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Pliocene cooling enhanced by flow of low-salinity Bering Sea water to the Arctic Ocean

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Warming of high northern latitudes in the Pliocene (5.33-2.58 Myr ago) has been linked to the closure of the Central American Seaway and intensification of North Atlantic Deep Water. Subsequent cooling in the late Pliocene may be related to the effects of freshwater input from the Arctic Ocean via the Bering Strait, disrupting North Atlantic Deep Water formation and enhancing sea ice formation. However, the timing of Arctic freshening has not been defined. Here we present neodymium and lead isotope records of detrital sediment from the Bering Sea for the past 4.3 million years. Isotopic data suggest the presence of Alaskan glaciers as far back as 4.2 Myr ago, while diatom and C_{37:4} alkenone records show a long-term trend towards colder and fresher water in the Bering Sea beginning with the M2 glaciation (3.3 Myr ago). We argue that the introduction of low-salinity Bering Sea water to the Arctic Ocean by 3.3 Myr ago preconditioned the climate system for global cooling.

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he period from 4.4-4.0 million years ago (Myr ago) was the warmest interval within the Pliocene epoch and was characterized by global mean temperatures $\sim 3 \,^{\circ}\text{C}$ warmer than today^{1,2}. The subsequent cooling throughout the late Pliocene culminated in the late-Pliocene climate transition (LPCT, 3.6-2.4 Myr ago), which led to major Northern Hemisphere glaciation at 2.73 Myr ago^{3,4}. There is evidence for restricted, local glaciers on Arctic continents during the Pliocene warmth⁵; however, the evolution of these glaciers during the LPCT is poorly constrained, as is the role of the Central American Seaway (CAS)⁶. Tectonic shoaling of the CAS may have reached a critical threshold between ~ 4.7 and $4.2 \,\mathrm{Myr}$ ago⁶⁻⁹ that restricted Pacific-Caribbean surface-water exchange and redirected warm, saline waters from the equatorial Atlantic to the North Atlantic. These changes in the ocean circulation system are believed to contribute to an initial intensification of the Atlantic Meridional Overturning Circulation (AMOC) and warming of the North Atlantic prior to 3.6 Myr ago^{9–12}. Yet, there is no consensus regarding what processes reduced the intensification of the AMOC and led to the late-Pliocene global cooling.

Modelling results suggest increased moisture supply (that is, snowfall) related to the increased AMOC was insufficient to produce the major glaciation of Greenland¹². Alternative explanations emphasize increased freshwater inputs to the Arctic Ocean (AO) that could have generated lower sea-surface salinities (SSSs), leading to sea ice formation, increased ice-albedo effects and reduced heat exchange between the ocean and atmosphere^{6,7}. The proposed source for this freshwater is the enhanced flow of Siberian rivers, driven by increased moisture transport to Eurasia by the AMOC⁷. Another possible source is low-salinity Bering Sea water $^{6,13-15}$. The influence of Bering Sea water on the AO during the LPCT is particularly relevant because the flow direction through the Bering Strait is believed to have shifted from southward to its present northward direction at 3.6 Myr ago in response to changes in the steric height gradient between the North Pacific and AO, generated by closure of the CAS^{11,13}. The freshwater influx to the AO today is derived from river discharge (38%), inflow of low-salinity Bering Sea water (30%) and net precipitation (24%)^{16,17}. Thus, the amount of freshwater transported from the Bering Sea into the AO currently influences the strength of deep-ocean convection in the North Atlantic¹⁸⁻²⁰. An excess influx of freshwater from the Bering Sea to the AO during the Pliocene may have compounded the effect of Siberian River inputs on the stability of the AMOC, resulting in cooling during the LPCT⁶.

Low salinities in the Bering Sea today are primarily derived from the glacier-fed Alaska Coastal Current (ACC)²¹ (Fig. 1). Therefore, Alaskan mountain glacier build-up and seasonal melting of ice should be necessary for establishing low salinities in the Bering Sea; however, the Pliocene evolution of this glacial input has been difficult to track due to limited records of the glacial history of Alaska and past surface-water properties in the Bering Sea. Here we generate Pliocene records of sediment provenance and surface-water properties in the Bering Sea to demonstrate the timing of cryospheric evolution in the Bering/ Alaskan region and clarify the relationship between flow of lowsalinity Bering Sea water to the AO and the late-Pliocene global cooling.

Results

Surface-water properties and Nd and Pb isotope records. In this study, we interpret the relative abundance of tetraunsaturated C_{37} alkenones to total C_{37} alkenones (% $C_{37:4}$ alkenone) as a proxy for temperature and/or salinity, with higher percentages reflecting cool and/or freshwater masses^{22,23}. The percentage of 'sea-ice

related' diatoms is the relative abundance of *Thalassiosira* antarctica resting spores, *Fragilariopsis cylindrus* and *Fr. oceanica* to the total number of diatoms²⁴. Today, these diatoms are common in surface sediment from the Bering Sea shelf and slope, where sea ice expands seasonally, but they are absent or found in low abundances in surface sediments in the central Bering Sea, where sea ice is less common²⁵. An additional proxy is the percent of *Actinocyclus* spp., which is a species that is abundant in surface water with meltwater-related stratification^{24,26}.

At IODP (Integrated Ocean Drilling Program) Site U1341B (Expedition 323) located at Bowers Ridge in the southern Bering Sea (Fig. 1; Methods; Supplementary Fig. 1; refs 27,28), all three of these surface-water proxies record gradual increases beginning around the time of MIS (marine isotope stage) M2 glaciation at 3.3 Myr ago and continuing to 2.75-2.5 Myr ago (Fig. 2d-f), indicating cooling and/or freshening and increased meltwaterrelated stratification. The highest % C37:4 alkenone values are observed during the mid-Pleistocene transition (MPT), probably reflecting additional cooling and/or freshening (Fig. 2f). The lowresolution % C37:4 alkenone record in the Bering Sea has remarkable similarities to a high-resolution % C37:4 alkenone record from Site 882 in the subarctic western North Pacific²⁹, which also records the highest values during the MPT and stable, lower values prior to 3.4 Myr ago (Figs 2f and 4e). The lack of correlation between % C_{37:4} alkenones and % Actinocyclus spp. during the MPT is attributed to higher percentages in T. trifulta group and T. antarctica resting spores²⁴, which prefer cold water and reduce the % Actinocyclus spp.

