Supplementary Information

Evidence for ephemeral middle Eocene to early Oligocene Greenland glacial ice and pan-Arctic sea ice

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This file contains:

Supplementary Methods

Supplementary Figure 1: Number of Fe oxide grains from Greenland and Arctic Ocean sources at Site 913 from 48 to 26 Ma compared to proxy indicators of global climate, ice volume, and carbon cycle changes. Same as Fig. 4 in main text with vertical blue lines.

Supplementary Figure 2: Same as Fig. 4 in main text but detailed inset of interval from 48-36 Ma with vertical blue lines.

Supplementary Figure 3: Same as Fig. 4 in main text but detailed inset of interval from 36-26 Ma with vertical blue lines.

Supplementary Figure 4: Same as Fig. 4 in main text but detailed inset of interval from 48-36 Ma.

Supplementary Figure 5: Same as Fig. 4 in main text but detailed inset of interval from 36-26 Ma.

References

Supplementary Methods: Contains full set of references for data sources.

Fe grain matching: Samples were measured and data analyzed blindly at Old Dominion University. The method for precise source determination uses the chemical signature of 14 elements in nine types of iron oxide minerals[1–5]. This provenance tool has also been compared to the use of lithic grains for source determination in several studies with compatible but far more precise results[2,6–9].

Comparison with records of Arctic sea ice: There are datasets for two different sites used to place constraints on Arctic sea ice as shown in Figures 3-5, and as discussed in the text: (1) Site 913 (IRD provenance data generated in this study; Data in Supplementary Data Tables 1-2) and (2) the ACEX site[3,10–23] (Data in Supplementary Data Table 3). We note there are two different age models proposed for ACEX[24,25] that yield different ages that places the first appearance of IRD in ACEX a few million years apart and produce different ice-rafting histories, with one age model[25] producing results that are broadly consistent with the data for Site 913. We show the results of using each of these age models in Figure 3, with the different color lines in the bottom panel, as described in the figure caption; all subsequent figures and the discussion uses the age model for ACEX that best matches the results for Site 913.

Comparison with records of Arctic sea ice*:* Estimates for Arctic sea ice onset come from multiple publications[3,10–23].

Comparison with records of Antarctic ice: Estimates for Antarctic ice storage come from multiple publications[26–37].

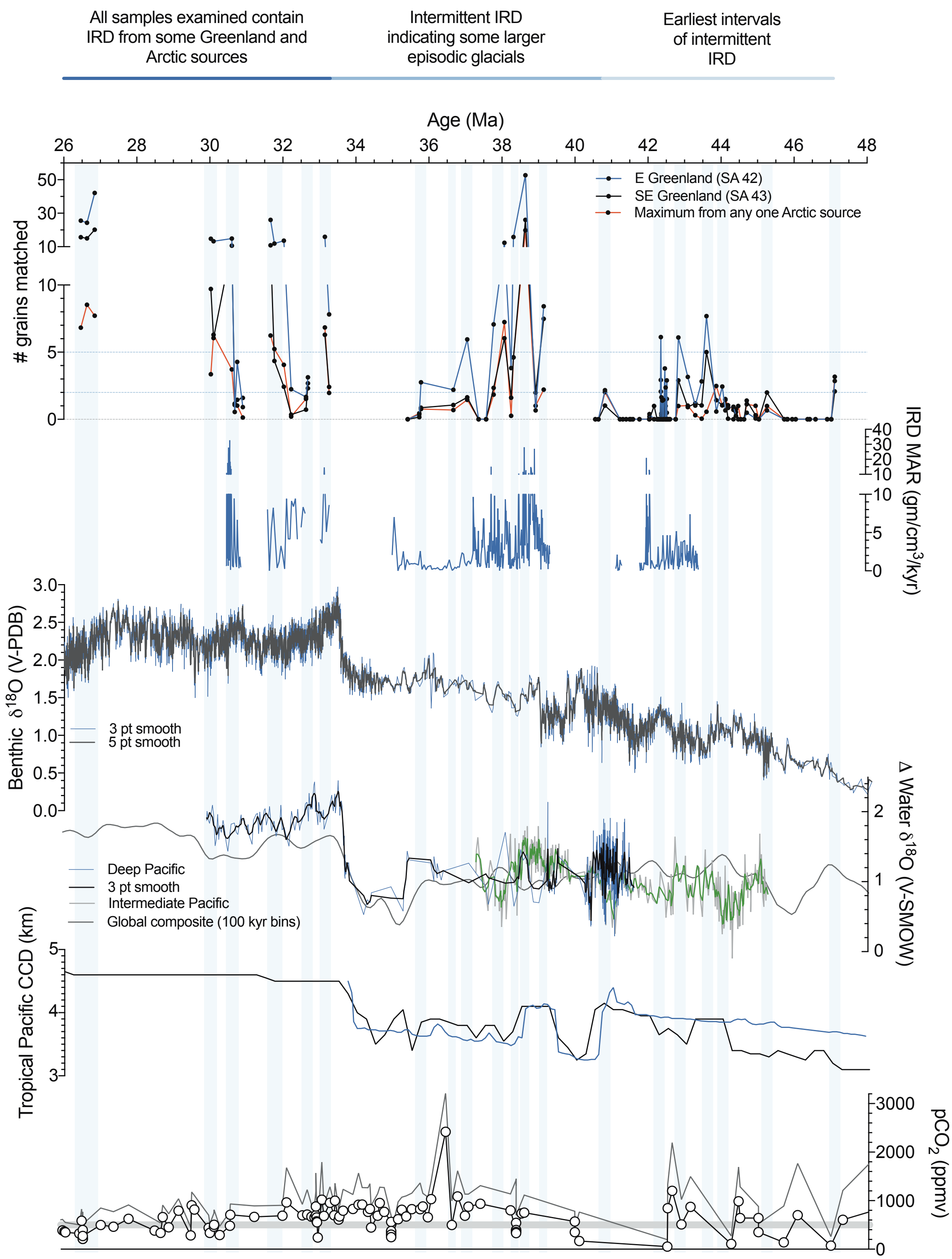
Composite deep-sea benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$: Benthic foraminiferal $\delta^{18}O$ and $\delta^{13}C$ are a compilation from multiple publications and sources therein[31,33,38,39]. Oxygen isotope adjustments are from publications[30,31,40,41]. Data are in Supplementary Data Table 4.

