Establishment of modern circulation pattern at *c.* 6000 cal a BP in Disko Bugt, central West Greenland: Opening of the Vaigat Strait

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Abstract

Variations in the Holocene circulation of the West Greenland Current (WGC) in the Disko Bugt region have been reconstructed from a suite of sediment cores. Palaeoceanographic proxies include magnetic susceptibility (MS) and X-ray fluorescence Titanium counts, which document a major shift in circulation at *c.* 6000 cal a BP. Before this date, sediments in southern Disko Bugt were characterised by high terrigeneous and basaltic input, suggesting widespread influence of meltwater plumes. Our data show that the WGC re-circulated in the southern Disko Bugt area because a potential northern pathway, the narrow Vaigat Strait, was blocked by icebergs that calved from marine outlet glaciers in eastern Disko Bugt. Sediments in southern Disko Bugt deposited after *c.* 6000 cal a. BP have significantly lower terrestrial and basaltic sediment input, which coincides with minimum Holocene ice sheet extent. The reduced meltwater and iceberg discharge to the embayment caused the Vaigat Strait to become free of blocking icebergs and terrigeneous input was partly diverted to the outer shelf. Thus, the modern circulation pattern of the WGC was established in the Disko Bugt region through the opening of the Vaigat Strait *c.* 6000 cal a BP.

Introduction

On its pathway into northern Baffin Bay the relatively warm and saline West Greenland Current (WGC) determines the modern oceanographic and climatic conditions along the West Greenland shelf and its coastal areas (e.g. Ribergaard *et al*., 2006). As it passes over the West Greenland shelf a branch of this water mass penetrates into Disko Bugt (Figure 1). In Disko Bugt, Jakobshavn Isbræ one of Greenland's largest outlet glaciers (draining today about 7 % of the Greenland Ice Sheet (GIS)), produces through calving more than 10 % of icebergs from the ice sheet (Bindschadler, 1984; Rignot and Kanagaratnam, 2006; Weidick and Bennike, 2007). Today, the majority of these icebergs are carried by the WGC northwards in Disko Bugt, through the Vaigat Strait into the Baffin Bay.

Temperature and salinity variability of the WGC exerts an important control (ocean forcing) on ice sheet dynamics; such as calving rates, meltwater-/iceberg production and glacier flow (e.g. Holland *et al.,* 2008; Rignot *et al.,* 2010) and modulates the palaeoceanographic development of the region on a Holocene time scale (e.g. Moros *et al.*, 2006; Seidenkrantz *et al.*, 2008; Krawczyk *et al.*, 2010; Lloyd *et al.*, 2007; 2011; Andresen *et al.*, 2011; Perner *et al.*, 2011, 2013). During the last glacial (MIS 2) central West Greenland, and Disko Bugt itself, was occupied by a large marine terminating ice stream, presumably an enlarged Jakobshavn Isbræ, which extended approximately 30 to 50 km westwards across the continental shelf of Disko Bugt (Kelly, 1985; Funder, 1989; Ingólfsson *et al.*, 1990; Bennike *et al.*, 1994). This ice stream became unstable sometime before 10500 cal a BP, and started to retreat into the eastern part of the embayment (Long *et al.*, 2006; O'Cofaigh *et al.*, 2012). Between 10000 and 9000 cal a BP re-appearance of the WGC in the Disko Bugt area is reported (Funder and Weidick, 1991; Lloyd *et al.*, 2005; Long *et al.*, 2006; Weidick and Bennike, 2007; Funder *et al.*, 2011). Initial WGC warming at this time has also been reported from the far north of Baffin Bay (Knudsen *et al.*, 2008; Jennings *et al.*, 2011). Recent benthic foraminifera based studies from the Disko Bugt area (Lloyd *et al.,* 2011; Perner *et al.,* 2011, 2013) highlight the prominent influence of ocean temperature variability on ice margin stability/position on a range of time scales during the Holocene. However, yet it is unclear when in the Holocene the large-scale modern circulation pattern in Disko Bugt was established and which role regional ocean-ice sheet interactions played during this process. A better understanding of the interaction between the ocean and cryosphere is fundamental to predict future ice sheet behaviour and the sea level change involved.

In this study we present a reconstruction of large scale regional changes in ocean circulation in the Disko Bugt region, which uses magnetic susceptibility (MS) and X-ray fluorescence Titanium (Ti) data. Based on distinct variability in the bedrock geology in the area (Figure 2) the provenance of sediments is investigated from a suite of sediment cores along a transect, following the modern flow path of the WGC through the Disko Bugt area during the Holocene.

Study area

Disko Bugt is a large marine embayment of about 40,000 km^2 located within the relatively wide and shallow shelf area in central west Greenland (Figure 1). The embayment is characterised by a rugged terrestrial and submarine topography, with two troughs across the central bay that join to form the deepwater trough, Egedesminde Dyb, at the south-western entrance of the bay. This deep water trough, up to 900 m water depth (Brett and Zarudzki, 1979), is thought to be of glacial origin (Long and Roberts, 2003; Roberts and Long, 2005) and extends south-westward across the inner shelf adjacent to Disko Bugt. Outside the deep trough water depths typically vary between 200 and 400 m (Kuijpers *et al.*, 2001; Long and Roberts, 2002). Disko Island lies to the north of Disko Bugt itself and is separated from the Nuussuaq Peninsula and the mainland by the Vaigat Strait. This narrow strait, not more than *c.* 25 km wide, is relatively shallow (average 300 m deep), is separated from central Disko Bugt by a wide and shallow threshold (245 m deep; Andersen, 1981) and connects the north-eastern part of Disko Bugt with the open shelf northwest of Disko, where the Uummannaq Trough is found (Figure 1).

Geological setting

The bedrock geology of eastern and south-eastern Disko Bugt is characterized by Precambrian crystalline rocks (Figure 2). Common rocks are metasedimentary and metavolcanic rocks, orthogneisses and granites (Escher *et al.*, 1976, Larsen and Pulvertraft, 2000). To the east of a divide running approximately north-south, close to the present day coast line of inner Disko Bugt the geology consists largely of Late Archaean orthogneisses (Grade and Steenfeldt, 1999). Disko Island and the north-western part of the Nuussuaq Peninsula are largely composed of Tertiary flood basalts with more restricted areas of Upper Cretaceous-Tertiary clastic sediments, particularly along the eastern coastline of Disko Island (Henricksen *et al.*, 2000). Tholeiitic picrites and olivine-rich basalts also underlie the outer continental shelf of Disko Bugt (Figure 2). The seafloor of inner Disko Bugt and the Vaigat Strait are mainly composed of Cretaceous-Palaeocene sediments (Figure 2). Precambrian basement forms the seafloor in south-eastern Disko Bugt (Bonow, 2005).