The detrital ε_{Nd} values from Site U1341B span a wide range from -6.2 to $+ 6.9 \varepsilon_{Nd}$ over the past 4.3 Myr ago, with large, rapid fluctuations from 2.8 to 2.0 Myr ago (Fig. 2c). The ε_{Nd} variability was confirmed by replicate analysis of some of the samples with high and low $\varepsilon_{\rm Nd}$ values (Supplementary Table 1). Further, similar highly variable detrital $\epsilon_{\rm Nd}$ values are documented in glacial-interglacial sediments at Bow-8A (-6.1 to +2.2 ε_{Nd} ; Supplementary Fig. 2) and at Site 884 (-1.2 to $+8.6 \varepsilon_{Nd}$; ref. 30) (Fig. 1). These highly variable detrital ε_{Nd} values suggest regional glacial-interglacial shifts of sediment sources and/or sediment transport processes. A lower-resolution detrital lead (Pb) isotope record (n = 29) also shows similar high variability (Supplementary Fig. 3; Supplementary Table 1). The long-term ε_{Nd} record (400-kyr running mean) demonstrates a marked shift from more radiogenic to less radiogenic values across the LPCT starting at 3.0 Myr ago and during the MPT starting at 1.2 Myr ago, coherent with the % C37:4 alkenone record (Fig. 2c,f). Further, the pronounced glacial MIS M2 is marked by the lower detrital $\varepsilon_{\rm Nd}$ value, together with the increases in % sea-ice-related diatoms and % Actinocyclus spp.

Sediment provenance. Detrital material is delivered to the Bering Sea from continental sources via rivers, ice and wind, and distributed by surface and deep currents. Today, the Yukon River, the largest river in the Bering Sea, provides > 63% $(55 \text{ Mt yr}^{-1})^{31}$ of the total sediment load to the Bering Sea in association with abundant freshwater discharge $(6,400 \text{ m}^3 \text{ s}^{-1})^{32}$ as it drains portions of the glaciated Alaska Range, Wrangell Mts and St Elias Mts in Alaska (Fig. 1; Supplementary Note 1). Approximately half of the annual suspended sediment exported via the Yukon River occurs during spring season snowmelt and the other half occurs during summer–autumn season glacier melt³³. The meltwater river plumes, and counterclockwise surface currents in the Bering Sea distribute these Yukon River detrital sediments over long distances and a wide area of the eastern Bering Sea shelf^{34,35} (Fig. 1).



Figure 1 | Locations of studied sediment cores and major surface currents. The Bering Strait is narrow (~85 km wide) and shallow (~50 m deep) at the far northern end of the Pacific Ocean that connects to the Arctic Ocean (AO). Glacial meltwater provides a substantial portion of the total freshwater runoff into the Alaska Coastal Current (ACC), and the low-salinity ACC flows to the AO. Grey arrows indicate subsurface flow at 40 m (ref. 37). On the map, numbers in the white boxes represent the e_{Nd} value and the ${}^{206}Pb/{}^{204}Pb$ ratio of detrital materials in the source regions. Isotopic data are compiled from the GEOROC database³⁸ and from the literature (see references in the figure caption of Fig. 3). Coloured circles represent sampling sites and their detrital e_{Nd} values of surface sediments³⁴. Red stars (this study) and white squares^{30,40,54} are the locations of core sites cited in this study. The black arrow represents the transport of Asian dust. Bathymetry and land topography are also shown.

The Alaskan material stored on the Bering Sea shelf is transported to Bowers Ridge by the southward-flowing current. Thus, despite the distance from the Yukon outflow to Bowers Ridge, potential detrital sources at Site U1341B in the southern Bering Sea include the Yukon-Tanana terrane, Aleutian arc and aeolian dust from the Asian continent. Aeolian sources from Alaska and the Anadyr River detrital material might be less significant because the core site is not downwind from Alaska³⁶, and the detrital flux from the Anadyr River is a small $(2 Mt yr^{-1})^{30}$ and is restricted to the northern shelf margins by the southwestward-flowing Kamchatka current³⁷, respectively. The three primary detrital sources, Yukon-Tanana terrane, Aleutian arc and Asian dust, have very distinct Nd and Pb isotopic signatures; Yukon-Tanana terrane Alaskan material has $\varepsilon_{\rm Nd}$ values of -8 to -9 and $^{206}\text{Pb}/^{204}\text{Pb}$ values of 19.16–19.67 (refs 30,38,39), Aleutian arc material has $\varepsilon_{\rm Nd}$ values of $\,+\,6$ to $\,+\,8$ and ${}^{206}\text{Pb}/{}^{204}\text{Pb}$ values of 18.73–18.95 (refs 30,38) and Asian dust has ε_{Nd} values ca. –10 and ${}^{206}\text{Pb}/{}^{204}\text{Pb}$ values of 18.88–18.97 (ref. 40-42) (Fig. 1). Therefore, these isotope data will be sensitive monitors of provenance for the southern Bering Sea sediments.

Nd and Pb isotopic compositions of detrital sediments from U1341B create linear arrays for isotope plots of $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{207}\text{Pb}/^{204}\text{Pb}$, $^{206}\text{Pb}/^{204}\text{Pb}$ versus $^{208}\text{Pb}/^{204}\text{Pb}$ and $^{206}\text{Pb}/^{204}\text{Pb}$ versus ϵ_{Nd} which connect Aleutian arc material and Yukon-Tanana terrane Alaskan material (Fig. 3a–c). In contrast, data from Site 885/886 in the subarctic North Pacific⁴⁰ create a distinct linear array that connects central–eastern Aleutian Arc materials and Chinese loess (Figs 1 and 3a–c). These data show that Site 885/886 is marked by higher fluxes of the Asian dust and lower detrital fluxes from the Aleutian arcs than U1341B. However, the Asian dust fluxes estimated at Site 885/886 for the past 5 Myr ago

 $(8-122 \,\mu g \, cm^{-2} \, yr^{-1}; ref. 40)$ and the fluxes observed in the modern North Pacific $(22-100 \,\mu g \, cm^{-2} \, yr^{-1}; ref. 43)$ are negligible compared with the higher mass accumulation rates of detrital materials for U1341B (8 mg cm⁻² yr⁻¹, assuming 14 cm kyr⁻¹ as the average sedimentation rate, 40 wt% of detrital material content and $1.4 \, g \, cm^{-3}$ of bulk sediment density²⁸). Thus, we interpret the detrital sediments of U1341B as a mixture dominated by sediments from the Aleutian and Alaskan sectors throughout the past 4.3 Myr ago.

