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LETTERS

The early Miocene onset of a ventilated circulation regime in the Arctic Ocean

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Deep-water formation in the northern North Atlantic Ocean and the Arctic Ocean is a key driver of the global thermohaline circulation and hence also of global climate[1]. Deciphering the history of the circulation regime in the Arctic Ocean has long been prevented by the lack of data from cores of Cenozoic sediments from the Arctic's deep-sea floor. Similarly, the timing of the opening of a connection between the northern North Atlantic and the Arctic Ocean, permitting deep-water exchange, has been poorly constrained. This situation changed when the first drill cores were recovered from the central Arctic Ocean[2]. Here we use these cores to show that the transition from poorly oxygenated to fully oxygenated ('ventilated') conditions in the Arctic Ocean occurred during the later part of early Miocene times. We attribute this pronounced change in ventilation regime to the opening of the Fram Strait. A palaeo-geographic and palaeo-bathymetric reconstruction of the Arctic Ocean, together with a physical oceanographic analysis of the evolving strait and sill conditions in the Fram Strait, suggests that the Arctic Ocean went from an oxygen-poor 'lake stage', to a transitional 'estuarine sea' phase with variable ventilation, and finally to the fully ventilated 'ocean' phase 17.5 Myr ago. The timing of this palaeo-oceanographic change coincides with the onset of the middle Miocene climatic optimum[3], although it remains unclear if there is a causal relationship between these two events.

The Integrated Ocean Drilling Program (IODP) Expedition 302 (ACEX) in 2004 cored a 428-m-thick sediment sequence from the crest of the Lomonosov ridge in the central Arctic Ocean[2] (Fig. 1). The sediments recovered from two neighbouring drill sites permit the first geological 'ground truth' validation of the Cenozoic palaeoenvironmental history of the central Arctic Ocean[4], which previously was based solely on interpretation of geophysical data[4–6]. Evidence for the onset of a ventilated circulation system in the central Arctic Ocean is preserved by distinct, documentable changes in the chemical and physical properties and micropalaeontology of the recovered seafloor sediments. Neogene and Quaternary sediments from the Lomonosov ridge are found within a single lithostratigraphic unit, subdivided into six subunits[2].

This study focuses on the interval around subunit 1/5, a 5.76-m-thick section between 193 and 199 metres composite depth (m.c.d.) containing a sequence of alternating grey and black layers (Fig. 2). The uppermost grey layers of this subunit are marked by a sharp colour change, with dark brown sediments above[7]. The black layers of subunit 1/5 contain much higher total organic carbon (TOC) contents (4.7–14.1%) than the lighter intervening grey layers (0.1–3.0%)[8]. Below this unit, TOC values are consistently 1–5%, and above they are $<0.5\%$ (ref. 2). Samples from the greyish layers in subunit 1/5 have an oxic character, whereas samples from dark layers have a euxinic character[8]. These changes in sediment properties all indicate that the interval around subunit 1/5 represents a time of transition from a poorly ventilated and land-locked sea with reduced salinities to a generally well-ventilated saline ocean. This transition is further supported by the sudden appearance of benthic agglutinated foraminifers in the brown interval directly above subunit 1/5 (lower subunit 1/4, 187.4 m.c.d.)[1]. Finally, the general lack of palynomorphs in subunit 1/4 and low TOC contents is consistent with oxic depositional conditions[9]. Taken together, these changes document that subunit 1/5 preserved the transition from euxinic to oxic conditions in the central Arctic Ocean (Fig. 2).

The timing of this transition is established by taking advantage of the fact that subunit 1/5 is unique in that it contains a monotypic assemblage of an abundant peridinioid taxon of Burdigalian age[10]. In the absence of more precise age information, we have used the midpoint of the late early Miocene (Burdigalian), 18.2 Myr ago[11], for the base of subunit 1/5. Sedimentation rates estimates suggest that this 5.76-m-thick subunit represents about 0.75 ± 0.1 million years of deposition, and that its top has an age of about 17.5 Myr when 18.2 Myr is used as the age for the base of the unit (see Methods for age model and Supplementary Information for uncertainties).

