content and presented as the median of all valid solutions returned by the 10,000 model runs, with 67% and 95% confidence intervals based on the 83.5–16.5% and 97.5–2.5% quantiles of all valid solutions, respectively (Extended Data Fig. 2).

Online Content

All references unique to these sections appear only in the online paper.

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Author Contributions

A.E.C., B.L.B. and J.S.S. had the idea for the study; A.V.R., A.E.C. and R.G.H. designed and conducted field research in Greenland; B.W. conducted grain-size analysis; A.V.R. and B.L.B. conducted isotopic analyses; K.W. sampled and R.G.H. designed and conducted field research in Greenland; C. Hillaire-Marcel for discussions of MD99-2227 stratigraphy and-source data; and E. Colville, P. Holm and S. Strano for assistance in the field. This research was supported by US NSF awards 0800271 (A.E.C., B.L.B.), 0902571 (A.V.R., A.E.C.) and 0902751 (J.S.S.) and a Canadian NSERC fellowship (A.V.R.).

Author Information

Greenland stream sediment and MD99-2227 data have been deposited with the NOAA National Climatic Data Center (http://hurricane.ncdc.noaa.gov/sps/paleo/fp=519:1;::;P1_STUDY_ID:16436). Reprints and permissions information is available at www.nature.com/reprints. The authors declare no competing financial interests. Readers are welcome to comment on the online version of the paper. Correspondence and requests for materials should be addressed to A.V.R. (areyes@ualberta.ca) or A.E.C. (acarlson@coas.oregonstate.edu).
from the residual eluent using 2.5 M HCl and AG50W-X8 cation-exchange resin, and rare-earth elements were eluted with 6 M HCl. Finally, rare-earth elements were separated using 0.15 M, 0.21 M and 0.5 M 2-methylacidic acid and AG50W-X4 cation-exchange resin in NH₃ form.

Pb, Rb–Sr and Nd isotope ratios were measured on a VG Sector 54 thermal ionization mass spectrometer; Rb, Sr, Sm and Nd concentrations were determined by isotope dilution. Pb was loaded onto single Re filaments with 1 M H₃PO₄ and Si gel, and isotope ratios were determined using a static multicolonlector analysis. Reported isotope ratios are the mean of 50 ratios measured at a typical ±0.1‰ Pb ion signal of 2 × 10⁻¹⁵ amps. Instrument mass bias was corrected by empirically determining a linear mass fractionation correction using the measured Pb⁉⁰/Pb⁹²Pb and Pb⁹⁸/Pb⁹⁰Pb ratios of NIST SRM 981 and SRM 982, respectively, run under similar conditions as the samples. Mass fractionation corrections were determined for each analytical session by averaging mass fractionation corrections for three analyses each on SRM 981 and SRM 982. This correction was typically 0.1% per a.m.u. The uncertainty in the mass fractionation correction results in an uncertainty of 0.03% per a.m.u. for Pb isotope ratios. The mean procedural blank for common Pb was ~600 pg (minimum and maximum of 183 and 1,484 pg, respectively), or conservatively <1% of the loaded Pb sample.

Sr was loaded on Ta filaments with H₂PO₄ and analysed using a three-jump dynamic multi-collector analysis routine, with exponential normalization to Sr⁹⁸/Sr = 0.1194. Reported isotope ratios are the mean of 120 ratios with a typical 88Sr ion signal of 3 × 10⁻¹⁵ ± 10⁻¹⁶. Analyses of NIST SRM 987 yielded mean Sr⁹⁸/Sr of 0.710263 ± 0.000013 (2σ, n = 46). The mean procedural blank for Sr was ~400 pg (minimum and maximum of 114 and 646 pg, respectively) or conservatively <50 p.p.m. of the loaded sample.

Nd was loaded on Re filaments with Si gel and H₂PO₄. Isotope ratios were determined as Nd²⁰⁰ using a dynamic multi-collector analysis routine, with exponential correction for mass fractionation using 146Nd/144Nd = 0.7189. Reported Nd isotope ratios are the mean of 150 ratios with a typical ⁴⁰Nd⁰⁰ ion signal of 1 × 10⁻¹⁵ ± 10⁻¹⁶. Analyses of internal Nd standards Ames I (n = 17), Ames II (n = 19) and La Jolla (n = 15) yielded mean ¹⁴⁴Nd/¹⁴⁰Nd (± 2σ) of 0.512137 ± 0.000022, 0.511967 ± 0.000015 and 0.511849 ± 0.000020, respectively. The mean procedural blank for Nd was ~200 pg (minimum and maximum of 48 and 730 pg, respectively) or conservatively <0.5% of the loaded sample. Nd isotope variations are presented in epison notation, which is defined as deviations from the present day ⁴⁰Nd/⁴⁰Nd of CHUR (chondritic uniform reservoir) in parts per ten thousand: εNd = [(¹⁴⁴Nd/¹⁴⁰Nd)sample/(¹⁴⁴Nd/¹⁴⁰Nd)CHUR – 1], where CHUR ¹⁴⁴Nd/¹⁴⁰Nd = 0.512638 (ref. 38).