Modern oceanographic setting

The present day oceanographic conditions along the coast of West Greenland are dominated by the WGC. The WGC is a combined water mass of: i) relatively warm and saline Atlantic-sourced water from the Irminger Current (IC), a branch of the North Atlantic Current (NAC); ii) Arctic-sourced cold, low-salinity water from the East Greenland Current (EGC; Buch, 1981; Tang *et al.*, 2004); and iii) local meltwater discharge along the SW Greenland coast (Figure 1). A branch of the WGC enters Disko Bugt from the southwest and flows northwards exiting primarily through the Vaigat Strait into Baffin Bay (Andersen, 1981; Bâcle *et al.*, 2002; Ribergaard *et al.*, 2006). Along this flow path icebergs and meltwater from a variety of outlet glaciers such as Jakobshavn Isbræ, Semerq Avangnardleq, Sermeq Kujatdleq and Kangersuneq, which have calving fronts at the eastern margin of Disko Bugt into the embayment, are carried into Baffin Bay (Figure 1). Fjords of these outlet glacier are separated by shallow thresholds (Jakobshavn Isbræ: 150 m deep (Hogan et al. 2011); Semerq Avangnardleq: 200 m deep (Rignot et al., 2010)) from Disko Bugt. As keel depths of calved icebergs can reach more than 200 m, they can get stuck at the fjords threshold.

Material and Methods

During the cruise of the German research vessel *Maria S. Merian* in Greenland waters (Harff *et al.*, 2007), sediment sequences were recovered using multi (MUC) and gravity (GC) cores from the shelf southwest of Disko Bugt (sites 343340 and 343300), the Egedesminde Dyb (site 343330), the Vaigat Strait (site 343390) and the Uummannaq Trough (site 343520). Location and core information is given in Figure 1 and Table 1.

Age-depth relationships for all sediment sequences are provided by accelerator mass spectrometry AMS ^{14}C dates based on benthic foraminifera and molluscs (Table 2), calibrated with the Marine09 (Reimer *et al.*, 2009) calibration curve in Calib6.02 (Stuiver and Reimer, 1993). Following previous results from Lloyd *et al.* (2011), we applied a reservoir age correction ΔR of 140±35 years, which represents the modern ΔR value for the Disko Bugt area, West Greenland.

X-ray fluorescence scanning (XRF) provides semi-quantitative geochemical sediment composition, and was performed on the Avaatech XRF core scanner from the Royal Netherlands Institute for Sea Research (NIOZ). XRF measurements were carried out directly on the split sediment core surface of the gravity cores during the cruise. The sediment surface was carefully flattened and smoothed, and covered with a thin (4 µm) Ultralene film. All measurements were carried out at 10 kV at a 1 cm step size. The analysed elements comprise Al, Si, S, Cl, K, Ca, Ti, Mn, and Fe (Richter *et al.*, 2006).

Magnetic susceptibility (MS) measurements were carried out onboard on all split sediment core sections, covered with a plastic film, using a Bartington MS2E1 sensor coupled to a TAMISCAN-TS1 automatic logging conveyor (Sandgren and Snowball, 2002). Down core resolution was set at 0.5 cm intervals for MUCs and GCs. Additional SIRM/X (saturation isothermal remanent magnetization) measurements from all core sites (I. Snowball, unpublished data) indicate that there have been no major grain sizes changes that can affect the MS measurements.

Results and interpretation

In this section sediment provenance changes, inferred from Ti and MS data, are presented for all gravity and multi cores that were taken on a transect following the present day flow path of the WGC through the Disko Bugt area (Figure 1 and 2); i) the shelf southwest of Disko Bugt (Figure 3); ii) the inner Egedesminde Dyb (Figure 4); iii) the Vaigat Strait and Uummannaq Trough (Figure 5). Sediment deposition at sites in the southern Disko Bugt region is influenced by the WGC and presently not subjected to direct meltwater discharge from outlet glaciers in eastern Disko Bugt (e.g. Andersen, 1981; Buch, 1981; Buch *et al.*, 2004). Icebergs and meltwater discharged by outlet glaciers such as Jakobshavn Isbræ in the eastern Disko Bugt region are routed along the flow path of the WGC and exit the embayment via the

Vaigat Strait. The geological setting of the Disko Bugt area, see Figure 2, allows to use the MS and Ti data as proxies for terrestrial sediment input, but also to identify provenance of the terrigeneous material. Tertiary basalts on Disko Island and the Nuussuaq Peninsula (Figure 2) are a source of easily magnetized minerals such as magnetite and ilmenite to the sediments, producing a relatively high MS signal, whereas Ti provides an index of terrigeneous sediment input originating from Precambrian basement rocks (orthogneisses and granites) in eastern Disko Bugt.

Modern distribution pattern of magnetic susceptibility data (MS) from the Disko Bugt area

The surface sections of the series of multi cores shows the modern regional variation in the sediment MS signals and hence in the content of magnetic minerals (Figure 2). On the south-western Disko Bugt shelf (343340-M, 343300-M) and in Egedesminde Dyb (343310-M, 343320-M, and 343330-M) a relatively low MS signal is found, ranging between 40 and *c.* 80 (10^{-6} SI). In contrast to this, multi cores from the Vaigat Strait (343380-M, 343390-M) and from the Uummannaq Trough (343520-M) exhibit significantly higher MS signals, with the highest signal in the Vaigat Strait, averaging 400 (10^{-6} SI) and a slightly lower of 200 (10^{-6} SI) in the Uummannaq Trough (Figure 2). This contrasting spatial distribution in the modern sediment magnetic properties suggests that sites north of Disko Island (343380-M, 343390-M, and 343520-M) receive proportionally more eroded material from the basaltic terrains of Disko Island and the Nuussuaq Peninsula compared to sites in the south. The distinct lower MS signals found at sites south of Disko Island suggests a generally reduced influence of terrestrial sediment input from basaltic terrain. Thus, a distinct southeast to northwest gradient in the magnetic mineral content of sediments, linked to the provenance of terrestrial sediments, is apparent along the modern flow path of the WGC in the Disko Bugt region (Figure 2).