In order to place our core results in a wider regional context, the sediment sequence that preserves this critical palaeo-oceanographic change was correlated with a seismic profile (AWI-91090), which was used to locate the IODP drill site (Fig. 1). The changes in physical properties of the sediments between subunits (1/6 to 1/4) are large enough that they can, through modelling, be related to seismic reflections (Fig. 2) (see Methods for seismic modelling). These reflectors can, in turn, be correlated with a seismostratigraphic subdivision (LR-3 to LR-6, where LR-6 is the uppermost unit) already established for the Lomonosov ridge sediment sequence[12]. The boundary between seismostratigraphic units LR-5 and LR-4 represents a set of reflectors that correlates both to the transition from ACEX unit 2 to subunit 1/6 (density controlled) and from subunit 1/6 to subunit 1/5 (velocity controlled) just preceding the early Miocene initiation of ventilated circulation in the Arctic Ocean (Fig. 2). The two subunits are separated by a hiatus. The set of reflectors defining the LR-5 and LR-4 boundary can be traced regionally on the Lomonosov ridge, and can also be linked to the seismic stratigraphy of the Amundsen and Makarov basins as well as the East Siberian continental margin slope[12,13]. Thus, the core obtained from the Lomonosov ridge reflects circulation changes that occurred over large parts of the Arctic Ocean.

To better understand the context of this crucial oceanographic transition, we have reconstructed the palaeo-geography and

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palaeo-bathymetry of the region during the early Miocene (see Methods and Supplementary Information). Major Cenozoic deltaic successions mapped in the Beaufort Mackenzie basin indicate continuous input of large volumes of fresh water into a land-locked Arctic Ocean basin[14]. Our palaeo-geographic and palaeo-bathymetric map for the late early Miocene suggests that the only significant outlet for Arctic Ocean fresh water was to the North Atlantic through the Fram Strait (Fig. 3). Straits are physiographic bottlenecks, strongly affecting the circulation by confining broad current flows[15,16]. The exchange through the present, >400 km wide, Fram Strait is sufficient to allow all layers in the Arctic Ocean to be ventilated through advection, down to the sill depth (2,550 m; ref. 17). Ventilation below that depth is at present driven by shelf-slope convection[18]. During Miocene times, when the Fram Strait opened and deepened through sea-floor spreading, the water exchange between the Arctic and North Atlantic must have developed through a series of changes that also influenced the upstream basin circulation and ventilation conditions within the Arctic Ocean.

The initial opening phase of the Fram Strait was restricted to a unidirectional hydraulically controlled freshwater outflow (Fig. 4a). During this 'Arctic lake' stage, ventilation of deep waters may have occurred via seasonal convection. We hypothesize that when the Fram Strait widened and deepened, a compensating inflow of saline North Atlantic water became possible, resulting in a bi-directional, two-layer flow through the strait (Fig. 4b). The Arctic then evolved from its lake-stage to an enclosed estuarine sea, much like the modern Black Sea. Anoxic conditions prevail in the Black Sea because of strong stable stratification and limited exchange through the 36–124 m deep and <4 km wide Bosporus Strait, where inflowing saline Mediterranean waters comprise the main source of ventilated waters to the deep Black Sea[19]. The volume of the Arctic Ocean and its present net freshwater discharge both are about 20 times greater compared to the Black Sea. The present in- and outflow water through the Fram Strait is about 10 Sv, with a net outflow of 2 Sv. This is 1,000 times larger than the exchanges through the Bosporus, and the low-salinity surface outflow is about 1 Sv, 50 to 100 times that of the Bosporus.

A possible explanation for the alternations between euxinic conditions (dark layers) and intervening more oxic conditions (grey layers), in the transitional subunit 1/5, is oscillations in sea level. Changes in sea level will create an 'on–off switch' for Arctic Ocean circulation: during low sea level, there would be 'lake stages' having seasonal convection and uni-directional one-layer outflow; during times of high sea level, there would be estuarine, 'Black