Prior to MIS M2 at 3.3 Myr ago, most of the detrital Nd isotope data plot between +5 and $+6 v_{Nd}$ (Fig. 2c), suggesting that sedimentation at the site was dominated by local Aleutian sources. However, there are four pulses that produced progressively less radiogenic values. These occurred at 4.2 Myr ago, 3.96 Myr ago, 3.55 Myr ago, and the MIS M2 glaciation (3.3 Myr ago). A simple binary mixing model estimates that Alaskansourced detrital materials accounted for 13% of the detrital sediment at 4.2Myr ago, 26% at 3.96Myr ago, 32% at 3.55Myr ago and 48% at 3.32 Myr ago (Methods), indicating that the proportion of Alaskan inputs increased in progressively younger samples.

Transport of Alaskan detrital material to Bowers Ridge. Coretop late-Holocene sediment from core Bow-8A at Bowers Ridge located near the Aleutian arc has an $\varepsilon_{\rm Nd}$ value of +2.2(Fig. 1; Supplementary Fig. 2). Simple binary mixing (Methods) suggests the core-top sediment is predominantly composed of central–eastern Aleutian material with a minor component of Alaskan material (18%). This Yukon River-derived Alaskan material stored on the Bering Sea shelf may have been transported



Figure 2 | Multi-proxy records from Bering Sea Site U1341B for the past 4.3 Myr ago. (a) Global stack of δ^{18} O record⁴. Records of (b) natural gamma radiation (NGR), (c) detrital Nd isotope values, (d) % *Actinocyclus* spp²⁴., (e) % sea-ice-related diatoms²⁴ and (f) % C_{37:4} alkenones from U1341B in the Bering Sea. The thick line in **c** represents the 400-kyr running mean, and the error bars correspond to $2\sigma_{\mu m}$ error (see details in Supplementary Table 1). From 4.3 to 3.3 Myr ago, there is no evidence of sea-ice-related diatoms in the southern Bering Sea. Some minor increases in % sea-ice-related diatoms before 3.3 Myr ago were not significant relative to error. These multi-proxy records from the Bering Sea highlight that the marine isotope stage (MIS) M2 glaciation at 3.3 Myr ago marks the beginning of the long-term trend towards cooling/freshening, meltwater-related stratification, expansion of sea ice and increased proportion of clay minerals in the southern Bering Sea. LPCT and MPT are Late-Pliocene climate transition and Mid-Pleistocene transition, respectively.

to Bowers Ridge by the southward-flowing current. In contrast, during the last deglaciation and the last glacial maximum (LGM), detrital sediments at Bow-8A have less radiogenic $\varepsilon_{\rm Nd}$ values of -6.1 to -4.1 (Supplementary Fig. 2), which translates to a much

greater contribution from Alaskan sources (60–78%). A measured decrease in diatom δ^{18} O in the northeast Bering Sea during the deglacial is believed to reflect a large flux of meltwater from retreating alpine glaciers in Alaska⁴⁴, which may have transported



Figure 3 | Pb and Nd isotope cross-plots for U1341B detrital sediments and potential local source rocks. (a) 206 Pb/ 204 Pb versus 207 Pb/ 204 Pb, (b) 206 Pb/ 204 Pb versus 208 Pb/ 204 Pb and (c) 206 Pb/ 204 Pb versus ϵ_{Nd} isotope plots. Core U1344 (open cross) was retrieved from the northern Bering slope near the Yukon River, and thus detrital sediments deposited during the LGM (last glacial maximum) and the last deglaciation are representative of Yukon River-delivered Alaskan detrital material. U1341B detrital sediments of Nd and Pb isotopes (open circle) represent a binary mixing line (coloured dashed line in c) showing a mixture of sediment from the Aleutian and Alaskan sectors^{30,38,39}, whereas detrital sediments at Site 885/886 (× -mark, ref. 40) represent a linear array (grey dashed line in a-c) connecting Chinese loess and central-eastern Aleutian Arc sectors^{38,41,42}. The coordinates of points (bar) on the Aleutian-Yukon (Alaska) mixing line (c) represent the proportion of the Alaskan detrital material (Methods). Detrital ϵ_{Nd} record from U1341B represents four pulses that produced progressively less radiogenic ϵ_{Nd} values prior to 3.3 Myr ago, and these data are marked with the ages in c. Although detrital materials from the Yukon-Tanana terrane have a wide range of 206 Pb/ 204 Pb ratios, the average 206 Pb/ 204 Pb ratio of Alaskan-sourced material is assumed to be 19.25 for the mixing line (Methods and Supplementary Table 3).

some of the detrital sediment. Evidence from diatom assemblages suggests the presence of drift ice at northern Bowers Ridge at the LGM⁴⁵. Given these results, it appears that meltwater plumes and sea ice rafting were responsible for transporting a large amount of Alaskan detrital materials from the prograded mouth of the Yukon River towards Bowers Ridge during deglacial and glacial periods, respectively.

During glacial periods when sea level fell, the closed Bering Strait (currently 50 m deep) would also have altered both surface and intermediate water circulation in the Bering Sea^{45,46}. Yet, the tight coupling between detrital Nd isotopes and foraminiferal δ^{18} O records from Bow-8A within the Bering Sea (Supplementary Fig. 2) and Site 884 in the North Pacific south of the Aleutian Arc³⁰ suggests delivery of Alaskan detrital material was driven by a process beyond the Bering Sea caused by the closure of the Bering Strait. Instead, changes driven by ice volume, such as the location of Alaskan river outflow, the extent of sea ice formation and the volume of meltwater, appear to provide better explanations of observed changes in the composition of detrital material during glacial-interglacial cycles.