Seawater $\delta^{18}O$: Seawater $\delta^{18}O$ from multiple publications and sources therein[33,38,39,42]. Data are in Supplementary Data Table 4.

Carbonate compensation depth: Reconstructed tropical Pacific and equatorial Pacific CCD from multiple publications[38,43]. Data are in Supplementary Data Table 4.

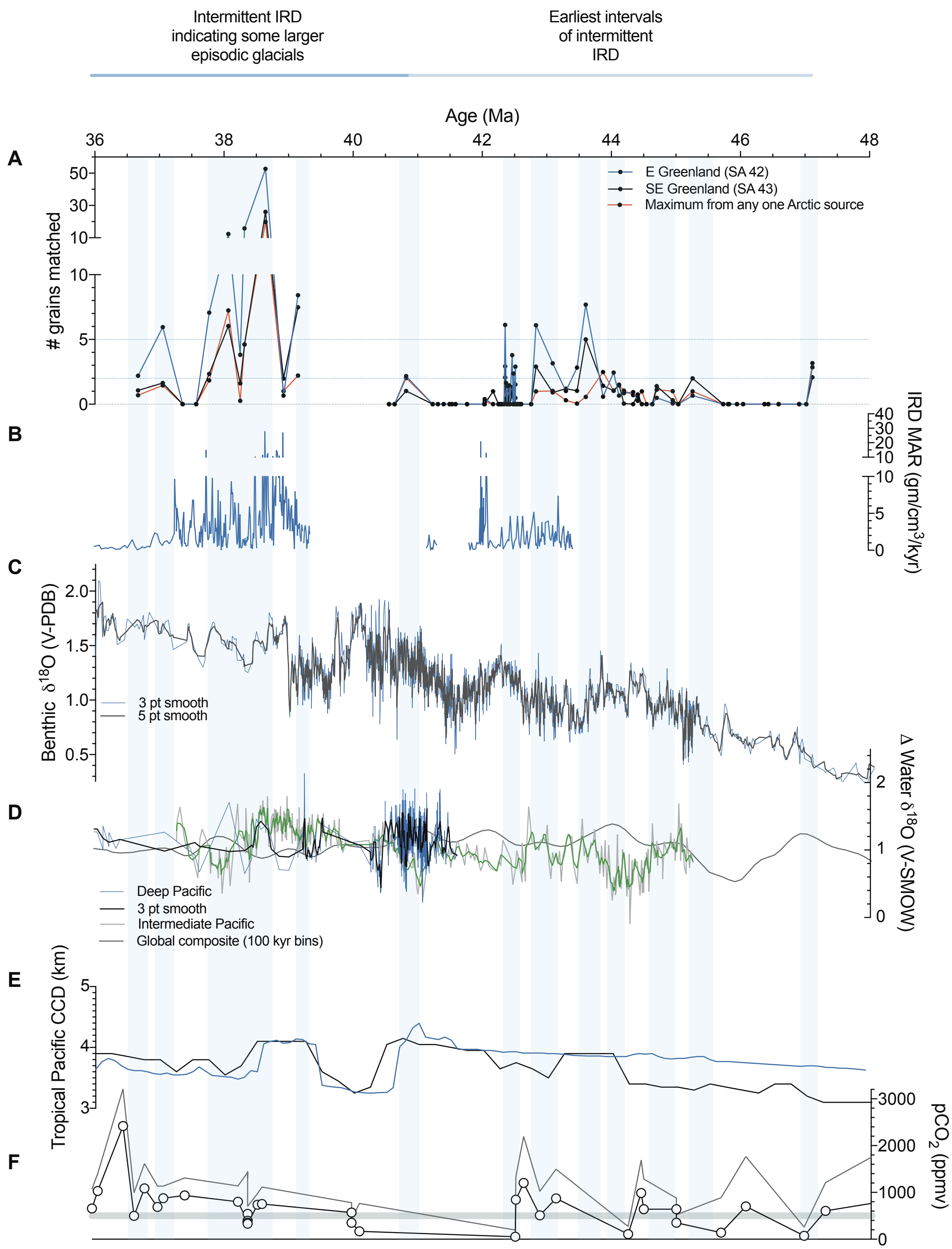
pCO_2: Proxy atmospheric CO_2 synthesis contains data from multiple publications and sources therein[44–85]. Data are in Supplementary Data Table 4.

Supplementary Figure 1: Number of Fe oxide grains from Greenland and Arctic Ocean sources at Site 913 from 48 to 26 Ma compared to proxy indicators of global climate, ice volume, and carbon cycle changes. Vertical blue lines mark intervals where Greenland-sourced IRD at Site 913 occurs or when there is an increase in $\delta^{18}O$. Comparison shows the occurrence of Greenland ice and circum-Arctic sea ice at Site 913 sometimes, though not always, coincides with increasing benthic foraminiferal $\delta^{18}O$ and Pacific water $\delta^{18}O$, increases in the carbonate compensation depth, and relatively low pCO_2. **A.** Ice-rafted Fe oxide grains from different source regions. Horizontal blue lines indicate 2 and 5 grains matched. **B.** IRD mass accumulation rates (MAR) at Site 913 shown, with intervals containing dropstones or grains >250 um in size indicated by underlying dotted blue line. **C.** Composite deep-sea benthic foraminiferal $\delta^{18}O$ record is shown with a 3-point and 5-point running mean. **D.** Changes in water isotopes at sites in the intermediate and deep Pacific are shown, with 3-point running mean for each, is plotted with a low-resolution global composite of reconstructed water $\delta^{18}O$. Underlying blue dotted lines indicate intervals where reconstructions show an increase in water $\delta^{18}O$ of more than 0.6 ‰. **E.** Carbonate compensation depth (CCD) for equatorial Pacific and tropical Pacific are shown, which are impacted by changes in sea level and carbon cycling. Dotted lines indicating where CCD is relatively deep or increases in depth. **F.** Composite proxy pCO_2 reconstruction is shown with lines indicating minimum and maximum values, and grey dotted line marking 500 ppmv. Complete list of data sources in Supplementary Methods. Same as Figure 4 but with no vertical lines.