Sediment provenance changes during the Holocene in the Disko Bugt area

Shelf southwest of Disko Bugt. Core 343340-GC is located mid-way across the shelf southwest of Disko Bugt (Figure 1) and AMS ^{14}C dates show that sediments cover approximately the last 12000 years (Table 2). Sediments deposited between *c.* 12000 to 8000 cal a BP are composed of light to medium olive grey to brown silty clay with darker brown mottling, occasional dropstones, shell fragments and polycheate tubes. This sediment facies exhibits relatively high MS values, for most of the section varying from 125 to 250 (10^{-6} SI), indicating abundant occurrence of magnetic minerals in the sediments (Figure 3). Characterised by high Ti counts ranging between 10000 to 8000 cps this site received large quantities of terrestrial sourced material during this time interval. The age-depth profile indicates a rapid sedimentation from *c.* 12000 to 8000 cal a. BP at a rate of *c.* 220 cm ka^{-1}. Initial decrease of the MS signal (average 40 (10^{-6} SI)), starting from *c.* 9000 cal. a BP, is accompanied by a notable decrease in the Ti counts (average 5000 cps) towards the top of the core from *c.* 8000 cal a BP (Figure 3). This indicates an initial reduction of high magnetic minerals, followed by an overall reduction in the contribution of terrigeneous clastic material to the site. Thus, a distinct shift in the sediment provenance occurred, which is accompanied by a decrease of the sedimentation rate to *c.* 25 cm ka^{-1}.

Core 343300-GC was collected from the inner south-western Disko Bugt shelf (Figure 1), which covers the last *c.* 10000 cal a BP (Table 2). From *c.* 10000 to 9000 cal a BP sediments are composed of light olive grey to olive grey clay, and include shell fragments and dropstones. In this sediment unit, similarly high MS (100 to 220 (10^{-6} SI)) and Ti (average 8000 cps) values are found as seen at the site on the outer shelf southwest of Disko Bugt (Figure 3). The age-depth profile shows rapid sedimentation at an average rate of *c.* 260 cm ka^{-1} between *c.* 10000 to 6000 cal a BP. The overlying sediments are composed of olive grey and moderate olive brown rich clay with occasional occurrence of shell fragments. From *c.* 9000 to 6000 cal a BP a prominent decline of the MS signal to a level of *c.* 40 (10^{-6} SI) is found, implying a decreased input of sediment rich in higher magnetic minerals. During this interval Ti values gradually decline to about 6000 cps, interrupted by a negative excursion at *c.* 8000 cal a BP to a level of 4000 cps. The overall Ti trend indicates a gradual reduction in the supply of terrigeneous clastic sediments to the site. The MS signal remains constantly low from *c.* 6000 cal a BP onwards, averaging *c.* 20 (10^{-6} SI), accompanied by low Ti values (average 5000 cps). While the MS and Ti values as well as the sedimentation rate (*c.* 60 cm ka^{-1}) are decreasing, the TOC content increases, reaching peak values from *c.* 3000 cal a BP onwards (Figure 3). This can be interpreted as representing a change in sediment provenance changed from terrestrial to marine sources, with evidence of hydrographic conditions in the late Holocene that favour marine productivity (Figure 3).

Outer Disko Bugt (Egedesminde Dyb). The core 343330-GC was collected from Egedesminde Dyb, in the outer Disko Bugt (Figure 1). AMS ^{14}C dates from this core indicate that sediments below *c.* 4.30 m core depth were deposited between 8000 to 9000 cal a BP, and record a relatively high sedimentation rate (> 200 cm ka^{-1}) at the site (see Table 2). From the base of the core up to 4.30 m the sediments are composed of light to medium olive grey clay. Pebbles and dropstones are common and occasionally shell fragments occur. This core section is characterised by relatively high MS values (average *c.* 70 (10^{-6} SI)) and Ti counts (7500 cps), accompanied by a low TOC (< 1.5 %) content (Figure 4). The MS signal at this site is notably weaker than seen at sites 343340-GC and 343300-GC on the shelf southwest of Disko Bugt, while Ti values are at a comparable level. This implies that in Egedesminde Dyb sedimentation is also subjected to terrestrial sediment input, though containing less magnetic minerals. Overlying this unit between 4.30 to 4.20 m core depth a distinct layer of moderate olive brown clay with an intercalated band of light olive grey clay and well sorted medium sand is found. An AMS ^{14}C date, obtained just above this layer, is dated to *c.* 6000 cal a BP. This layer is characterised by a marked decrease in the MS signal (drop to 5 (10^{-6} SI)), Ti counts (drop to 3000 cps) and TOC content (drop below 0.5%). In the following from *c.* 6000 cal a BP onwards the TOC content increases to an average of *c.* 2 % and Ti counts gradually decline to an average of *c.* 6000 cps, while the MS signal remains at a low level (Figure 4). This distinct shift in the sediment properties indicates a change in the sediment provenance, from terrestrial supply to a mainly marine source.

The Vaigat Strait. Core 343390-GC was obtained from the central Vaigat Strait north of Disko Island (Figure 1). Three available AMS ^{14}C dates indicate that this core covers approximately the last 2000 cal a BP (Table 2). Sediments from this site are composed of light olive grey clay with occasional occurrence of dropestones. Throughout the core, little variation is seen in MS values (average 380 (10^{-6} SI)) and these indicate a high magnetic mineral concentration (Figure 5). The MS signal from this core is about two times higher compared to that of sediments recovered from the shelf southwest of Disko Bugt and in Egedesminde Dyb (Figures 3 and 4). In addition, Ti counts varying between 12000 and 9000 cps are also significantly higher than found at sites south of Disko Island (Figure 5). A stable MS signal and consistently high Ti counts imply no changes in sediment properties or provenances at the site through the last *c.* 2000 cal a BP. This is interpreted as reflecting a consistent input of terrigeneous material rich in basaltic material from Disko Island and the Nuussuaq Peninsula.

Uummannaq Trough. Core 343520-GC was recovered to the northwest of Disko Island from the Uummannaq Trough system (Figure 1). According to AMS ^{14}C dates shown in Table 2, sediments from this site cover approximately the last 10000 cal a BP. Sediments are composed of olive grey clay with minor silt and occasional shell fragments. The MS signal ranges from 160 to 250 (10^{-6} SI) between 10000 to 8000 cal a BP and decreases to an average level of *c.* 180 (10^{-6} SI) from 8000 to 6000 cal a BP (Figure 5). During the period from 10000 to *c.* 6000 cal a BP the Ti counts average *c.* 10000 cps, being significantly higher than found on the shelf southwest of Disko Bugt during this time period. The sedimentation rate averages *c.* 100 cm ka^{-1} during this interval. In the period from *c.* 6000 to *c.* 4000 cal a BP an increase in the MS (up to 280 (10^{-6} SI)) and Ti (10700 cps) values is found, indicating that more terrestrial sourced sediments, containing more magnetic minerals, were deposited at the core site. This is accompanied by a decrease in the sedimentation rate to *c.* 66 cm ka^{-1}. From *c.* 4000 cal a BP towards the top of the core, the gradual decrease of the Ti counts suggests reduction in the terrigeneous sediment supply to the core site. Also a decreasing MS signal indicates reduced contribution of magnetic minerals until *c.* 1000 cal a BP. During this interval the sedimentation rate increases slightly to *c.* 78 cm ka^{-1}. It should be noted, however, that sediment provenance and accumulation at this site is controlled by sediment supply from both Vaigat Strait sources and from the Uummannaq fjord system to the north.