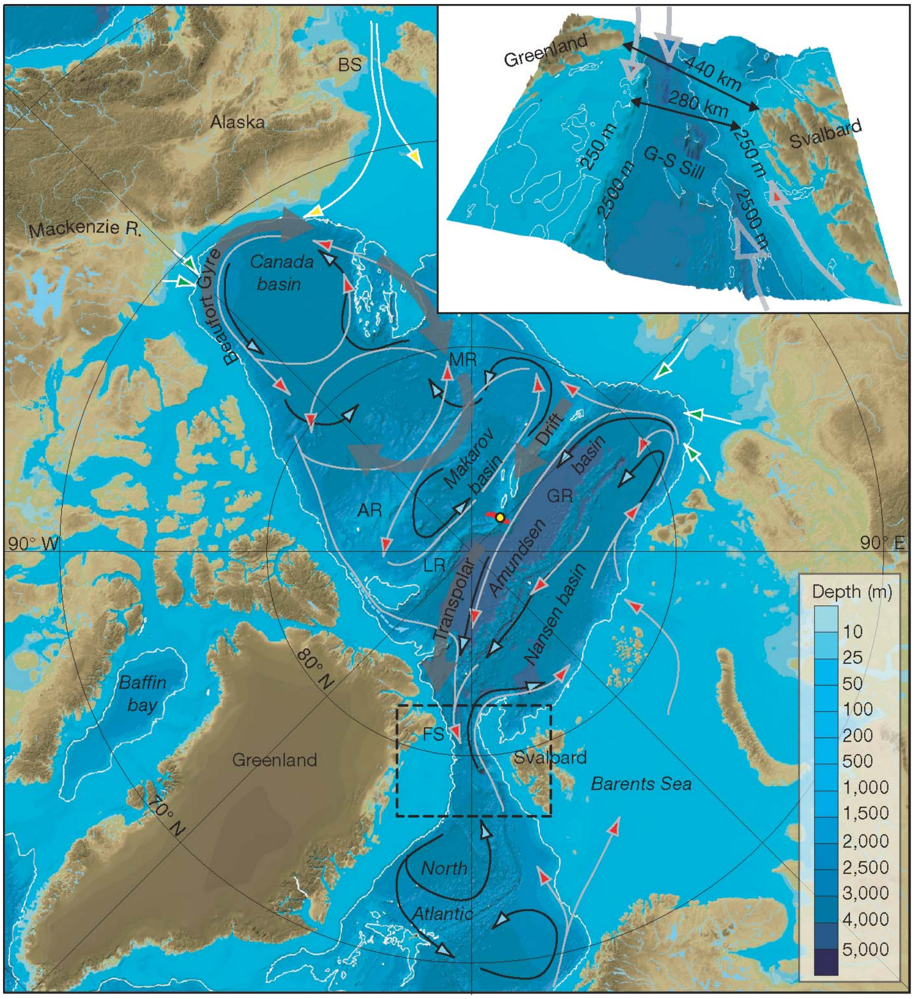

Figure 1 | Schematic map of the present ocean circulation in the Arctic Ocean. Shown are the present circulation of intermediate waters of Atlantic origin (grey arrows, red arrowheads), and deep waters (black arrows, light blue arrowheads), updated from ref. 18, and major freshwater inputs by rivers (white arrows, green arrowheads); also shown is the Pacific water influx through the Bering Strait (white arrows, yellow arrowheads). ACEX coring site, yellow circle; seismic reflection profile AWI-91090[12], red line. Bathymetry is from the International Bathymetric Chart of the Arctic Ocean (IBCAO)[29]. The white contour line represents the 1,000 m isobath. Physiographic features: AR, Alpha ridge; BS, Bering Strait; FS, Fram Strait; GR, Gakkel ridge; LR, Lomonosov ridge; MR, Mendeleev ridge. Inset, present seafloor morphology of the Fram Strait (dashed box in main figure) based on IBCAO updated with multibeam bathymetry[17]. Shortest distances between Svalbard's and Greenland's 250 m isobaths, and coastlines, are shown. G-S, Greenland-Spitsbergen sill. Arrows indicate generalized water mass exchange between the Arctic Ocean and the North Atlantic.