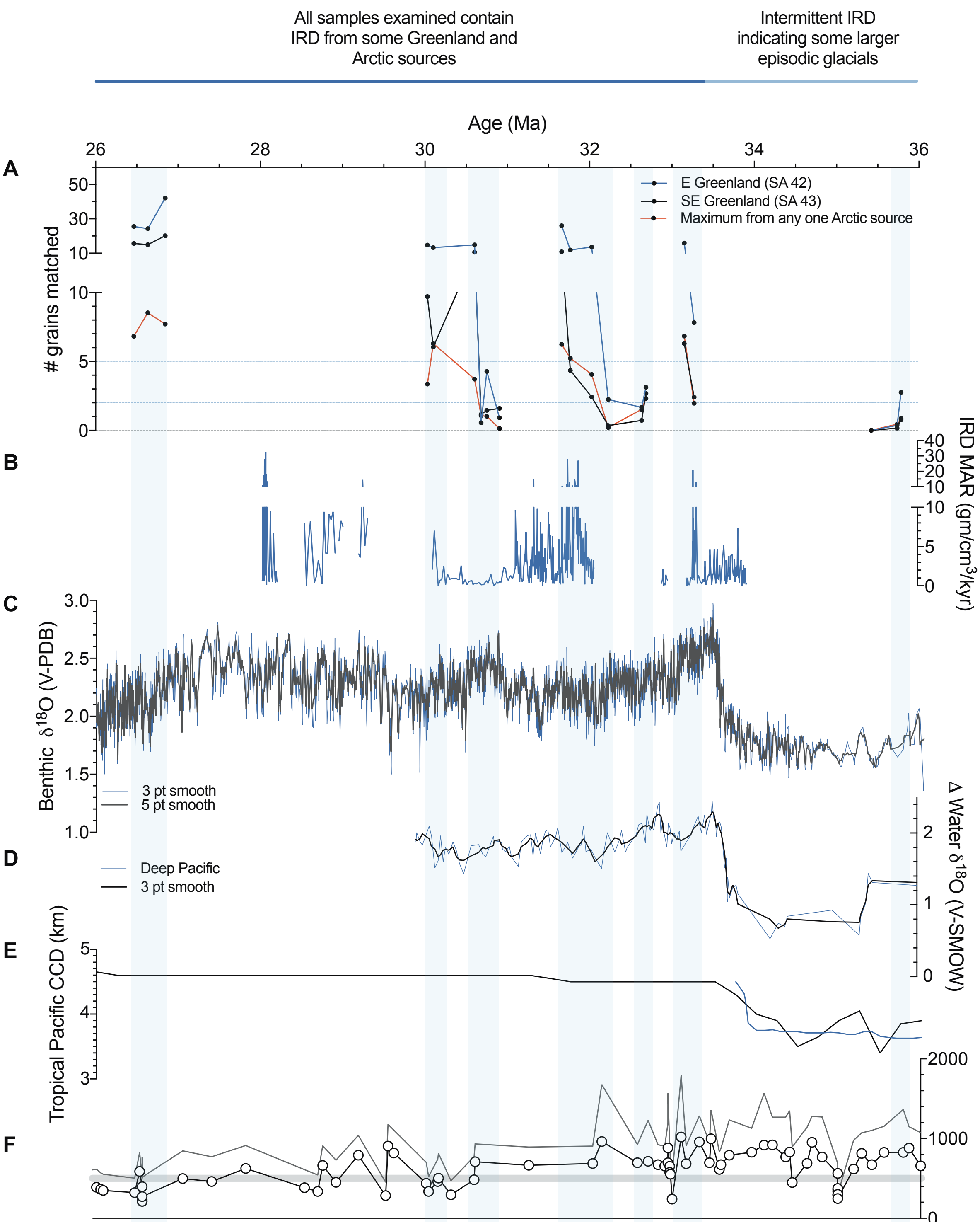


All samples examined contain IRD from some Greenland and Arctic sources
Intermittent IRD indicating some larger episodic glacials
Earliest intervals of intermittent IRD
Age (Ma)
A
B
C
D
E
F
grains matched
E Greenland (SA 42)
SE Greenland (SA 43)
Maximum from any one Arctic source
IRD MAR (gm/cm³/kyr)
Benthic δ¹⁸O (V-PDB)
3 pt smooth
5 pt smooth
Δ Water δ¹⁸O (V-SMOW)
Deep Pacific
3 pt smooth
Intermediate Pacific
Global composite (100 kyr bins)
Tropical Pacific CCD (km)
pCO₂ (ppmv)

