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► **To cite this version:**

Camilla Andresen, Marie-Alexandrine Sicre, Fiammetta Straneo, David Sutherland, Torben Schmith, et al.. A 100-year long record of alkenone-derived SST changes by Southeast Greenland. *Continental Shelf Research*, 2013, 71, pp.45-51. 10.1016/j.csr.2013.10.003 . hal-03207455

**HAL Id: hal-03207455**

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Submitted on 28 Apr 2021

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### Deposited in DRO:

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### Version of attached file:

Accepted Version

### Peer-review status of attached file:

Peer-reviewed

### Citation for published item:

Andresen, Camilla S. and Sicre, Marie-Alexandrine and Straneo, Fiammetta and Sutherland, David A. and Schmith, Torben and Hvid Ribergaard, Mads and Kuijpers, Antoon and Lloyd, Jerry M. (2013) 'A 100-year long record of alkenone-derived SST changes by Southeast Greenland.', *Continental shelf research.*, 71 . pp. 45-51.

### Further information on publisher's website:

<https://doi.org/10.1016/j.csr.2013.10.003>

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## Highlights

- Alkenone analysis on sediment core from Sermilik Fjord, SE Greenland.
- Reconstruction of ocean surface temperature changes of the past 100 years.
- Alkenones advected and represent temperature changes on nearby shelf.
- Warm ocean c. 1940 concurs with increased calving from Helheim Glacier
- Similar to observation from Disko Bay and Jakobshavn Isbræ in West Greenland.

## A 100-year long record of alkenone-derived SST changes by Southeast Greenland

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### Abstract

Sediment core ER07 from Sermilik Fjord by Helheim Glacier in Southeast Greenland was analysed for alkenones to document sea surface temperature (SST) changes over the past 100 years. The alkenone SST values, ranging from 8 to 12°C, contrasts with colder values (0-4°C) obtained from recent hydrographic surveys inside the fjord. We suggest that advection of allochthonous alkenones produced in the warm Irminger Current waters circulating on the shelf likely accounts for this difference. The temperature range of the alkenone-derived record is similar to in situ observations of 8-11°C on the shelf just outside Sermilik Fjord, and its variability over the past 100 years resembles the constructed variability over the shelf using remote instrumental data. This suggests that oceanographic changes on the adjacent shelf are linked to regional changes of the Irminger Current and the East Greenland Current. The subsurface water heat content has previously been suggested as an important control on Greenland outlet glacier stability and underlined by an episode

1 of warm subsurface waters ~ 1940 concurrent with markedly increased calving and retreat of  
2 Helheim Glacier. Our results therefore suggest that alkenone-derived SST time series from high-  
3 sedimentation rate glacial fjords may provide a new approach for reconstruction of past changes of  
4 shelf water properties and variability around Greenland.  
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12 **Key words:** Southeast Greenland, Sermilik Fjord, Helheim Glacier, alkenones, sea surface  
13 temperature, ocean-cryosphere interaction, outlet glacier stability  
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## 17 **1. Introduction**