Discussion

Distinct regional variations have been observed in the MS signal of modern sediments along the core transect, which are linked to the source of sediments deposited at respective sites, with high MS values relating to proportionally greater input of basaltic material (Figure 1 and 2). Modern sediments on the shelf southwest of Disko Bugt and in Egedesminde Dyb exhibit distinctively lower MS signals than those found in the Vaigat Strait and in the Uummannaq Trough. These distinct contrasts follow the modern WGC flow path and reflect differences in sediment provenance related to geological variations in the Disko Bugt area (Figures 1 and 2). The higher magnetic mineral content of the sediments in the Vaigat Strait and Uummannaq Trough points to a significant contribution of basaltic material from Tertiary Basalts on Disko Island and the Nuussuaq Peninsula. This basaltic material is presumably washed into the Vaigat by meltwater, transport from glacier-fed rivers as well as from meltout of material from icebergs, and then under the influence of the WGC via the Vaigat further dispersed towards the shelf northwest of Disko Island.

However, this modern spatial distribution pattern of the MS signal found in surface sediments was different in the past, as demonstrated by the gravity core records represented here. These cores display a marked change in sediment provenance and sedimentation rate, which occurs at *c.* 6000 cal a BP (Figures 3 and 4). High sedimentation rates (> 200 cm ka^{-1}), MS signals and Ti counts (Figures 3 and 4) prior to *c.* 6000 cal a BP indicate rapid sediment deposition from large meltwater plumes emerging from melting glaciers in eastern Disko Bugt, which also included glacial (basaltic) sources on Disko Island. Previous terrestrial and marine studies show that following the LGM the ice sheet retreated from the shelf west of Disko Bugt eastwards into the embayment and reached the eastern coast by *c.* 10000 to 9000 cal a BP (Long and Roberts, 2002; Lloyd *et al.*, 2005; Weidick and Bennike, 2007; Hogan *et al.,* 2011). This retreat is thought to be in response to a pronounced temperature rise over the GIS (Dahl-Jensen *et al.*, 1998; Vinther *et al.*, 2009). It is likely that a relatively warm WGC also supported regional deglaciation during this period in the Disko Bugt area (Lloyd *et al.,* 2005). A similar early initiation of the WGC system has been reported from northern Baffin Bay (Knudsen *et al.*, 2008). We postulate that the high content of terrigeneous sediments prior to *c.* 6000 cal a BP reflects discharge of large volumes of meltwater from the retreating ice sheet in the eastern Disko Bugt area that primarily exited the embayment via the (outer) shelf to the southwest rather than through the Vaigat Strait (Figure 6A). Relatively high atmospheric temperatures over Baffin Bay (Kerwin *et al.*, 2004) and a relatively warm WGC (Lloyd *et al.*, 2005; Perner *et al.*, 2013) supports significant ice sheet melting within the area, which led to the production of large volumes of meltwater and enhanced iceberg calving. Such a strong early Holocene meltwater influence on sediment deposition in inner Disko Bugt has also been reported by Seidenkrantz *et al.* (2012). The gradual decrease in deposition of basaltic material (decreasing MS signals) between 8000 to 6000 cal a BP, on the south-western shelf

(Figure 3), implies an initial decline in the meltwater discharge from the ice sheet, which might be linked to an initial opening of the Vaigat Strait or to an overall reduction in meltwater production and iceberg calving. The strong meltwater imprint on the sediment composition south of Disko Island prior to *c.* 6000 cal a BP provides evidence of markedly reduced WGC flow into central and eastern Disko Bugt, which suggests that the WGC was unable to exit Disko Bugt through the Vaigat Strait. We assume that the narrow and shallow Vaigat Strait mainly acted as a meltwater conduit and was largely blocked by icebergs discharged from the outlet glaciers. Thus, the WGC was forced to re-circulate in Disko Bugt, and to continue its northwards flow via the shelf southwest of Disko Island (Figure 6A).

The marked shift in sediment provenance at *c.* 6000 cal a BP; i.e. reduced deposition of terrigeneous clastics rich in basaltic material, a lower sedimentation rate (< 100 cm ka^{-1}) and increase of the TOC content, implies that the influence of meltwater discharge from eastern Disko Bugt was significantly reduced on the south-western shelf and in Egedesminde Dyb (Figure 3 and 4). From *c.* 6000 cal a BP onwards the WGC is the dominant water mass controlling environmental conditions and sediment deposition in this area. Benthic foraminiferal assemblage data from Perner *et al*. (2013) provide further support for this change to dominant WGC influenced conditions after *c.* 6000 cal a BP in the southern Disko Bugt region. This shift in the palaeoceanographic circulation pattern of the WGC occurs simultaneously with the reported Holocene minimum ice sheet extent in eastern Disko Bugt from *c.* 6000 to 4000 cal a BP (Weidick and Bennike, 2007; Briner *et al.*, 2010, Young *et al.*, 2011) and maximum sea surface temperatures in the north-western part of Baffin Bay (Ledu *et al.*, 2010). As the ice sheet and outlet glaciers became progressively land-based, the relatively warm WGC could no longer cause basal tidewater glacier melting on a large scale. Consequently, calving activity of outlet glaciers (e.g. Jakobshavn Isbræ, Sermeq Avangnardleq, and Sermeq Kujadtleq; Figure 1) and meltwater supply to the embayment was markedly reduced. This allowed the WGC to circulate via the Vaigat Strait, which led to further enhanced melting of icebergs and in turn, increased WGC flow-through (Figure 6B).