Supplementary Figure 2: Number of Fe oxide grains from Greenland and Arctic Ocean sources at Site 913 from 48 to 36 Ma compared to proxy indicators of global climate, ice volume, and carbon cycle changes. Vertical blue lines mark intervals where Greenland-sourced IRD at Site 913 occurs or when there is an increase in $\delta^{18}O$. Comparison shows the occurrence of Greenland ice and circum-Arctic sea ice at Site 913 sometimes, though not always, coincides with increasing benthic foraminiferal $\delta^{18}O$ and Pacific water $\delta^{18}O$, increases in the carbonate compensation depth, and relatively low pCO_2. **A.** Ice-rafted Fe oxide grains from different source regions. Horizontal blue lines indicate 2 and 5 grains matched. **B.** IRD mass accumulation rates (MAR) at Site 913 shown, with intervals containing dropstones or grains >250 um in size indicated by underlying dotted blue line. **C.** Composite deep-sea benthic foraminiferal $\delta^{18}O$ record is shown with a 3-point and 5-point running mean. **D.** Changes in water isotopes at sites in the intermediate and deep Pacific are shown, with 3-point running mean for each, is plotted with a low-resolution global composite of reconstructed water $\delta^{18}O$. Underlying blue dotted lines indicate intervals where reconstructions show an increase in water $\delta^{18}O$ of more than 0.6 ‰. **E.** Carbonate compensation depth (CCD) for equatorial Pacific and tropical Pacific are shown, which are impacted by changes in sea level and carbon cycling. Dotted lines indicating where CCD is relatively deep or increases in depth. **F.** Composite proxy pCO_2 reconstruction is shown with lines indicating minimum and maximum values, and grey dotted line marking 500 ppmv. Complete list of data sources in Supplementary Methods. Same as Fig. 4 in main text but detailed inset of interval from 48-36 Ma and with vertical blue lines.