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20 In the early part of this century, the Greenland Ice Sheet (GIS) experienced a marked increase in net  
21 mass loss (Rignot and Kanagaratnam, 2006; van den Broeke et al., 2009), stimulating research for  
22 better understanding how such future glacier changes will affect global sea level rise. In Southeast  
23 Greenland, outlet glaciers thinned, accelerated and retreated between 2003 and 2005 (Howat et al.,  
24 2007, 2008; Moon and Joughin, 2008; Stearns and Hamilton, 2007; Luckman et al., 2006, Rignot  
25 and Kanagaratnam, 2006), and it was suggested that concurrent rising temperatures of subsurface  
26 ocean currents may have triggered the onset of this acceleration (Nick et al., 2009; Straneo et al.,  
27 2010; 2011, 2012; Murray et al., 2010). Likewise, the early 2000's thinning, retreating and doubling  
28 of flow velocity of the Jakobshavn Isbræ in West Greenland has been linked to a pulse of warm  
29 waters in the West Greenland Current (WGC) propagating up the West Greenland coast and  
30 entering Disko Bay in 1997 (Holland et al., 2008). The exact processes involved in ocean-forced  
31 destabilisation of outlet glaciers is still not well understood, but it is believed that rapid submarine  
32 melting of calving faces is an important mechanism for glacier calving (Rignot et al., 2002, 2010)  
33 and that changes in North Atlantic ocean heat transport may decrease the support from the  
34 buttressing ice mélange in front of the glacier margin (Vielı and Nick, 2011).  
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47 Ice sheet mass changes of the GIS have only been estimated for the past 20-30 years  
48 using satellite data. Likewise, the observational SST record on the continental shelf around  
49 Greenland is sparse in space and time, and hydrographic surveys in the near-shore and fjord waters  
50 virtually absent prior to 2008 (cf. Straneo et al., 2010; Murray et al., 2010). Therefore, in order to  
51 establish a more firm causal relationship between ocean variability and glacier dynamical changes  
52 we need to explore longer timescales, which requires the use of proxy records (Andresen et al.,  
53 2011, 2012).  
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1 In this paper, we present a 100-year long SST time-series based on the  $C_{37}$  alkenone  
2 from a sediment core retrieved in Sermilik Fjord. Alkenone biomarkers in the open ocean waters are  
3 mainly produced by the prymnesiophytae, *Emiliania huxleyi*, growing in the photic zone (Volkman  
4 et al., 2000). The unsaturation index of the  $C_{37}$  alkenones ( $U_{37}^K$ ) in marine waters has been shown to  
5 be highly correlated to water temperature on a global scale (Prahl et al., 1988; Conte et al., 2006).  
6 We argue that alkenone SSTs derived from the fjord core are indicative largely of property changes  
7 of surface waters occurring just outside of Sermilik Fjord. This conclusion is supported by  
8 comparing our results to oceanographic data obtained from the broader shelf region. Finally, we  
9 discuss the link between ocean variability and glacier dynamical changes on longer timescales by  
10 comparing alkenone SSTs with a proxy record of Helheim Glacier calving.  
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## 21 **2. Setting**

22 Sermilik Fjord is c. 80 km long with a width varying between 7 and 13 km. The  
23 bathymetry documents a U-shaped fjord with steep side walls and depths of 920 m at the mouth and  
24 600 m at the northern end of the fjord extending approximately in a north-south direction (Schjøth  
25 et al., 2012). The northern end of the fjord branches into three fjords each containing ice-calving  
26 glaciers. The westernmost glacier – the Helheim Glacier – is a fast flowing glacier and the third  
27 most prolific exporter of icebergs in Greenland (Rignot and Kanagaratnam, 2006). The two  
28 northern glaciers, Midgaard and Fenris Glaciers are far less ice productive compared to Helheim  
29 (Mernild et al., 2010).  
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38 According to MODIS satellite images for the past few years  
39 (<http://ocean.dmi.dk/arctic/modis.php>), open water conditions occur frequently in the fjord  
40 throughout the winter as fjord-ice is broken, likely due to strong currents and storms. A marked ice-  
41 mélange, with inter-annually varying extension, is situated in front of the Helheim Glacier.  
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45 The oceanographic conditions on the Southeast Greenland shelf are characterized by  
46 the East Greenland Current (EGC), which transports cold and fresh sea ice-laden surface waters  
47 derived from the Arctic Ocean and glacial melt water from East Greenland that has an inner near  
48 coastal branch, the East Greenland Coastal Current (EGCC) (Sutherland and Pickart, 2008) (Fig. 1).  
49 Off Southeast Greenland, this cold upper (< 250 m) layer is underlain by warmer and saltier waters  
50 derived from the Irminger Current (IC) (Malmberg 1985, Murray et al., 2010), which is a branch of  
51 the North Atlantic Current. Deep troughs (300-800 m) transect the shallow shelf (100-200 m) and  
52 thereby allow not only the upper cold waters, but also the warm subsurface waters to circulate  
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1 within the Sermilik Fjord, either through estuarine circulation (Murray et al., 2010) or shelf-driven  
2 exchange (Straneo et al., 2010). Hence, the hydrographic conditions in Sermilik Fjord are  
3 characterized by a two-layer stratification with warm (3.5 to 4°C) IC-derived waters from a depth of  
4 200-300 m and downwards overlain by -1 to +1°C cold Polar Waters advected by the EGC-EGCC  
5 water mass system (Fig. 2). In summer, the uppermost 10-20 m are characterised by low-salinity  
6 waters from glacier runoff and the temperature can be up to several °C due to solar heating (Straneo  
7 et al., 2010).

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14 Interaction between the IC and EGC/EGCC over the shelf influences temperatures and  
15 the interface depth (i.e. the thermocline), potentially altering the amount of heat reaching the glacier  
16 margins and its ice-mélange in the fjord (Straneo et al., 2010, 2011; Sutherland et al., 2013).