Once the WGC was able to exit Disko Bugt through the Vaigat Strait, establishing the modern circulation pattern, iceberg and meltwater discharge from outlet glaciers was routed via the Vaigat Strait into Baffin Bay (Figure 6B). The available sediment record from the Vaigat only extends back until *c.* 2000 cal a BP and another record from the Vaigat Strait (Andresen *et al.*, 2011) covers the last *c.* 5200 cal a BP. These cores are too short to cover the change at *c.* 6000 cal a BP shown here from the cores from the southern Disko Bugt region. The Uummannaq Trough site (343520-GC), which covers the last *c.* 10000 cal a BP, exhibits similar high MS and Ti values as found on the shelf southwest of Disko Bugt and in Egedesminde Dyb prior to *c.* 6000 cal a BP. Following the opening of the Vaigat Strait, the sedimentation rate decreases and a higher proportion of basaltic material from Vaigat Strait origin is deposited until *c.* 4000 cal a BP at site 343520-GC (Figure 5). This site in the Uummannaq Trough receives not only sediments from the Vaigat Strait, but also from the Uummannaq fjord system to the north. Therefore, changes in sediment provenance recorded in this core may also be influenced by changes in input from glaciers flowing into the Uummannaq Trough system.

Conclusions

Investigations of sediment provenance from a suite of sediment cores from the Disko Bugt region reveal that significant meltwater production during Deglaciation from the Greenland Ice sheet influenced local environmental conditions within the area, lasting until *c.* 6000 cal a BP. Our data show a marked shift in sediment provenance at *c.* 6000 cal a BP recording the development of the modern circulation pattern of the West Greenland Current (WGC) in the Disko Bugt area. Before this time, meltwater and icebergs discharged from outlet glaciers in eastern Disko Bugt (e.g. Jakobshavn Isbræ) filled the Vaigat Strait, the modern exit of the WGC from Disko Bugt and prevented the WGC reaching the innermost part of the embayment. We find that establishment of the modern circulation pattern by the opening of the Vaigat Strait at *c.* 6000 cal a BP coincided with minimum ice sheet extent in eastern Disko Bugt. It is likely that, before the opening of the Vaigat Strait a warm WGC supported basal melting of outlet glaciers. Thus extensive meltwater plumes and iceberg calving forced the WGC to re-circulate in the southern Disko Bugt area and to continue north over the shelf southwest of Disko Island. Once the ice sheet had retreated to a predominantly land-based position decreased meltwater and iceberg discharge permitted the WGC to enter and flow through the Vaigat Strait, similar to the present day situation. Our results show that the interaction between ice sheet and ocean circulation changes (WGC) modulated the local environmental conditions during the Holocene within the Disko Bugt region.

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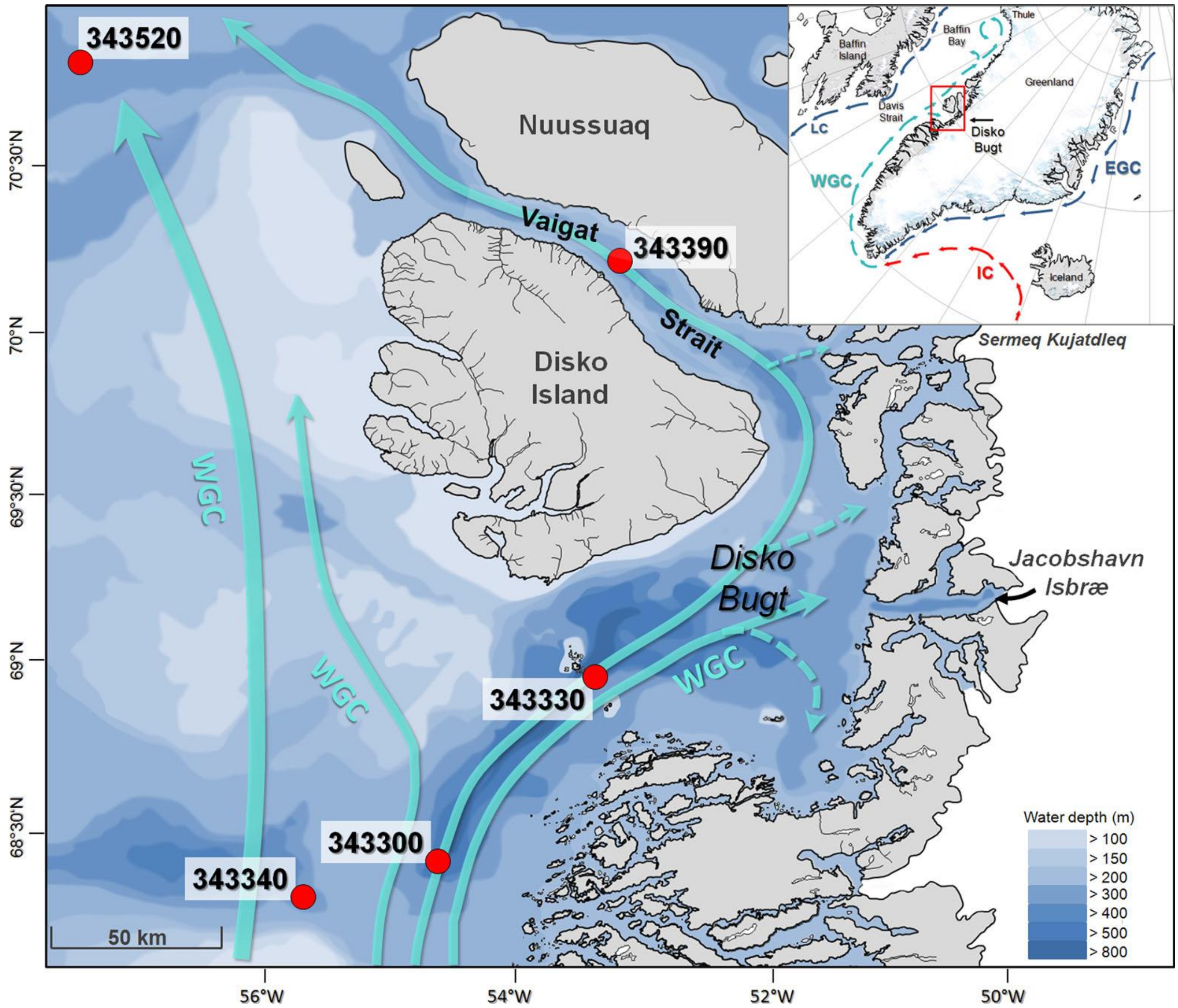

Figure 1: Map of study area with schematic sea floor topography and coring sites from MSM05/03 on the shelf southwest of Disko Bugt (sites 343340 and 343300), in Egedesminde Dyb (site 343330), the Vaigat Strait (site 343390) and the Uummannaq Trough (site 343520), along the modern flow path (green arrows) of the West Greenland Current (WGC) in the Disko Bugt area. The inset shows the WGC's source currents, the East Greenland Current (EGC) and the Irminger Current (IC).