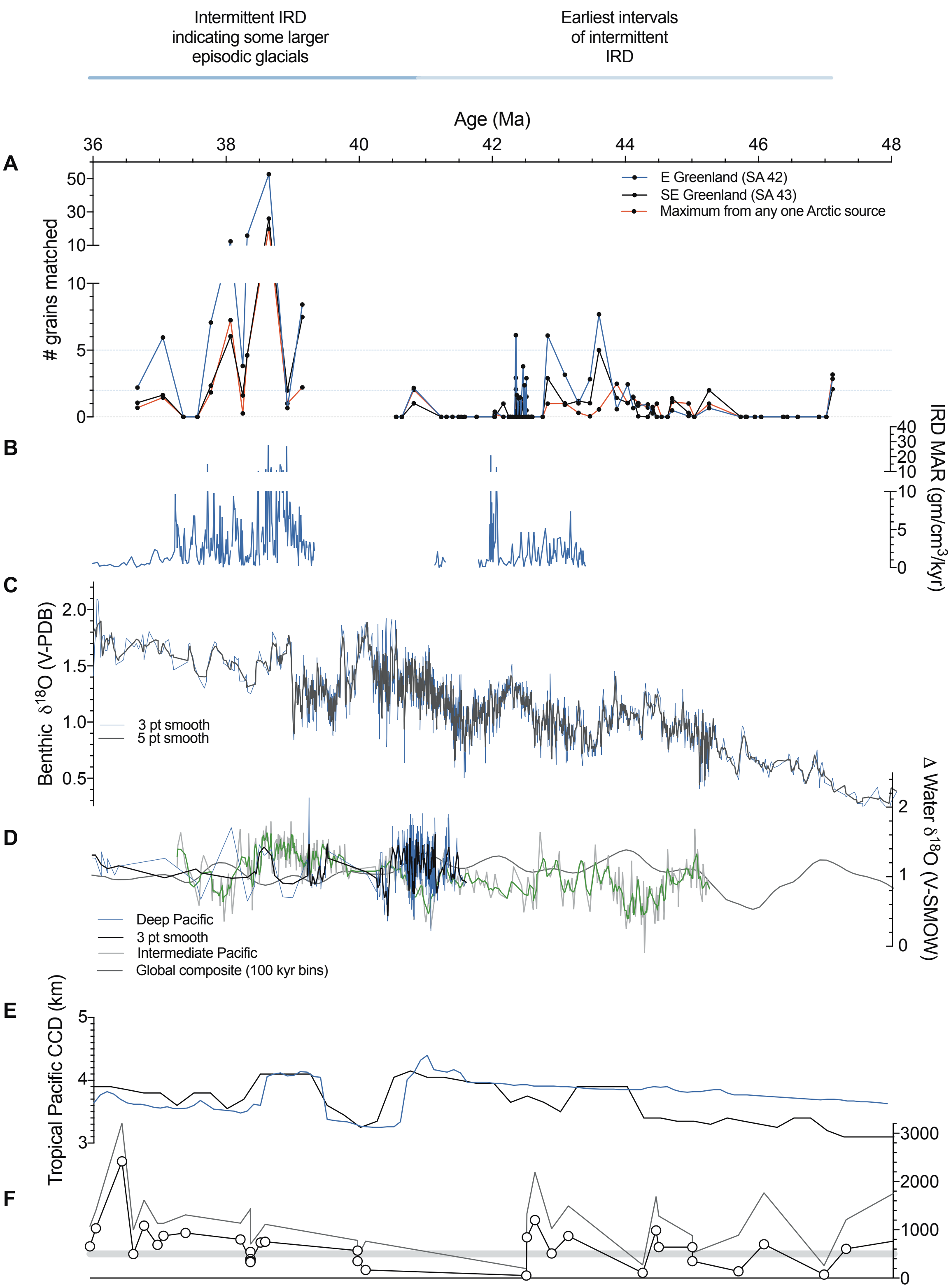

Intermittent IRD indicating some larger episodic glacials
Earliest intervals of intermittent IRD
Age (Ma)
36 38 40 42 44 46 48
A
grains matched
E Greenland (SA 42)
SE Greenland (SA 43)
Maximum from any one Arctic source
B
IRD MAR (gm/cm3/kyr)
C
Benthic δ18O (V-PDB)
3 pt smooth
5 pt smooth
D
Δ Water δ18O (V-SMOW)
Deep Pacific
3 pt smooth
Intermediate Pacific
Global composite (100 kyr bins)
E
Tropical Pacific CCD (km)
F
pCO2 (ppmv)

Supplementary Figure 3: Number of Fe oxide grains from Greenland and Arctic Ocean sources at Site 913 from 36 to 26 Ma compared to proxy indicators of global climate, ice volume, and carbon cycle changes. Vertical blue lines mark intervals where Greenland-sourced IRD at Site 913 occurs or when there is an increase in $\delta^{18}O$. Comparison shows the occurrence of Greenland ice and circum-Arctic sea ice at Site 913 sometimes, though not always, coincides with increasing benthic foraminiferal $\delta^{18}O$ and Pacific water $\delta^{18}O$, increases in the carbonate compensation depth, and relatively low pCO_2. **A.** Ice-rafted Fe oxide grains from different source regions. Horizontal blue lines indicate 2 and 5 grains matched. **B.** IRD mass accumulation rates (MAR) at Site 913 shown, with intervals containing dropstones or grains >250 um in size indicated by underlying dotted blue line. **C.** Composite deep-sea benthic foraminiferal $\delta^{18}O$ record is shown with a 3-point and 5-point running mean. **D.** Changes in water isotopes at sites in the intermediate and deep Pacific are shown, with 3-point running mean for each, is plotted with a low-resolution global composite of reconstructed water $\delta^{18}O$. Underlying blue dotted lines indicate intervals where reconstructions show an increase in water $\delta^{18}O$ of more than 0.6 ‰. **E.** Carbonate compensation depth (CCD) for equatorial Pacific and tropical Pacific are shown, which are impacted by changes in sea level and carbon cycling. Dotted lines indicating where CCD is relatively deep or increases in depth. **F.** Composite proxy pCO_2 reconstruction is shown with lines indicating minimum and maximum values, and grey dotted line marking 500 ppmv. Complete list of data sources in Supplementary Methods. Same as Fig. 4 in main text but detailed inset of interval from 36-26 Ma and with vertical blue lines.