### 21 3. Methods

22 Alkenone analysis was carried out on sediment core ER07 obtained from Sermilik fjord (Fig. 1B).  
23 This core was retrieved from 525 m water depth (66°00'59"N, 37°51'07"W) and dated by means of  
24 <sup>210</sup>Pb chronology and analysed for grain size composition using a Malvern laser sedigraph. The  
25 chronology was calculated using the CRS-model (Constant Rate of Supply (Appleby and Oldfield,  
26 1978) and calculations of the activities of unsupported <sup>210</sup>Pb in the lower part of the cores were  
27 based on regression of activity versus accumulated mass depth in order to increase the robustness of  
28 the age models. Further details on methodologies behind ER07 <sup>210</sup>Pb chronology and sedimentology  
29 are provided in Andresen et al. (2012). The upper 24 cm of ER07 was sampled continuously every  
30 ½ cm for alkenone determination leading to 43 levels to be analysed (higher sampling density in the  
31 upper part of the core).

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34 Alkenones were extracted from freeze-dried sediments using a  
35 dichloromethane/methanol mixture (2:1 v/v) and isolated from the total lipid extract by silicagel  
36 chromatography (Ternois et al., 1999). The purified fractions were then analysed by gas  
37 chromatography using a Varian 3400CX gas chromatograph and a CPSi15 capillary column (50m  
38 length, 0.3 2i.d., 0.25 µm film thickness) equipped with a FID detector and a septum programmable  
39 injector (SPI). Helium was used as a carrier gas. The C<sub>37</sub> alkenone distribution comprises C<sub>37:3</sub>, C<sub>37:2</sub>  
40 and C<sub>37:4</sub> as expected from cold and low salinity waters of the Northern Hemisphere. While C<sub>37:4</sub>  
41 notably is absent in Southern ocean polar waters (Ternois et al., 1998), its presence in high  
42 abundances has been reported in the Nordic Seas (Sicre et al., 2002 ; Bendle et al., 2005), the Baltic  
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1 Sea (Shulz et al., 2011) and more recently in Greenland lakes (D'Andrea et al., 2011) suggesting a  
2 production that might be linked to species other than *E. huxleyi*.  
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5 However, the compilation of open-ocean water samples of Sikes and Sicre (2002)  
6 showed that at cold temperatures, even when  $C_{37:4}$  is abundant, the use of  $U_{37}^K (C_{37:2} - C_{37:4}) / (C_{37:2}$   
7  $+ C_{37:3} + C_{37:4})$  instead of  $U_{37}^K (C_{37:2}) / (C_{37:2} + C_{37:3})$  does not improve SST estimates and we  
8 therefore use the  $U_{37}^K$  index to calculate temperatures. In coastal regions such as estuarine or fjords,  
9 where other species presumably contribute to alkenone production and where  $C_{37:4}$  is abundant even  
10 at elevated T, local calibration are needed for both indexes.  
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#### 19 **4. Results**

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21 Core ER07 is massive diamiction facies and contains on average 20 % sand in the 63-1000  $\mu\text{m}$   
22 fraction, 45 % silt and 35 % clay (Fig. 3A). The upper 24 cm represent the last 100 years according  
23 to  $^{210}\text{Pb}$  chronology (Fig. 3B-C). The time resolution is on average 2.5 years per sample and age  
24 uncertainties are in the order of +/- 2-6 years.  
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28 The  $C_{37}$  alkenone distribution is dominated by  $C_{37:4}$  in Sermilik Fjord sediments  
29 representing on average 65% of the total  $C_{37}$  alkenones, which is quite unusual for open ocean  
30 waters even cold and low salinity ones. However,  $C_{37:4}$  have been reported in cold ocean surface  
31 waters of the North Atlantic and Nordic Seas (Sicre et al., 2002) yet at lower abundances (up to  
32 35%). Percent of  $C_{37:4}$  in estuarine sediments of Chesapeake Bay reached up to 40% of the total  $C_{37}$   
33 alkenones at temperature above 25°C (Mercer et al., 2005). This result indicates that besides marine  
34 producers local haptophyceae contributed to the production of this compound.  
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41  $U_{37}^K$  values in Sermilik Fjord range from 0.31 to 0.47 (Fig. 4) contrasting with the  
42 lower values found in the coastal waters of Chesapeake Bay (0.118 to 0.313) (Mercer et al., 2005)  
43 and those found in a Norwegian fjord (Conte et al. (1994). Higher  $U_{37}^K$  index in Sermilik fjord  
44 sediments therefore suggest a dominant marine alkenone source with only minor contribution of  
45 autochthonous haptophyceae in Sermilik fjord sediments.  $U_{37}^K$  converted to SSTs using Prahl et al.'s  
46 calibration range between 8 and 12.5°C with a mean value of c. 10°C (Fig. 4). For comparison,  
47 SSTs calculated from the calibration establish by Mercer et al. (2005) ( $U_{37}^K = 0.013T - 0.04$ ) for  
48 coastal/estuarine settings leads to unrealistic values ranging from 26.8 to 38.9°C, from which we  
49 hypothesize that the marine calibration likely provide better SST estimates and useful indication of  
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1 its variability. SSTs along the core vary but are generally higher during the late 1930s and show a  
2 broad increase since 2000. Marked minima are observed in the 1960s, 1980s and 1990s.  
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## 6 **5. Discussion**