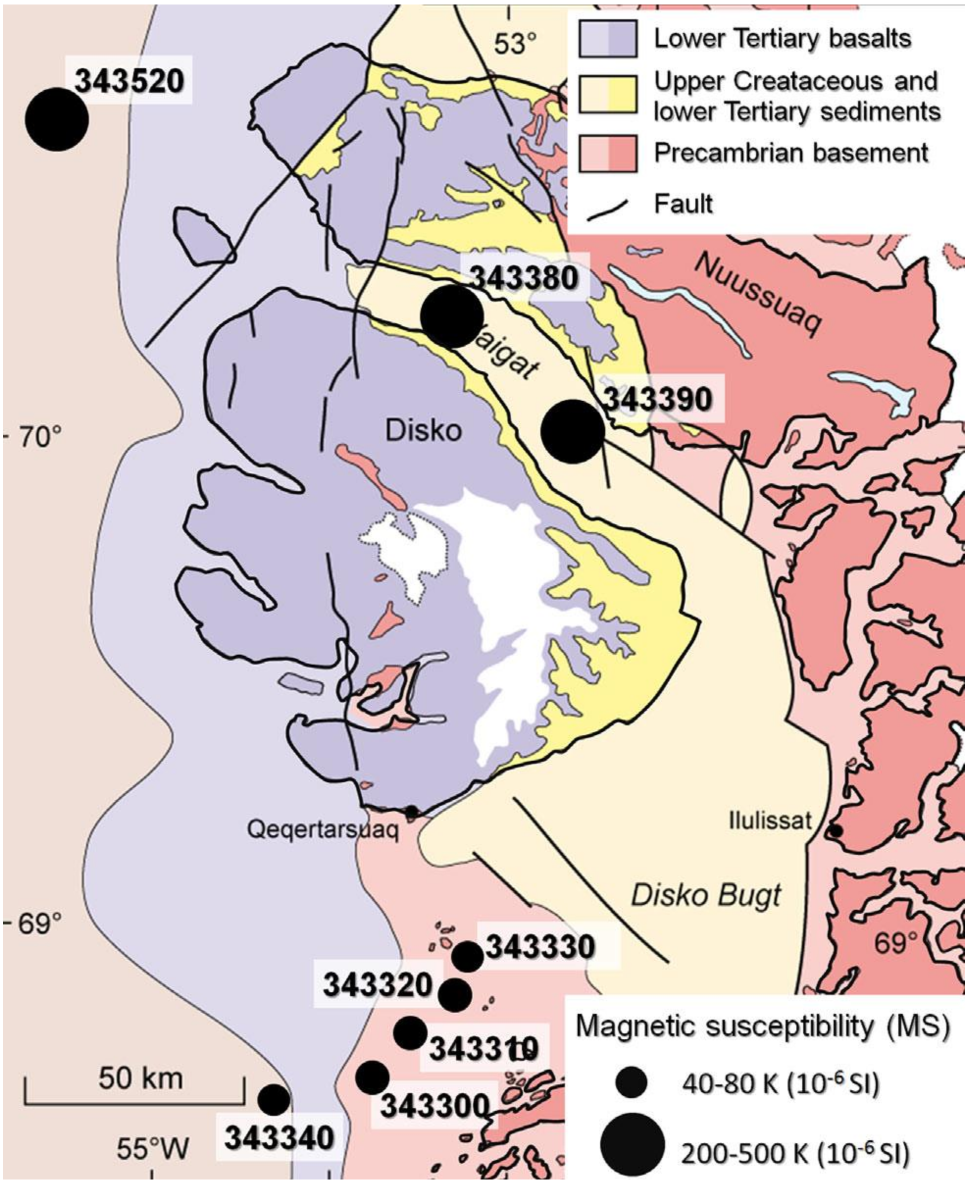

Figure 2: Geological setting of the Disko Bugt area adapted from Weidick and Bennike (2007). Full colours display the onshore, whereas pastel shades display the offshore geology. Additionally, the range of magnetic susceptibility (MS) signals is plotted for multi cores from the area, as listed in table 1.

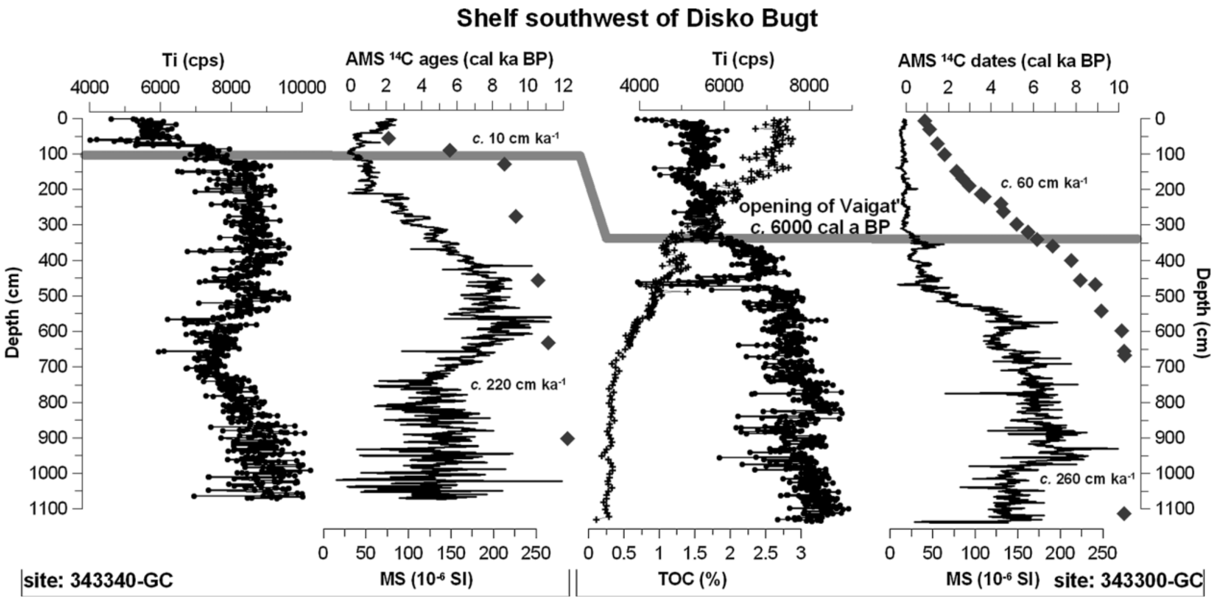

Figure 3: MS (solid line), Ti (circles), and TOC (crosses) data plotted against core depth (cm) from site 343340-GC on the outer south-western Disko Bugt shelf and from site 343300-GC on the inner shelf. Additionally AMS ^{14}C radiocarbon ages are shown from the respective core sites. Red shaded bar marks depth in cores of sediment provenance changes, displaying the time of the opening of the Vaigat Strait. Average sedimentation rates are presented for the time period before and after *c.* 6000 cal a BP.