All samples examined contain IRD from some Greenland and Arctic sources
Intermittent IRD indicating some larger episodic glacials
Age (Ma)
26
28
30
32
34
36
A
B
C
D
E
F
grains matched
E Greenland (SA 42)
SE Greenland (SA 43)
Maximum from any one Arctic source
IRD MAR (gm/cm^3/kyr)
Benthic δ^{18}O (V-PDB)
3 pt smooth
5 pt smooth
Deep Pacific
3 pt smooth
Δ Water δ^{18}O (V-SMOW)
Tropical Pacific CCD (km)
pCO_2 (ppmv)

Supplementary Figure 4: Number of Fe oxide grains from Greenland and Arctic Ocean sources at Site 913 from 48 to 36 Ma compared to proxy indicators of global climate, ice volume, and carbon cycle changes. Comparison shows the occurrence of Greenland ice and circum-Arctic sea ice at Site 913 sometimes, though not always, coincides with increasing benthic foraminiferal $\delta^{18}O$ and Pacific water $\delta^{18}O$, increases in the carbonate compensation depth, and relatively low pCO_2. **A.** Ice-rafted Fe oxide grains from different source regions. Horizontal blue lines indicate 2 and 5 grains matched. **B.** IRD mass accumulation rates (MAR) at Site 913 shown, with intervals containing dropstones or grains >250 um in size indicated by underlying dotted blue line. **C.** Composite deep-sea benthic foraminiferal $\delta^{18}O$ record is shown with a 3-point and 5-point running mean. **D.** Changes in water isotopes at sites in the intermediate and deep Pacific are shown, with 3-point running mean for each, is plotted with a low-resolution global composite of reconstructed water $\delta^{18}O$. Underlying blue dotted lines indicate intervals where reconstructions show an increase in water $\delta^{18}O$ of more than 0.6 ‰. **E.** Carbonate compensation depth (CCD) for equatorial Pacific and tropical Pacific are shown, which are impacted by changes in sea level and carbon cycling. Dotted lines indicating where CCD is relatively deep or increases in depth. **F.** Composite proxy pCO_2 reconstruction is shown with lines indicating minimum and maximum values, and grey dotted line marking 500 ppmv. Complete list of data sources in Supplementary Methods. Same as Fig. 4 in main text but detailed inset of interval from 48-36 Ma.