In the early Pliocene, most of the Nd isotopic data are centred on +5 to $+6 \varepsilon_{Nd}$, higher than the Bow-8A core-top value (+2.2 $\varepsilon_{\rm Nd}$) (Fig. 2c), and there is no evidence of sea-ice-related diatoms from 4.3 to 3.3 Myr ago²⁴ (Fig. 2e). These findings indicate that the southern Bering Sea was relatively warm and there was insufficient ice or glacial melt to transport Alaskan detrital material, consistent with the general view of Pliocene warmth^{1,2,47} (Fig. 4b-d). The relatively stable and radiogenic $\varepsilon_{\rm Nd}$ values observed from 4.3 to 3.3 Myr ago transition to an interval of high-amplitude variations and overall decreasing ε_{Nd} values across the LPCT from 3.3 Myr ago to the MPT starting at 1.2 Myr ago. This long-term shift of detrital ε_{Nd} coincides with (1) greater variability and a general increase in global ice volume (Fig. 2a) and (2) increasing natural gamma radiation in the core, indicating an increased proportion of clay minerals particularly during glacial intervals⁴⁸ (Fig. 2b) and (3) increasing % C37:4 alkenones, indicating cooling and/or freshening of water masses^{22,23} (Fig. 2f). These proxies further support the interpretation of increasing glacial ice volume in the Bering/ Alaskan region during the LPCT to MPT. The correlation between increased ice volume, increased proportions of clay minerals and lower detrital Nd isotopes argues that sea ice rafting and snow/glacier melt discharge from the Yukon River supplied a larger fraction of the Alaskan detrital material to Site U1341B for these periods.

Discussion

Previous research on Gulf of Alaska sediments shows the presence of tidewater glaciers in southeastern Alaska since the Late Miocene, with more definitive evidence for glaciers based on the presence of dropstones beginning at 4.2–4.3 Myr ago⁴⁹. The Pliocene detrital $\varepsilon_{\rm Nd}$ record from U1341B shows pulses of progressively greater inputs of Alaskan detrital material beginning as early as 4.2 Myr ago (Figs 2c and 4f). The first pulse of Alaskan detrital inputs that coincides with a slight increase in % sea-ice-related diatoms and a significant increase in % *Actinocyclus* spp. occurs during the MIS M2 glaciation at 3.3 Myr ago (Fig. 2c–e). This correlation indicates the first Alaskan glaciers large enough to produce associated meltwater and sea ice appeared at 3.3 Myr ago.

In contrast, other early pulses of Alaskan detrital material inputs at 4.2, 3.96 and 3.55 Myr ago lack a response in % $C_{37:4}$ alkenones and % *Actinocyclus* spp. Although Alaskan mountain glaciers appear to have developed in the early Pliocene, the lack of coherent responses suggests that Alaskan glaciations were probably limited in size and early-glacial meltwater plumes were not large enough to produce stratification and freshening in the southern Bering Sea. However, initial deposition of Alaskansourced detrital material on the Bering Sea shelf may have been sourced by smaller glacial meltwater pulses and transported to Bowers Ridge by the southward-flowing current, as seen in the Holocene. The details of current processes that transported Alaskan detrital sediments to the Bowers Ridge remain uncertain, but an important point is that pulses of Alaskan detrital inputs ARTICLE



Figure 4 | Comparison of global and regional data from the Pliocene-Pleistocene. (a) Sand mass accumulation rate in the Caribbean Sea⁹, (b) Alkenonederived SST records in the North Atlantic⁶⁰, (c) Winter SST records based on transfer function methods of planktic foraminifera assemblages in the western North Pacific⁵¹, (d) Alkenone-derived SST records in the eastern North Pacific⁵², (e) $C_{37:4}$ alkenone abundance from the subarctic western North Pacific²⁹, (**f-h**) Records of detrital Nd isotopes, sea-ice-related diatom abundance²⁴ and $C_{37:4}$ alkenone abundance from Bering Sea Site U1341B. Restriction of the CAS (Central American Seaway) started at 4.6-4.7 Myr ago^{8,9}. The presence of Alaskan mountain glaciers was as far back as 4.2 Myr ago, and the flow direction of Bering Strait throughflow has shifted from southward to its present northward direction at 3.6 Myr ago¹³ (dashed line). Introduction of lowsalinity Bering Sea water into the AO might have started by at least 3.3 Myr ago. Thick lines in **a,b,d** and **f** represent the 400-kyr running mean.

identified by detrital Nd isotopes in the early Pliocene support growth of Alaskan mountain glaciers as a necessary precondition for the deposition of Alaskan-sourced detrital material on the Bering Sea shelf. Further, we also propose that increased volumes of melt with progressively larger glaciers from 4.2 Myr ago would have increased the depositional area of Alaskan-sourced detrital material on the Bering Sea shelf, resulting in progressively greater inputs of Alaskan detrital material to the Bowers Ridge.

Early-Pliocene evolution of Alaskan mountain glaciers (~ 4.2 -3.3 Myr ago) capable of producing a sedimentary signature of Alaskan material at Bowers Ridge may be related to a series of ocean-climate feedbacks triggered by the restriction of the CAS starting 4.6-4.7 Myr ago (Fig. 4a). A coupled ocean-atmosphere general circulation model found that meridional heat transport in the North Pacific weakened in response to reduced transport of saline water to the equatorial Pacific as the CAS shoaled⁵⁰. This change in heat transport facilitated cooler air temperatures around the North Pacific and more snow accumulation over Alaska and western Canada⁵⁰. Pronounced decreases in seasurface temperature (SST) in the western subtropical and eastern North Pacific from ~ 4.4 to 4.6 Myr ago^{51,52} (Fig. 4c,d) and persistent cooling of the Chinese Loess Plateau beginning $\sim 4 \,\mathrm{Myr}$ ago⁵³ support this modelling result. We acknowledge the lack of the detrital Nd isotopic record prior to 4.3 Myr ago limits our evaluation of the relationship between restriction of the CAS and growth of Alaskan mountain glaciers. However, terrigenous mass accumulation rates from ODP 887 in the Gulf of Alaska also increased from 4.55 Myr ago, with relatively higher values after 4.24 Myr ago⁵⁴, again supporting a relationship between the sediment flux from Alaska and restriction of the CAS. On the basis of these data around Alaska, we propose that the growth of Alaskan mountain glaciers in the early Pliocene was accelerated by the reduction of northward heat transport in the North Pacific due to the restriction of the CAS at 4.6-4.7 Myr ago.