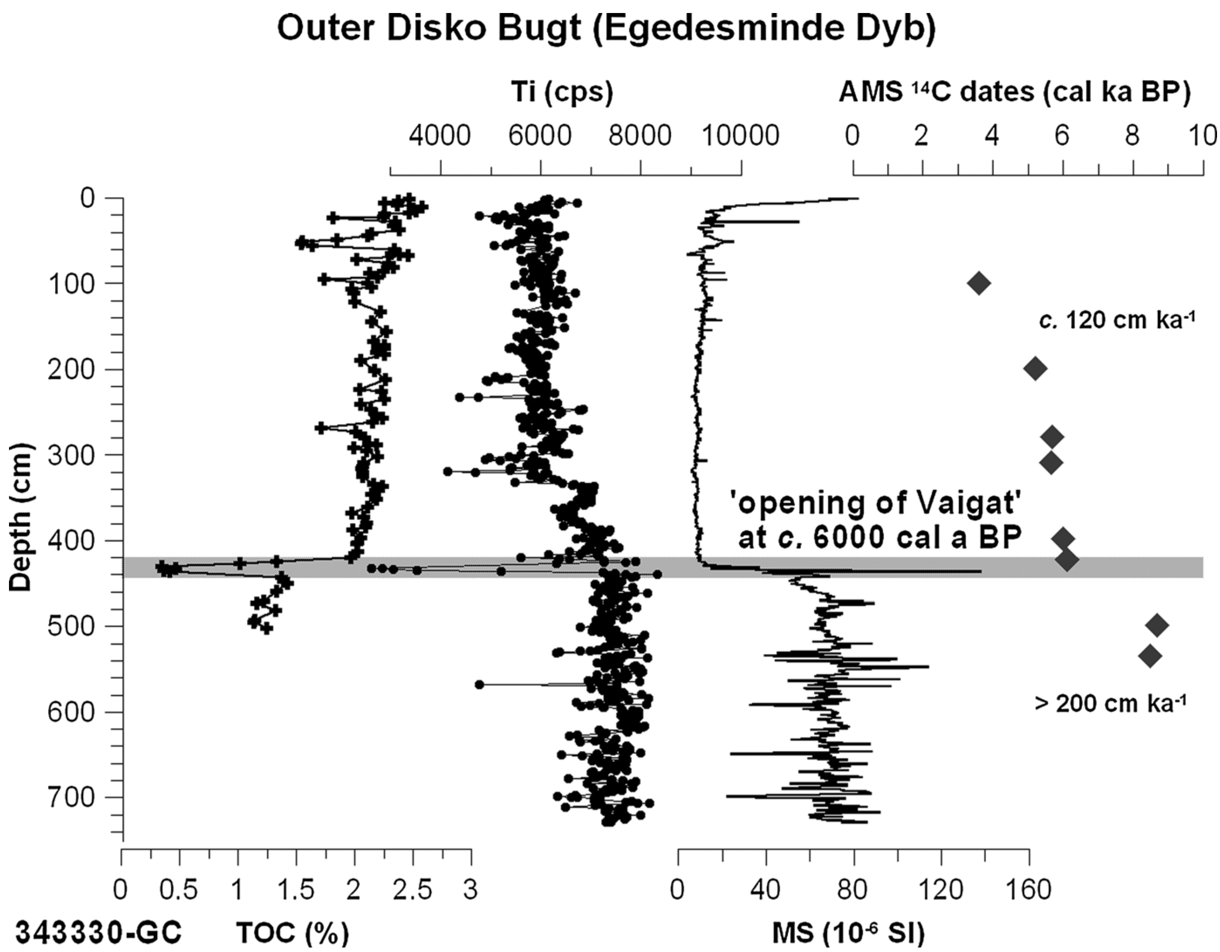

Figure 4: MS (solid line), Ti (circles), and TOC (crosses) data plotted against core depth (cm) from site 343330-GC from Egedesminde Dyb. Additionally, AMS ^{14}C radiocarbon ages are shown. Red shaded bar marks depth in cores of sediment provenance changes, displaying the time of the opening of the Vaigat Strait. Average sedimentation rates are presented for the time period before and after *c.* 6000 cal a BP.