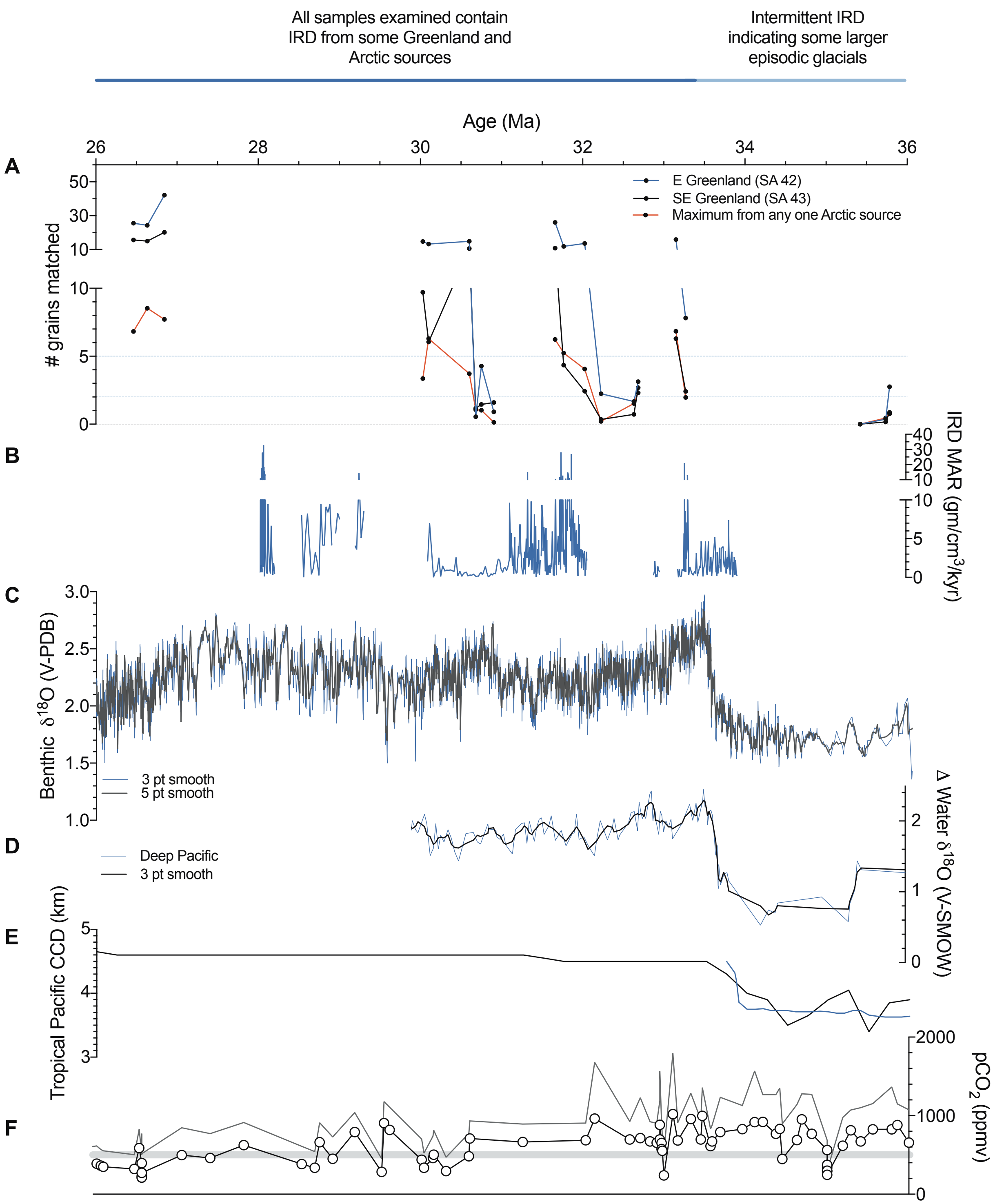

Intermittent IRD indicating some larger episodic glacials
Earliest intervals of intermittent IRD
Age (Ma)
36
38
40
42
44
46
48
A
grains matched
E Greenland (SA 42)
SE Greenland (SA 43)
Maximum from any one Arctic source
B
IRD MAR (gm/cm³/kyr)
C
Benthic δ18O (V-PDB)
3 pt smooth
5 pt smooth
D
Δ Water δ18O (V-SMOW)
Deep Pacific
3 pt smooth
Intermediate Pacific
Global composite (100 kyr bins)
E
Tropical Pacific CCD (km)
F
pCO2 (ppmv)

156

157

158

Supplementary Figure 5: Number of Fe oxide grains from Greenland and Arctic Ocean sources at Site 913 from 36 to 26 Ma compared to proxy indicators of global climate, ice volume, and carbon cycle changes. Vertical blue lines mark intervals where Greenland-sourced IRD at Site 913 occurs or when there is an increase in $\delta^{18}O$. Comparison shows the occurrence of Greenland ice and circum-Arctic sea ice at Site 913 sometimes, though not always, coincides with increasing benthic foraminiferal $\delta^{18}O$ and Pacific water $\delta^{18}O$, increases in the carbonate compensation depth, and relatively low pCO_2. **A.** Ice-rafted Fe oxide grains from different source regions. Horizontal blue lines indicate 2 and 5 grains matched. **B.** IRD mass accumulation rates (MAR) at Site 913 shown, with intervals containing dropstones or grains >250 um in size indicated by underlying dotted blue line. **C.