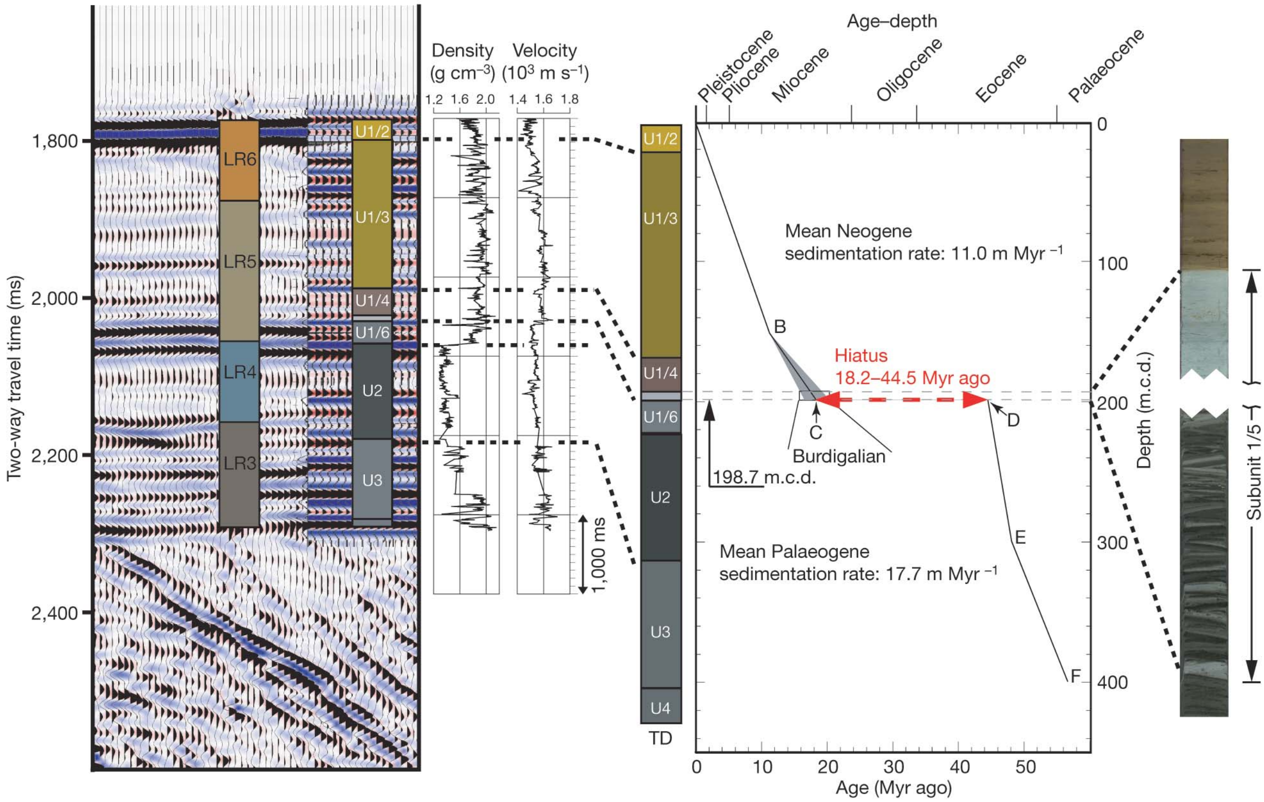

Figure 2 | Correlation between a synthetic seismogram representing the stratigraphy of the ACEX sites and seismic reflection profile AWI-91090, and the ACEX age model. The shown section of seismic reflection profile AWI-91090 crosses Site M0004[2]. Stratigraphic units U1–U4 are as inferred by ref. 2, and seismic units LR6–LR3 are as inferred in ref. 12. See Methods for age model and Supplementary Information for age uncertainties. Measured density and velocity records are shown next to the synthetic seismogram, which is re-sampled in two-way travel time. Age control points (Myr ago): B, 12.3; C, 18.2; D, 44.4; E, 48.6; and F, 55 (see Supplementary Information). TD, terminal depth.

Sea like' conditions, with two-layer, bi-directional flow. Sea-level varied between about 15 and 30 m during late early Miocene times[20].