### 7 **5.1 Sedimentation regime in the fjord**

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10 A large number of sediment core studies from other East Greenland fjords; Kangerlussuaq (Syvitski  
11 et al., 1996; Smith & Andrews 2000), Nansen Fjord (Smith and Andrews 2000; Jennings and  
12 Weiner, 1996; Jennings et al., 2001) and Scoresbysund (Dowdeswell et al., 1993, 1994a; Ó Cofaigh  
13 & Dowdeswell 2001), also situated by marine-terminating glaciers, describe in details the  
14 characteristic sediment lithofacies and the glacial processes involved in their formation. This  
15 information has been used to study the sediment cores from Sermilik Fjord. The massive diamicton  
16 facies, with abundant pebbles in cores from the mid-part of the fjord, have been interpreted as  
17 resulting from iceberg delivery of heterogeneous debris under the assumption that sand grains are  
18 too large to be carried in suspension by the melt water plume. Calving variability of Helheim  
19 Glacier for the past 120 years has been reconstructed in a previous study (Andresen et al., 2012) by  
20 averaging three <sup>210</sup>Pb dated records, including ER07, of sand deposition (amount of sand deposited  
21 per year) taken from the mid-region of the fjord. The general conclusions from this study, thus  
22 taking into account changes in sand deposition in all three cores, are that iceberg discharge was  
23 markedly higher in the 1930s and 2000-2005 (Fig 5F).  
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36 The occurrence of microfossils (foraminifera and diatoms) is low in the mid-fjord  
37 cores, most likely because harsh environmental conditions in the fjord waters restrict biological  
38 productivity. Limited light penetration due to sea ice and icebergs and high loads of sediments in  
39 the turbid, fresh and cold surface waters will likely decrease the photosynthetic activity of  
40 phytoplankton inhabiting these fjord waters.  
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### 49 **5.2 SST variability offshore Southeast Greenland**

50 The temperatures calculated from C<sub>37:3</sub> and C<sub>37:2</sub> relative abundances in ER07 sediments are found  
51 to be up to 8°C higher than the maximum summer temperatures observed in the upper 100 m of the  
52 fjord water column (<4°C, Fig. 2 and Straneo et al. 2010; 2011), suggesting that alkenones  
53 deposited in the fjord sediments are not primarily produced in the fjord. To account for this large  
54 offset, we hypothesize lateral advection of detrital alkenones from the Irminger warmer waters  
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1 flowing from outside the fjord. This mechanism is consistent with the finding that Sermilik fjord  
2 waters are quickly and continuously replenished through a wind-driven exchange with the shelf  
3 (Straneo et al., 2010) thus allowing warm ‘detrital’ alkenones to enter the fjord and settle to the  
4 bottom floor. Several studies involving modern datasets already highlighted potential biases  
5 introduced by lateral advection of alkenones by strong surface ocean currents (Conte et al., 2006;  
6 Rühleman and Butzin, 2006; Mollenhauer et al., 2006). Sediments of the last glacial period from the  
7 Southern Indian Ocean revealed offsets between alkenone and foraminiferal transfer function SSTs  
8 due to advective transport of ‘warm’ alkenones by the Agulhas retroflexion to the core site (Sicre et  
9 al., 2005). A similar phenomenon related to Irminger Sea Water transport by the East- and West  
10 Greenland Current system has been reported in the north eastern Labrador Sea during the last  
11 deglacial period by Knutz et al. (2011).