The evolution of a relatively fresh ACC is poorly constrained, but is presumably linked to the onset of Alaskan glaciation, which had started by at least 4.2 Myr ago. Smaller Alaskan mountain glaciers in the early Pliocene might have started to feed glacial meltwater to the coastal Bering Sea, but the combination of the small volume and the southward flow direction of Bering Strait throughflow limited the impact in the AO. Reversal of the Bering Strait throughflow at 3.6 Myr ago^{11,13} might be related to a change in the steric sea-level gradient between the Arctic and Bering Sea basins driven by increases in SSS in the North Atlantic and decreases in SSS in the North Pacific in response to restriction of the CAS. The resulting flow might have first introduced northern Bering Sea coastal water into the AO, but freshwater inputs from the Bering Sea to the AO were not significant enough to perturb the freshwater balance in the AO.

Our evidence for long-term cooling/freshening, meltwaterrelated stratification and expansion of sea ice in the southern Bering Sea by 3.3 Myr ago supports the establishment of more extensive ice on Alaska by this time, which enhances the likelihood that a fresher ACC developed in the eastern Bering Sea and delivered low-salinity water to the AO. Progressively larger fluxes of meltwater from progressively larger Alaskan mountain glaciers that developed from 3.3 to 2.8–2.5 Myr ago, as documented in $C_{37:4}$ alkenone and *Actinocyclus* spp. records, would have further reduced salinity in ACC and ultimately in the AO.

Introduction of low-salinity Bering Sea water into the AO, starting by at least 3.3 Myr ago, would have perturbed the freshwater budget in the AO. Development of a low-salinity surface layer in the AO would have isolated the warmer, more saline intermediate waters from the atmosphere, and promoted expansion of sea ice in the North Atlantic that began at 3.2 Myr ago^{55,56} as well as freshening of the East Greenland Current between 3.25 and 3.16 Myr ago¹⁴. This scenario sets up northern high-latitude cooling through ice-albedo feedbacks. Ultimately, outflow of this low-salinity Arctic water to the North Atlantic water (4.0–3.0 Myr ago)^{10,57}, further contributing to major

continental glaciation in the Northern Hemisphere. Indeed, a recent coupled ocean-atmosphere climate model conducted under boundary conditions at 112 kyr supports this sequence of events, with introduction of low-salinity water from the Bering Sea to the AO perturbing the freshwater balance in the AO and the subpolar North Atlantic, muting the AMOC and leading to cooling in the Northern Hemisphere²⁰. Even if the inflow of the low-salinity Bering Sea water into the AO was not the ultimate driver of the Pliocene climate cooling, Bering Strait throughflow of freshwater transport into the AO might have worked as an effective amplifier to cool the northern high latitudes starting at 3.3 Myr ago.

In summary, our Nd isotopic data highlight the presence of Alaskan detrital material at the Bowers Ridge as far back as 4.2 Myr ago. Transport of this material by sea ice and meltwater plumes supports development of Alaskan mountain glaciers in the early Pliocene; timing that coincides with proposed North Pacific cooling in response to restriction of the CAS. Increasing fluxes of meltwater from progressively larger Alaskan mountain glaciers from 3.3 to 2.8–2.5 Myr ago are indicated by the Nd isotopic data, as well as % *Actinocyclus* spp. and % $C_{37:4}$ alkenones at Site U1341B. Introduction of low-salinity Bering Sea water into the AO starting by at least 3.3 Myr ago would have strengthened halocline development and sea-ice formation in the AO, leading to subarctic cooling/freshening from 3.2 to 3.3 Myr ago through ice-albedo feedbacks.

We argue that the multiple gateway events (restriction of the CAS and reversal of the Bering Strait throughflow) in the Pliocene established the glacier-fed, low-salinity Bering Sea water and its inflow into the AO, respectively. The effect of Bering Strait throughflow on freshwater transport into the AO during the early to late Pliocene should be tested quantitatively by numerical modelling to better understanding the outflow of low-salinity Arctic water to the North Atlantic and its impact on the stability of the AMOC in the Pliocene.

Methods

Sediment core samples. We analysed detrital Nd and Pb isotopes from sediment cores obtained at Site U1341B (54°02.00'N, 179°00.52'E, 2,140 m water depth) at Bowers Ridge in the southern Bering Sea, and at Site U1344 (59°03.02'N, 179°12.20'E, 3,173 m water depth) at the northern Bering slope during the IODP Expedition 323 (Fig. 1; ref. 27). Supplementary detrital Nd isotope data were also obtained from core Bow-8A (54°47'N, 176°55'E, 884 m water depth) near site U1341B during the R/V Hakuho-maru cruise KH99-3 (Fig. 1).

Sediments obtained from site U1341B are composed of a variable mixture of detrital, biogenic and authigenic components; there is a major contribution of biogenic opal and detrital clay/silt, and calcium carbonate content is generally low throughout the core $(<1.0 \text{ wt}\%)^{27,28}$. The initial age model for Site U1341B was originally based on several paleomagnetic and siliceous microfossil datums that have been determined from an on-board study^{27,28}. However, in this paper the age model has been updated using detailed onshore biostratigraphy²⁴, magnetostratigraphy and foraminifera δ^{18} O stratigraphy (Supplementary Fig. 1; Supplementary Table 2). The age-depth plot at Site U1341B was produced by assuming linear sedimentation rates between the age control points, and by extrapolating the sedimentation rate beyond the oldest diatom-based datum (3.87 Myr ago); this resulted in an estimated bottom sediment age of \sim 4.3 Myr ago (Supplementary Fig. 1; Supplementary Table 2). We sampled U1341B at constant depths (4.5 and 7.5 m) in each core (n = 115). Variations in the sedimentation rate produced apparent variations in the sample density (time intervals range from 5 to 116 kyr) of 115 Nd isotope data points plotted against age (Fig. 2c; Supplementary Fig. 1). Furthermore, we also generated Pb isotopic compositions of detrital sediments (n = 29) from U1341B (Supplementary Fig. 3). Other detailed sedimentological and geochemical data relating to core U1341 can be seen in associated literature^{24,48,58}

Core U1344 is characterized by higher proportions of siliciclastic components than core U1341B. The last deglaciation and the LGM sediments of core U1344 show the Nd and Pb isotopic compositions ($\varepsilon_{\rm Nd} = -5.8$ and -6.6; $^{206}\text{Pb}/^{204}\text{Pb} = 19.23$ and 19.27) that are close to those of source rocks in the Yukon-Tanana terrane in Alaska ($\varepsilon_{\rm Nd} = -9$ to -8; $^{206}\text{Pb}/^{204}\text{Pb} = 19.16$ to 19.67; Fig. 3a–c).