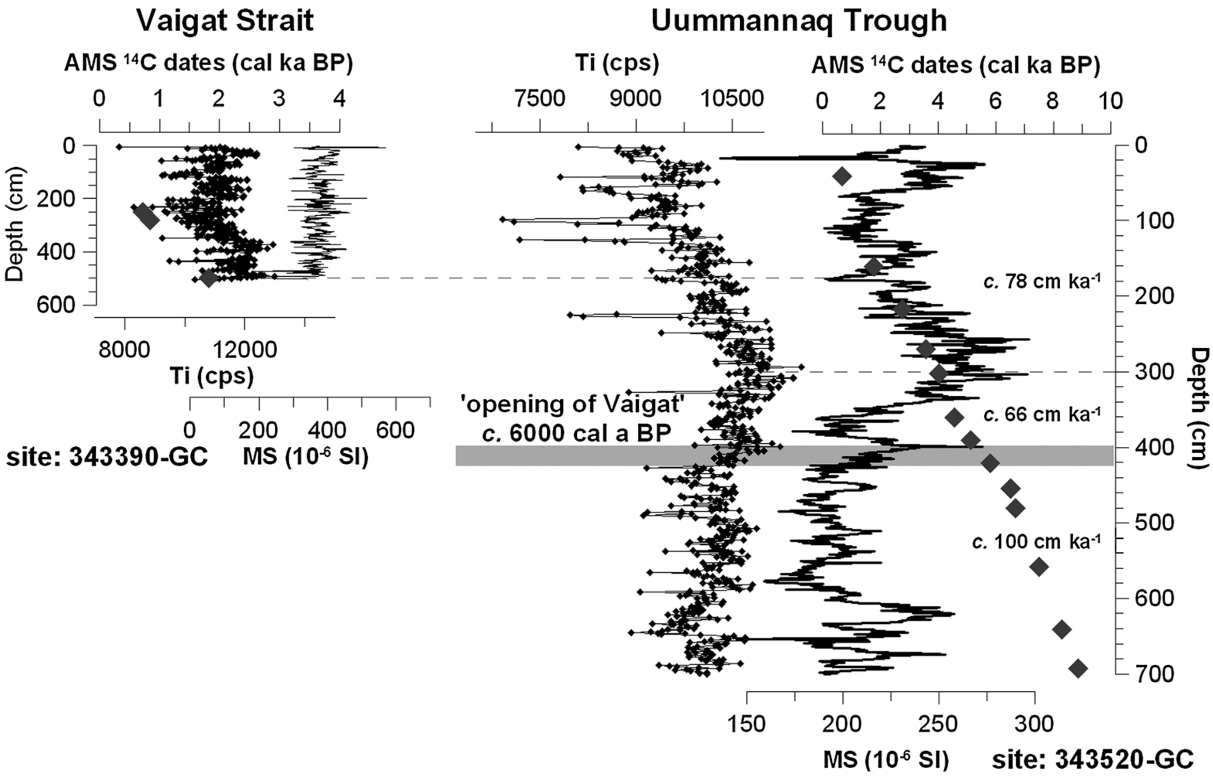

Figure 5: MS (solid line) and Ti (circles) data plotted against core depth (cm) and AMS ^{14}C radiocarbon ages, plotted against core depth, from site 343520-GC in the Uummannaq Trough and site 343390-GC from the Vaigat Strait. Red shaded bar marks depth in cores of sediment provenance changes, displaying the time of the opening of the Vaigat Strait. Average sedimentation rates for core 343520-GC are presented for the time period before and after *c.* 6000 cal a BP.

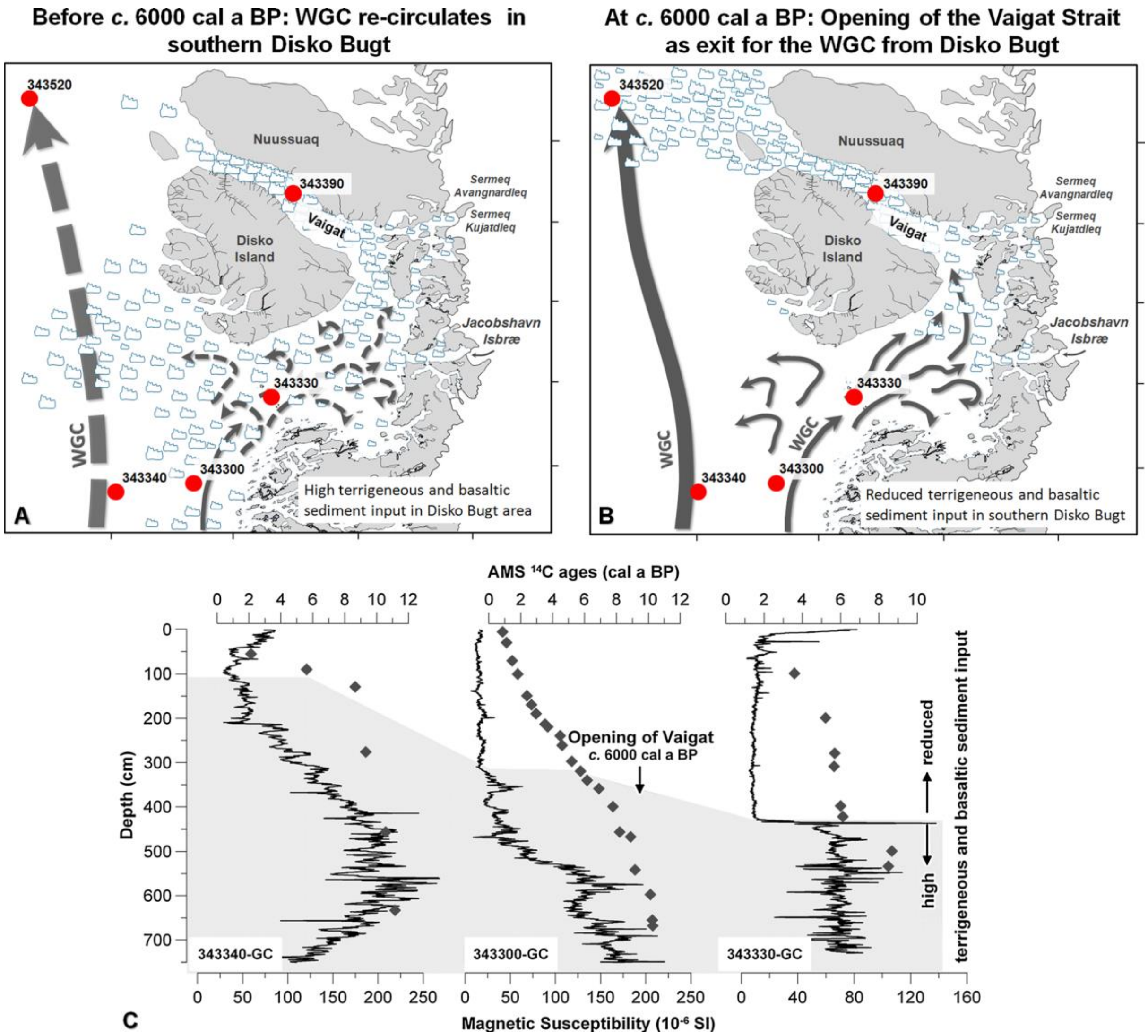

Figure 6: Schematic illustration of the evolution of the West Greenland Current (WGC) in Disko Bugt during the Holocene. A) Conditions before *c.* 6000 cal a BP. The Vaigat Strait is blocked by ice bergs. The flow path of the WGC is shown by green arrows entering the western region of Disko Bugt. The WGC re-circulates and exits back out of Disko Bugt and continues flowing northwards. B) Conditions from *c.* 6000 cal a BP onwards. Modern circulation system in Disko Bugt develops as the Vaigat Strait becomes unblocked. The flow path of the WGC is shown in green arrows flowing through Disko Bugt and the Vaigat Strait into the Uummannaq system to the northwest. C) Magnetic susceptibility transect of gravity cores (343340-GC, 343300-GC, and 343330-GC) south of Disko Island. Cores mark clearly shift in sediment provenance from high to reduced terrigeneous and basaltic sediment input at *c.* 6000 cal a BP.