** Composite deep-sea benthic foraminiferal $\delta^{18}O$ record is shown with a 3-point and 5-point running mean. **D.** Changes in water isotopes at sites in the intermediate and deep Pacific are shown, with 3-point running mean for each, is plotted with a low-resolution global composite of reconstructed water $\delta^{18}O$. Underlying blue dotted lines indicate intervals where reconstructions show an increase in water $\delta^{18}O$ of more than 0.6 ‰. **E.** Carbonate compensation depth (CCD) for equatorial Pacific and tropical Pacific are shown, which are impacted by changes in sea level and carbon cycling. Dotted lines indicating where CCD is relatively deep or increases in depth. **F.** Composite proxy pCO_2 reconstruction is shown with lines indicating minimum and maximum values, and grey dotted line marking 500 ppmv. Complete list of data sources in Supplementary Methods. Same as Fig. 4 in main text but detailed inset of interval from 36-26 Ma.



All samples examined contain IRD from some Greenland and Arctic sources
Intermittent IRD indicating some larger episodic glacials
Age (Ma)
26 28 30 32 34 36
A
B
C
D
E
F
grains matched
E Greenland (SA 42)
SE Greenland (SA 43)
Maximum from any one Arctic source
IRD MAR (gm/cm3/kyr)
Benthic δ18O (V-PDB)
3 pt smooth
5 pt smooth
Deep Pacific
3 pt smooth
Δ Water δ18O (V-SMOW)
Tropical Pacific CCD (km)
pCO2 (ppmv)

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