Detrital Nd and Pb isotopes. We leached bulk sediments (~ 1.0 g) for 24 h on an orbital shaker at room temperature in 0.02 M hydroxylamine hydrochloride-25%

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Optima acetic acid, buffered to pH 4 with Optima sodium hydroxide. This reductive cleaning step also completely removed carbonate (av. 0.9 wt%, ref. 28) from the bulk sediment. Following centrifugation and triple rinses in ultrapure water, the samples were dried in an oven at 60 °C. The oxide-free bulk sediments $(\sim 40 \text{ mg})$ were dissolved in a 7-ml Teflon vial by digestion in a concentrated Optima HF-HNO₃ mixture (1:3 v/v) for ~48 h on a hotplate (~120 °C). Bulk rare-earth elements were separated by a primary column using cation-exchange resin (Mitsubishi diaion CK08P, 75-150 µm) and 1.7 N HCl as an eluent. Nd was then isolated by passing the REE aliquot through Eichrom Ln-spec resin (50-100 µm) with 0.25 N HCl as an eluent. Nd aliquots were dried and then redissolved in 2% HNO3 for analysis on a Nu Plasma MC-ICP-MS with a DSN-100 nebulizer at the University of Florida⁵⁹. The total procedural blank for Nd is negligible (14 pg) compared with the amount of Nd in the samples. Pb aliquots were redissolved in 1 N seastar HBr and passed through Dowex 1-X8 (100-200 mesh) resin. Pb was collected in 20% Optima HNO3. The total procedural blank for Pb is 10-30 pg Pb and is negligible. Thallium (Tl)-spiked Pb concentrates dissolved in 2% HNO3 were adjusted for appropriate dilution to obtain a 2-5-V beam on ²⁰⁸Pb. Samples were aspirated through a DSN-100 nebulizer and Pb isotopes were measured by a Nu Plasma MC-ICP-MS. A Tl normalization technique was used for Pb isotope analyses. Long-term NBS 981 values analysed over several years at the University of Florida are ${}^{206}\text{Pb}/{}^{204}\text{Pb} = 16.937 \pm 0.004 (2\sigma)$, ${}^{207}\text{Pb}/{}^{204}\text{Pb} = 15.489 \pm 0.003 (2\sigma)$ and ${}^{208}\text{Pb}/{}^{204}\text{Pb} = 36.695 \pm 0.008 (2\sigma)$.

C_{37:4} **alkenone abundance.** Total lipids were extracted from 1–3.5 g of dried sediments with dichloromethane/methanol (95:5) using an accelerated solvent extractor (ASE 200, Dionex) at 100 °C and 1,000 p.s.i. for 10 min. The total extracts were separated into three fractions using silica gel column chromatography: aliphatic and aromatic hydrocarbons, aliphatic ketones (alkenones) and alcohol plus fatty acid fractions. The C₃₇ alkenones were analysed with an HP6890 gas chromatograph (GC) equipped with an on-column injector-fused silica capillary column (CPSIL-5 CB, 50 m length × 0.32 mm inner diameter, film thickness of 0.12 mm), and a flame ionization detector. The GC oven temperature was programmed to increase from 80 to 180 °C at 10 °C min ⁻¹, and then from 180 to 310 °C at 5 °C min ⁻¹. The relative abundance of the tetraunsaturated C₃₇ alkenones to total C₃₇ alkenones (% C_{37:4}) was defined as % C_{37:4} = [C_{37:4}]/ ([C_{37:2}] + [C_{37:3}] + [C_{37:4}]) × 100.

Isotope mass balance calculation. A simple isotope mass balance calculation is based on a two-end-member mixing model. If A and B are components containing different concentrations of element X, and if R^X is an isotope ratio of X, then the following equation can be obtained:

$$\mathbf{R}_{M}^{X} = \frac{R_{A}^{X}X_{A}f + R_{B}^{X}X_{B}(1-f)}{X_{A}f + X_{B}(1-f)}$$
(1)

where R_{M}^{X} is the isotope ratio of X in a mixture of components A and B, X_{A} and X_{B} are concentrations of X in A and B, respectively, and f is the weight fraction of A.

In our study, based on Nd and Pb isotope analyses, we consider Aleutian arc and Alaskan materials as end-members (see Fig. 3 and details in the text). The average values of Nd and Pb (206 Pb/ 204 Pb) isotopic compositions and their concentrations in the Aleutian and Alaskan materials were estimated from the GEOROC database³⁸ and relevant literature^{34,39} (Supplementary Table 3). However, there were no available data for Pb concentrations in the Alaskan detrital material. Therefore, we evaluated a number of binary mixing curves that had different Pb concentrations (5, 10, 15 and $20 \,\mu g g^{-1}$) in Alaskan detrital material (Supplementary Fig. 4). The Nd–Pb isotopic compositions of the U1341B detrital sediments were then plotted around a mixing line with a Pb concentration of $10 \,\mu g g^{-1}$ (Supplementary Fig. 4). Therefore, we set a value of $10 \,\mu g g^{-1}$ as the Pb concentration in Alaskan-sourced detrital material, and then calculated the contribution from Alaskan-sourced detrital materials to the sediments at 4.2 (13%), 3.96 (26%), 3.55 (32%) and 3.32 Myr ago (48%).

References

- Haywood, A. M. & Valdes, P. J. Modelling Pliocene warmth: contribution of atmosphere, oceans and cryosphere. *Earth Planet. Sci. Lett.* 218, 363–377 (2004).
- Fedorov, A. V. *et al.* Patterns and mechanisms of early Pliocene warmth. *Nature* 496, 43–49 (2013).
- Haug, G. H., Sigman, D. M., Tiedemann, R., Pedersen, T. F. & Sarnthein, M. Onset of permanent stratification in the subarctic Pacific Ocean. *Nature* 401, 779–782 (1999).
- Lisiecki, L. E. & Raymo, M. E. A Pliocene-Pleistocene stack of 57 globally distributed benthic δ¹⁸O records. *Paleoceanography* 20, PA1003 (2005).
- Nielsen, T. & Kuijpers, A. Only 5 southern Greenland shelf edge glaciations since the early Pliocene. Sci. Rep. 3, 1875 (2013).
- Haug, G. H., Tiedemann, R., Zahn, R. & Ravelo, A. C. Role of Panama uplift on oceanic freshwater balance. *Geology* 29, 207–210 (2001).
- Driscoll, N. W. & Haug, G. H. A short circuit in thermohaline circulation: a cause for Northern Hemisphere Glaciation? *Science* 282, 436–438 (1998).