We carried out identical digestion, element separation and mass spectrometry on a powdered split of USGS reference sample BCR-1, yielding the following values (errors are based on internal counting statistics and are reported as ± 2 s.e.): ¹⁴⁴Nd/¹⁴⁰Nd of CHUR = 0.512627 ± 0.000008, Nd = 28.4 ± 0.1 ppm; ⁶⁰Sr/⁶⁰Sr = 0.705303 ± 0.000010, Sr = 327 ± 2 p.p.m.; ⁶⁰Sr/⁶⁰Sr = 18.83 ± 0.002, Pb = 15.665 ± 0.002; and ⁶⁰⁰Pb/⁶⁰⁰Pb = 38.79 ± 0.004. Procedural blanks were negligible compared with sample size, and no blank corrections were applied. Analytical results for MD99-2227 and stream sediment samples are presented in Supplementary Tables 1 and 2, respectively.

Geological context and isotope geochemistry of south Greenland terranes. The area under study is made up of gneisses and granite that formed during the Early Jurassic and the Late Jurassic (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1). Thus, bedrock from a given terrane in southwest Greenland roughly west to east and outcrop from under the ice sheet along the south, east and west coasts40–42 (Fig. 1).

greenland stream sediments. Fine-grained glacially derived sediments from south Greenland meltwater streams were collected during the summers of 2008, 2009, 2010 and 2011, to substantially add to a stream sediment isotope geochemistry data set reported earlier13. We selected 20 samples of glacially derived silt, with a focus on samples collected from large, turbid meltwater systems draining major outlet glaciers of the GIS (Extended Data Fig. 3), including one collected for us by B. Hudson. We also analysed four samples from south Greenland glacioclastite sediment recently discharged into ice-marginal lakes (Extended Data Fig. 3e; samples collected by N. Larsen, S. Kelley, and J. Briner), five samples of poorly sorted debris entrained in icebergs near calving glacier margins (Extended Data Fig. 4a, b). We also analysed four samples from south Greenland glacioclastite sediment recently discharged into ice-marginal lakes (Extended Data Fig. 3e; samples collected by N. Larsen, S. Kelley, and J. Briner), five samples of poorly sorted debris entrained in icebergs near calving glacier margins (Extended Data Fig. 4a, b), and one sample of moraine diamicton. The sediments we sampled represent broad spatial areas of bedrock composition that best reflect the fine sediment produced by subglacial erosion and delivered to the marine sediment core. All samples were size-separated using the same procedure described above for MD99-2227 sediment, but were not acid-leached.

isotope geochemistry. All chemical separation and isotope analyses were conducted at the University of Wisconsin-Madison Radiogenic Isotope Laboratory. Acids used for sample preparation were purified by sub-boiling distillation, and diluted to 0.005 M using ultrapure water. Approximately 100 mg of dry sediment from the silt (<63 μm) size fraction was weighed into Savillex PFA vials and spiked with a mixed ⁸⁷Rb–⁸⁶Sr tracer and a rare-earth-element tracer containing ¹⁴⁷Sm and ¹⁴⁶Nd. Spiked samples were digested on hotplates overnight in 3 ml 29 M hydrofluoric acid and 300 μl 14 M HNO₃, and then evaporated. Next we added 4 ml 29 M hydrofluoric acid and 400 μl 14 M HNO₃, transferred the slurry to PTFE sleeves in Parr bombs and heated the sealed bombs for 48 h at 180–200 °C. Samples were transferred back to PFA beakers and evaporated, and this was followed by addition of 4 ml 8 M HCl and 24 h of digestion in sealed Parr bombs at 180–200 °C. The samples were then prepared for complete mineral dissolution using a binocular microscope before evaporation.