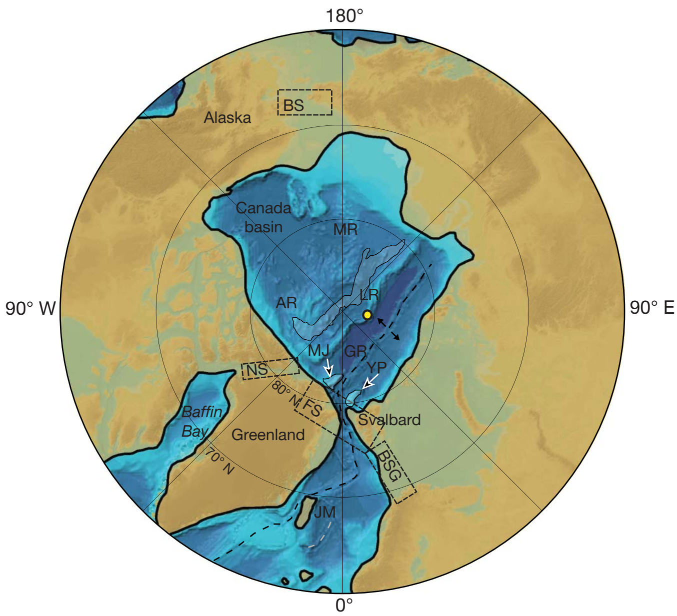

Figure 3 | Palaeo-geographic/palaeo-bathymetric reconstruction for the late early Miocene. Symbols and abbreviations as Fig. 1, with the addition of: BSG, Barents Sea gateway; JM, Jan Mayen microcontinent; KR, Knipovich ridge; MJ, Morris Jessup rise; NS, Nares Strait; YP, Yermak plateau. See Methods for compilation approach.

As the strait deepened further, the sea-level changes were no longer sufficient for a reversal to 'Arctic lake' conditions. Estuarine conditions would then prevail, with hydraulic control of the outflow of low-salinity water in the upper layer, and deep inflow of saline Atlantic water. The final transition occurred when the strait became wider than the internal Rossby radius of the upper layer. In the final regime, the outflow in the upper layer was rotationally controlled, rather than hydraulically controlled[21].

We have considered the scaling of the estuarine circulation using a simple analytic two-layer model (Supplementary Information). In this model, the circulation is forced by the wind-driven vertical mixing and by the freshwater influx from rivers to the Arctic basin. We find that the strait width at which the transition from hydraulic control to rotational control occurs is independent of the mixing, which is the most uncertain parameter, and that for the present freshwater forcing of about 0.2 Sv the transition width is 13 km. (Note, however, that the transition between the two regimes is gradual, rather than sharp.)

In the rotationally controlled regime, the outflow of low-salinity surface water is concentrated at the western (Greenland) continental slope of the strait, as is the case today (Fig. 4c). This opens the eastern part of the strait for flow driven by mechanisms other than turbulent entrainment in the Arctic Ocean interior—that is, barotropic currents, attached to the bathymetry and driven by the large-scale wind field, can enter the Arctic Ocean. The total present inflow via the Fram Strait is 5 to10 times greater than the outflow of low-salinity surface water[22]. Much of this exchange represents recirculation within the strait, although 4–5 Sv, at least, enters the Arctic Ocean and will contribute to ventilating its deep waters[22,23].

At what point in this development did the deep circulation become strong enough to prevent anoxic conditions in the Arctic

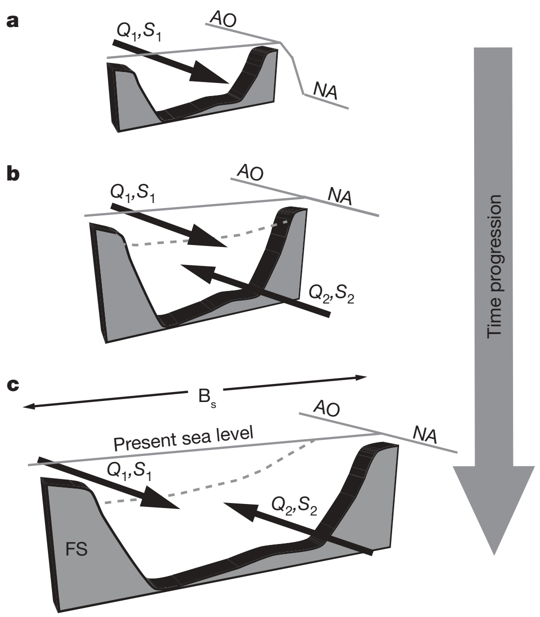

Figure 4 | A schematic illustration of the Fram Strait opening and hypothetical water exchange development between the Arctic Ocean and North Atlantic. AO, Arctic Ocean; NA, North Atlantic. **a**, A narrow strait resulting in a uni-directional hydraulically controlled outflow from the Arctic. S_1 is the salinity of the out-flowing flux of water Q_1. **b**, A wider and deeper strait allowing the establishment of a bi-directional, two-layer flow through the strait due to a compensating inflow (Q_2) of saline (S_2) North Atlantic water. This phase in the Arctic's palaeo-oceanographic development is analogous to the present Black Sea. **c**, The Fram Strait becomes wide enough that the influence of the Earth's rotation changes the water flow through the strait to a rotationally controlled bi-directional two-layer flow. This opens the possibility of a barotropic current flow through the strait. Our scaling analysis (Supplementary Information) suggests that this turning point is independent of the mixing and can, assuming the present freshwater input of 0.2 Sv, occur at a strait width of 13 km. At present the strait width (B_s) is >400 km for the Fram Strait.