- Keigwin, L. Isotopic paleoceanography of the Caribbean and East Pacific: role of Panama uplift in Late Neogene time. *Science* 217, 350–353 (1982).
- Haug, G. H. & Tiedemann, R. Effect of the formation of the Isthmus of Panama on Atlantic Ocean thermohaline circulation. *Nature* 393, 673–676 (1998).
- Steph, S. *et al.* Early Pliocene increase in thermohaline overturning: a precondition for the development of the modern equatorial Pacific cold tongue. *Paleoceanography* 25, PA2202 (2010).
- Maier-Reimer, E., Mikolajewicz, U. & Crowley, T. Ocean general circulation model sensitivity experiment with an open Central American Isthmus. *Paleoceanography* 5, 349–366 (1990).
- Lunt, D. J., Valdes, P. J., Haywood, A. & Rutt, I. C. Closure of the Panama Seaway during the Pliocene: implications for climate and Northern Hemisphere glaciation. *Clim. Dyn.* **30**, 1–18 (2008).
- Marincovich, L. Central American paleogeography controlled Pliocene Arctic Ocean molluscan migrations. *Geology* 28, 551–554 (2000).
- 14. Sarnthein, M. et al. Mid-Pliocene shifts in ocean overturning circulation and the onset of Quaternary-style climates. Clim. Past 5, 269–283 (2009).
- Marincovich, L. & Gladenkov, A. Y. Evidence for an early opening of the Bering Strait. *Nature* 397, 149–151 (1999).
- Serreze, M. C. et al. The large-scale freshwater cycle of the Arctic. J. Geophys. Res. 111, C11010 (2006).
- Woodgate, R. A. & Aagaard, K. Revising the Bering Strait freshwater flux into the Arctic Ocean. *Geophys. Res. Lett.* **32**, L24603, doi:10.1029/2004GL021747 (2005).
- Hu, A. et al. Response of thermohaline circulation to freshwater forcing under present-day and LGM conditions. J. Clim. 21, 2239–2258 (2008).
- Shaffer, G. & Bendtsen, J. Role of the Bering Strait in controlling North Atlantic ocean circulation and climate. *Nature* 367, 354–357 (1994).
- Hu, A. et al. Influence of Bering Strait flow and North Atlantic circulation on glacial sea-level changes. Nat. Geosci. 3, 118–121 (2010).
- Kipphut, G. W. Glacial meltwater input to the Alaska Coastal Current: evidence from oxygen isotope measurements. J. Geophys. Res. 95, 5177–5181 (1990).
- Rosell-Melé, A. Interhemispheric appraisal of the value of alkenone indices as temperature and salinity proxies in high-latitude locations. *Paleoceanography* 13, 694–703 (1998).
- Sicre, M.-A., Bard, E., Ezat, U. & Rostek, F. Alkenone distributions in the North Atlantic and Nordic sea surface waters. *Geochem. Geophys. Geosyst.* 3, doi:10.1029/2001GC000159 (2002).
- Onodera, J., Takahashi, K. & Nagatomo, R. Diatoms, silicoflagellates, and ebridians at Site U1341 on the western slope of Bowers Ridge, IODP Expedition 323. Deep Sea Res. Pt II (in the press) doi:10.1016/j.dsr2.2013.03.025.
- Sancetta, C. Distribution of diatom species in surface sediments of the Bering and Okhotsk seas. *Micropaleontology* 28, 221–257 (1982).
- Sancetta, C. & Silvestri, S. Pliocene-Pleistocene evolution of the North Pacific Ocean-Atmosphere system, interpreted from fossil diatoms. *Paleoceanography* 1, 163–180 (1986).
- Takahashi, K., Ravelo, A. C. & Zarikian, C. A. IODP expedition 323—Pliocene and Pleistocene paleoceanographic changes in the Bering Sea. *Sci. Drill.* 11, 4–13 (2011).
- Takahashi, K., Ravelo, A. C. & Zarikian, C. A. Proceedings of the Integrated Ocean Drilling Program (Integrated Ocean Drilling Program Management International, Inc., 2011).
- Martinez-Garcia, A., Rosell-Mele, A., McClymont, E. L., Gersonde, R. & Haug, G. H. Subpolar link to the emergence of the Modern Equatorial Pacific Cold Tongue. *Science* 328, 1550–1553 (2010).
- VanLaningham, S., Pisias, N. G., Duncan, R. A. & Clift, P. D. Glacialinterglacial sediment transport to the Meiji Drift, northwest Pacific Ocean: evidence for timing of Beringian outwashing. *Earth Planet. Sci. Lett.* 277, 64–72 (2009).
- Eberl, D. D. Quantitative mineralogy of the Yukon River system: changes with reach and season, and determining sediment provenance. *Am. Mineral.* 89, 1784–1794 (2004).
- Brabets, T. P. & Walvoord, M. A. Trends in streamflow in the Yukon River Basin from 1944 to 2005 and the influence of the Pacific Decadal Oscillation. *J. Hydrol.* 371, 108–119 (2009).
- 33. Dornblaser, M. M. & Striegl, R. G. Suspended sediment and carbonate transport in the Yukon River Basin, Alaska: fluxes and potential future responses to climate change. *Water Resour. Res.* 45, W06411 (2009).
- 34. Asahara, Y. *et al.* Provenance of terrigenous detritus of the surface sediments in the Bering and Chukchi Seas as derived from Sr and Nd isotopes: Implications for recent climate change in the Arctic regions. *Deep Sea Res. Pt II* 61–64, 155–171 (2012).
- 35. Nagashima, K. *et al.* Contribution of detrital materials from the Yukon River to the continental shelf sediments of the Bering Sea based on the electron spin resonance signal intensity and crystallinity of quartz. *Deep Sea Res. Pt II* 61–64, 145–154 (2012).