Following sample digestion, we used ion-exchange column chromatography to sequentially separate Pb, Rb–Sr and rare-earth elements. Pb was separated using HBr, HCl and AG1-X8 100-200 mesh anion-exchange resin. Rb–Sr were separated...
Proterozoic and Phanerozoic orogeny and tectonic events39–42,48–50. Stream sediment silts from AB watersheds reflect this antiquity, with very low \(^{206}\)Pb/\(^{204}\)Pb (Extended Data Fig. 1; see also ref. 50) and high \(^{87}\)Sr/\(^{86}\)Sr (Extended Data Fig. 1d). To the north, the NMB is a complex belt of folded and metamorphosed Archaean and Palaeoproterozoic gneisses and granite with local metasedimentary and metavolcanic rocks51. Although AB and NMB silts occupy distinct fields on \(^{187}\)Rb/\(^{87}\)Sr and \(^{143}\)Sm/\(^{144}\)Nd isochron plots (Extended Data Fig. 1d, e), their separation is more problematic when based solely on \(^{87}\)Sr/\(^{86}\)Sr and \(^{206}\)Pb/\(^{204}\)Pb (Extended Data Fig. 1f).

Isotopic mixing model and terrane endmembers. We used a four-component mixing model to estimate the relative proportions of terrigenous silt in MD99-2227 that originated from KMB, AB, NMB and Palaeogene volcanic source regions5,6,70. Endmember values for the KMB, AB and NMB are based on concentration and isotopic composition data of stream sediment silts (Supplementary Table 2), whereas the Palaeogene volcanic endmember values are based on whole-rock data compiled from the literature and analyses of glaciomarine sediments (Supplementary Table 3).

There is broad agreement between our stream sediment silt geochemical data and the whole-rock data compiled in ref. 16, although there are some key differences. Concentration-weighted mean \(^{87}\)Sr/\(^{86}\)Sr and \(^{187}\)Rb/\(^{87}\)Sr are much higher in the whole-rock data set (Extended Data Fig. 1c, d) for the three Precambrian terranes, probably reflecting some combination of sampling bias towards high-Rb/Sr rocks or loss of radiogenic Sr during chemical weathering, or both. Concentration-weighted silt \(^{206}\)Pb/\(^{204}\)Pb is quite large, particularly for the AB (Extended Data Fig. 1f). AB whole-rock \(^{206}\)Pb/\(^{204}\)Pb and \(^{208}\)Pb/\(^{204}\)Pb also exhibit substantial scatter and lower mean values, relative to stream sediment silt (Extended Data Fig. 1a, b).

We generated 1,000 random combinations of endmember isotope composition and concentration within ten evenly spaced bins between the 0.165 and 0.835 quantiles for each terrane geochemical data set (that is, spanning 67% of the asymmetric probability envelope), for a total of 10,000 random combinations of endmember values. We did not measure the Pb concentration of stream sediment silts by isotope dilution, and Pb concentration was rarely reported in the studies we compiled for the Palaeogene volcanic endmember. Thus, for each of the 10,000 randomly generated endmember combinations, we estimated the Pb concentration for the four terranes using the arithmetic mean of Pb concentration estimated from mean continental crustal Pb/Sr and Pb/Nd ratios4.

We implemented the four-component mixing model in R72 using
Table 5), and the LIG and Termination II (Supplementary Table 6). Our re-analysis results in a greater number of possible mixing equation solutions (Extended Data Fig. 7a). The median $f$ values are similar to the mean $f$ values reported in ref. 16, with the most important difference being the slightly greater modelled fraction of CaCO$_3$-free silt from the AB in our analysis. We also re-calculate the fractional contribution from each terrane expressed as a percentage of total core sediment (Fig. 3b) because we discovered some isolated and minor errors in the percentage CaCO$_3$-free silt and percentage silt data reported in ref. 16. For affected samples, the corrected results underscore the unprecedented nature of the low silt contribution from these terranes during MIS 11 (Fig. 3). Indeed, the corrected results underscore the unprecedented nature of the low silt contribution from these terranes during MIS 11 (Fig. 3).

Comparison to ice-sheet models. To estimate the sea-level contribution due to MIS 11 GIS retreat, we qualitatively compared our interpretation of a dramatically reduced south GIS with numerical models that simulate GIS response to projected future warming or reconstructed MIS 5e climate. We identified model simulations that satisfied our interpretation of largely ice-free AB and NMB; some residual ice on the KMB; ice at Summit Greenland; and ice at coastal north-central east Greenland. The GIS retreat in these simulations represents a range of global mean sea-level contributions spanning 4.5–6 m.