basin? Our scaling analysis indicates that with today's wind speed and freshwater forcing, this may have occurred before the transition to the rotationally controlled regime. However, this result is very sensitive to the wind speed, which is unknown during the early Miocene. Moreover, the analysis neglects processes (for example, shelf convection) that would tend to strengthen the deep stratification, and thereby inhibit the ventilation of the deep waters. It is therefore likely that oxygenated conditions were not established until a rotationally controlled regime had been established, when the strait was wide enough for barotropic currents to meet there. For this, a strait width of 40–50 km should be sufficient (Supplementary Information).

According to the age model used, the change in ventilation history for the Arctic Ocean began during the late early Miocene about 18.2 Myr ago and was completed about 0.7 Myr later, about 17.5 Myr ago. The Arctic Ocean seafloor spreading had propagated at least as far south as 81° N at 16.2 Myr ago (chron C5Cn.1), according to new seismic reflection and aeromagnetic data[24]. According to the age–width estimation using these geophysical data (Supplementary Fig. S5), the Fram Strait began to open at great depths (present-day water depth >2,000 m) by 13.7 Myr ago, that is, 3.8 Myr after the Arctic Ocean had gone through its transitional phase into a ventilated circulation, as marked by the end of subunit 1/5. However, an initial corridor of immature seafloor spreading may have developed between Greenland and Svalbard before the full spreading extended through this gateway[25], and it is difficult to quantify the volumetric exchange of water with the North Atlantic on the basis of this estimate.

METHODS SUMMARY

The ACEX age model is based on ^{10}Be stratigraphy in the upper 151 m.c.d. (ref. 7) and biostratigraphy from 151 m.c.d. to 400 m.c.d. (ref. 2). A single geomagnetic reversal boundary is used (top chron C25n). The timescale used is compiled as follows: Neogene[11]; top chron C6n.3n to base chron C19n[26]; top chron 20n and older[27]. Our palaeo-geographic and palaeo-bathymetric reconstruction is based on plate tectonic maps generated from the Ocean Drilling Stratigraphic Network (ODSN) tools available online at http://www.odsn.de. Lithosphere plates were moved to 18 Myr ago (mid-point of the Burdigalian) relative to the hotspot reference frame of ref. 28. To derive the palaeo-bathymetry, the International Bathymetric Chart of the Arctic Ocean (IBCAO)[29] Digital Terrain Model (DTM) was rectified to fit the plate tectonic reconstruction using the coast line as reference. Published information was used to infer details about eustatic sea level, location of palaeo-shorelines, uplift or subsidence of regions, and opening of gateways (Supplementary Fig S2). Sea level data were adopted from ref. 20. Synthetic seismic modelling assuming planar waves, with no multiples or signal attenuation, has been performed using software by Divesto. To simulate the seismic reflection profile AWI-91090 crossing the ACEX sites, a Ricker wavelet with a peak frequency of 40 Hz and a period of 19.5 ms was used as source function for convolution with the ACEX core impulse response (reflectivity function), which was calculated using the bulk density and P-wave velocity records. The reflectivity function was sampled at 0.25 ms before convolution with the Ricker wavelet and the generation of synthetic traces. Logged P-wave velocities were not corrected to simulate *in situ* conditions with respect to water depth (pressure) and temperature. Nor were any corrections for porosity rebound applied owing to the dominantly terrigenous composition of the sediment. Details can be found in Supplementary Information.

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Supplementary Information is linked to the online version of the paper at www.nature.com/nature.

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Author Contributions M.J. and J.B. initiated the paper. M.J. compiled the palaeo-bathymetric reconstruction, performed the core-seismic integration and took part in the development of the oceanographic analysis, which was led by B.R. and J.N. The age model was developed by J.B., M.F provided ^{10}Be data, H.B and F.S. provided micropalaeontological information, and J.K provided palaeointensity data. W.J. compiled the age-width estimation for the Fram Strait from geophysical data. All authors discussed the results and provided input to the manuscript during its development.

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