- Wang, J., Hu, H., Mizobata, K. & Saitoh, S. Seasonal variations of sea ice and ocean circulation in the Bering Sea: a model-data fusion study. *J. Geophys. Res.* 114, C02011 (2009).
- 37. Stabeno, P. J. & Reed, R. K. Circulation in the Bering Sea Basin observed by satellite-tracked drifters: 1986–1993. J. Phys. Oceanogr. 24, 848–854 (1994).
- 38. GEOROC database. at http://georoc.mpch-mainz.gwdg.de/georoc/.
- 39. Aleinikoff, J. N., Lang Farmer, G., Rye, R. O. & Nokleberg, W. J. Isotopic evidence for the sources of Cretaceous and Tertiary granitic rocks, east-central Alaska: implications for the tectonic evolution of the Yukon-Tanana Terrane. *Can. J. Earth Sci.* 37, 945–956 (2000).
- 40. Pettke, T., Halliday, A. N., Hall, C. M. & Rea, D. K. Dust production and deposition in Asia and the north Pacific Ocean over the past 12 Myr. *Earth Planet. Sci. Lett.* **178**, 397–413 (2000).
- Jones, C. E., Halliday, A. N., Rea, D. K. & Owen, R. M. Eolian inputs of lead to the North Pacific. *Geochim. Cosmochim. Acta* 64, 1405–1416 (2000).
- 42. Sun, J. & Zhu, X. Temporal variations in Pb isotopes and trace element concentrations within Chinese eolian deposits during the past 8 Ma: Implications for provenance change. *Earth Planet. Sci. Lett.* **290**, 438–447 (2010).
- 43. Uematsu, M. et al. Transport of mineral aerosol from Asia over the North Pacific Ocean. J. Geophys. Res. 88, 5343-5352 (1983).
- Sancetta, C., Heusser, L., Labeyrie, L., Naidu, A. S. & Robinson, S. W. Wisconsin—Holocene paleoenvironment of the Bering Sea: evidence from diatoms, pollen, oxygen isotopes and clay minerals. *Mar. Geol.* 62, 55–68 (1984).
- 45. Katsuki, K. & Takahashi, K. Diatoms as paleoenvironmental proxies for seasonal productivity, sea-ice and surface circulation in the Bering Sea during the late Quaternary. *Deep Sea Res. Pt II* 52, 2110–2130 (2005).
- Horikawa, K., Asahara, Y., Yamamoto, K. & Okazaki, Y. Intermediate water formation in the Bering Sea during glacial periods: evidence from neodymium isotope ratios. *Geology* 38, 435–438 (2010).
- Salzmann, U. et al. Climate and environment of a Pliocene warm world. Palaeogeogr. Palaeoclimatol. Palaeoecol. 309, 1–8 (2011).
- Aiello, I. W. & Ravelo, A. C. Evolution of marine sedimentation in the Bering Sea since the Pliocene. *Geosphere* 8, 1231–1253 (2012).
- Lagoe, M. B., Eyles, C. H., Eyles, N. & Hale, C. Timing of late Cenozoic tidewater glaciation in the far North Pacific. *Geol. Soc. Am. Bull.* 105, 1542–1560 (1993).
- Motoi, T., Chan, W.-L., Minobe, S. & Sumata, H. North Pacific halocline and cold climate induced by Panamanian Gateway closure in a coupled oceanatmosphere GCM. *Geophys. Res. Lett.* **32**, L10618 (2005).
- Wang, L. Sea surface temperature history of the low latitude western Pacific during the last 5.3 million years. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 108, 379–436 (1994).
- LaRiviere, J. P. et al. Late Miocene decoupling of oceanic warmth and atmospheric carbon dioxide forcing. Nature 486, 97–100 (2012).
- 53. Jiang, H., Mao, X., Xu, H., Thompson, J. & Ma, X. ~4 Ma coarsening of sediments from Baikal, Chinese Loess Plateau and South China Sea and implications for the onset of NH glaciation. *Palaeogeogr. Palaeoclimatol. Palaeoecol.* 298, 201–209 (2010).
- Rea, D. K. & Snoeckx, H. Sediment fluxes in the Gulf of Alaska: paleoceanographic record from Site 887 on the Patton-Murray seamount platform. *Proc. ODP Sci. Res.* 145, 247–255 (1995).
- Jansen, E., Fronval, T., Frack, F. & Channell, J. E. T. Pliocene-Pleistocene ice rafting history and cyclicity in the Nordic Seas during the last 3.5 Myr. *Paleoceanography* 15, 709–721 (2000).

- 56. Lacasse, C. & van den Bogaard, P. Enhanced airborne dispersal of silicic tephras during the onset of Northern Hemisphere glaciations, from 6 to 0 Ma records of explosive volcanism and climate change in the subpolar North Atlantic. *Geology* **30**, 623–626 (2002).
- Raymo, M. E., Grant, B., Horowitz, M. & Rau, G. H. Mid-Pliocene warmth: stronger greenhouse and stronger conveyor. *Mar. Micropaleontol.* 27, 313–326 (1996).
- März, C., Schnetger, B. & Brumsack, H. J. Nutrient leakage from the North Pacific to the Bering Sea (IODP Site U1341) following the onset of Northern Hemispheric Glaciation? *Paleoceanography* 28, 68–78 (2013).
- 59. Kamenov, G., Perfit, M., Mueller, P. & Jonasson, I. Controls on magmatism in an island arc environment: study of lavas and sub-arc xenoliths from the Tabar–Lihir–Tanga–Feni island chain, Papua New Guinea. *Contrib. Mineral. Petrol.* 155, 635–656 (2008).
- 60. Lawrence, K. T., Herbert, T. D., Brown, C. M., Raymo, M. E. & Haywood, A. M. High-amplitude variations in North Atlantic sea surface temperature during the early Pliocene warm period. *Paleoceanography* 24, PA2218, doi:10.1029/ 2008pa001669 (2009).

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Author contributions

K.H. and E.E.M. conceived the study. K.H. analysed the Nd isotope. C.B. analysed the Pb isotope. O.S. and M.I. analysed the alkenone. J.O. analysed the diatom. T.S. and S.S. measured foraminiferal $\delta^{18}O$ and developed the $\delta^{18}O$ stratigraphy for core U1341B. All the authors contributed to the interpretation of the data and preparation of the manuscript.

Additional information

Supplementary Information accompanies this paper at http://www.nature.com/ naturecommunications

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