Extended Data Figure 1 | Whole-rock and stream sediment silt Sr–Nd–Pb isotope composition for south Greenland bedrock terranes. a, b, $^{207}$Pb/$^{204}$Pb (a) and $^{208}$Pb/$^{204}$Pb (b) versus $^{206}$Pb/$^{204}$Pb. c, d, $^{87}$Sr/$^{86}$Sr versus $^{87}$Rb/$^{86}$Sr for the range of whole-rock (WR) and stream sediment (SED) compositions (c) and restricted to the range of stream sediment compositions (d). e, $^{143}$Nd/$^{144}$Nd versus $^{147}$Sm/$^{144}$Nd. f, g, $^{87}$Sr/$^{86}$Sr versus $^{187}$Os/$^{184}$Os. h, $^{87}$Sr/$^{86}$Sr versus $^{206}$Pb/$^{204}$Pb (g) and $^{208}$Pb/$^{204}$Pb (h). Whole-rock data for KMB, AB and NMB compiled in ref. 16; Palaeogene volcanic whole-rock and glacigenic shelf sediment data are presented in Supplementary Table 3. Mean values (large symbols) are concentration-weighted means for Rb–Sr and Sm–Nd isotopic compositions, whereas Pb isotope ratios are arithmetic means.
Extended Data Figure 2 | Summary of mixing model results for each south Greenland terrane. MD99-2227 inferred silt provenance expressed as median flux of CaCO$_3$-free silt (a) and median percentage of total CaCO$_3$-free silt (b). Values for the Holocene and LIG are recast from CaCO$_3$-free silt Sr–Nd–Pb isotope ratios in ref. 16. Thick black and thin grey vertical lines mark the 16.5–83.5% and 2.5–97.5% quantile ranges, respectively, of valid mixing solutions from all 10,000 model runs. Uncertainty estimates are conservative, because the Monte Carlo procedure for random endmember determination can result in unrealistic combinations of source-terrane isotope composition and elemental concentration. Note different y-axis scale for Palaeogene volcanic data.
Extended Data Figure 3 | Selected sediment sampling sites in west Greenland. Site coordinates are provided in Supplementary Table 2: a, Qa11-04; b, Qa11-01; Qa11-03; c, stream sediment sampling sites near Narsaq; d, Kn11-03; e, proglacial lake, iceberg debris and proglacial outwash sampling sites near Nuuk; f, Kp11-01.
Extended Data Figure 4 | Age models for MD99-2227 and ODP Site 646.

a, Age–depth model for MD99-2227. Circles mark tie points based on $^{14}$C dates$^{18}$, $\delta^{18}$O (ref. 35) and RPI. b, MD99-2227 RPI and the PISO-1500 RPI stack$^{34}$, plotted on their individual age models. Crosses mark RPI tie points. c, MD99-2227 and ODP Site 646 magnetic susceptibilities, plotted on the MD99-2227 age model. For comparison purposes, the ODP Site 646 age–depth model was fitted to MD99-2227 using the magnetic susceptibility tie points indicated by crosses.
Extended Data Figure 5 | Comparison of MD99-2227 sedimentation rates and provenance estimates from south Greenland terranes.

a, *Neogloboquadrina pachyderma* (s) δ¹⁸O from ODP Site 646 (ref. 4; green) and MD99-2227 (Methods; blue). Yellow bar marks the interval of MD99-2227 that is affected by core stretching. b, MD99-2227 inferred silt provenance estimated using four-component endmember modelling, expressed as flux of CaCO₃-free silt. Values for the Holocene and LIG are recast from CaCO₃-free silt Sr–Nd–Pb isotope ratios in ref. 16. c, MD99-2227 sedimentation rates (left axis, thick blue line) and dry bulk density (right axis, thin red line). Note different y-axis scale for the Holocene/TI panels at far left for b and c.
Extended Data Figure 6 | Sediment sources and sedimentation processes. Conceptual model of terrigenous silt sources and transport processes for a given bedrock terrane during full glaciation (a), glacial termination and deglaciation (b), and near-complete deglaciation (c). SSC, sand/silt/clay.
Extended Data Figure 7 | Isotope mixing model comparison. Comparison of mixing model output for MIS 1, Termination I, MIS 5e and Termination II samples presented in ref. 16 with model output using the Monte Carlo approach reported here. a, Number of valid mixing equation solutions. b, c, Mean CaCO₃-free silt fractions for the KMB, AB and NMB (b), and the Palaeogene volcanics (c).