21 Our hypothesis is supported by a recent analysis of data from the Southeast Greenland  
22 shelf derived from deep diving seals tagged with satellite relay depths loggers equipped with  
23 temperature sensors (Sutherland et al., 2013). These data show that the water column in connection  
24 with the deep trough just outside Sermilik Fjord (Box 1 in Fig. 1B) is often characterized by 8-11°C  
25 warm water with no vertical variation during summer and fall (Fig. 2), and it was suggested that this  
26 warm water originates from the Irminger Current flowing along the continental slope. Indeed the  
27 temperature range derived from the seal data is similar to that recorded by alkenones deposited  
28 inside Sermilik Fjord. This supports the notion that the alkenones are mostly from outside the fjord  
29 and that they are indicative of water temperatures on the shelf region outside Sermilik Fjord and to  
30 a lesser degree also further upstream of the warmer waters of the IC. This conclusion is supported  
31 by Sutherland et al.’s (2013) observation that the region just outside Sermilik Fjord is a frontal  
32 region between warm surface IC and cold surface EGC. In such a region an associated enhanced  
33 vertical turbulent supply of nutrients (Gawarkiewicz, 1992) would sustain primary production,  
34 including prymnosiphytae, as also observed by more northerly frontal regions of the Denmark Strait  
35 (Thordardottir 1977; Knudsen and Eiríksson, 2002). Increased biological production in this area is  
36 also supported by the high concentration of seal dives recorded with respect to neighboring regions  
37 (Sutherland et al., 2013). Considering the temperature values of the upper waters inside the fjord  
38 (<4°C; Fig 2), local production is unlikely to have contributed significantly to sedimentary alkenone  
39 and it is therefore most probable that alkenone distributions reflect advection of subsurface waters  
40 into the fjord.

### 5.3 Assessing alkenone SSTs

In order to evaluate the alkenone SSTs as reflecting SST variability outside Sermilik Fjord, they are compared with the Shelf Index established by Andresen et al. (2012) (Fig. 5D). Even though this data set is generated by data from regions relatively remote from Sermilik Fjord, they still belong to the same regional front system and should thus display the same temporal variability.

The Shelf Index was previously proposed (Andresen et al., 2012) to describe the oceanographic variability in Sermilik Fjord and the nearby shelf accounting for the combined variability of the presence of Irminger Water and Polar Waters. We briefly summarize it here. Variability in the IC was reconstructed using a time series from 1876 to 2007 of annual mean SSTs in an area south of Iceland, where the IC Waters upstream Greenland occupy a layer of several hundred meters extending to the surface (Fig. 5A). Periods of increased IC temperatures have been associated with a thickening of the Atlantic water layer (Våge et al., 2011). The Storis Index (Schmith and Hansen, 2005 and updated 2000-2007 in Andresen et al., 2012) is used as a proxy for Polar Waters. It is defined as the amount of multi-year sea ice that exits the Arctic Ocean via Fram Strait, around Cape Farewell and onto the SW Greenland shelf (Fig. 5B) and is available for the period 1820-2007. It has been defined as the northernmost position on the southwest coast, relative to Cape Farewell, of Storis exported through Fram Strait based on ice charts from the Danish Meteorological Institute (Valeur, 1976). A significant cross-correlation has been found between the Storis Index and the volume transport of sea-ice through Fram Strait derived from an ocean model (Schmith and Hansen, 2005). We use the Storis Index as a proxy for the Polar Water transport within the EGC assuming that the sea-ice export is correlated with the fresh water export through Fram Strait (Andresen et al., 2012). These Atlantic and Polar water records were subsequently normalised (by subtracting the mean and dividing by the standard deviation) and a Shelf Index was obtained by subtracting the resultant EGC Current index from the IC Water index. By doing so the two water masses are assumed weighted 1:1 in the Shelf Index in absence of information indicating different weighting of either water mass. A positive (negative) Shelf Index implies increased (decreased) influence of Irminger Water and decreased (increased) influence from the EGC on the shelf.

The Shelf Index was previously assessed by comparison with repeat hydrographic surveys from Fylla Bank off Southwest Greenland (Andresen et al. 2012, Fig. 5C). The Fylla Bank surveys were performed for the 1950–2010 period (Ribergaard 2011) and extended back to 1876 (Ribergaard et al., 2008) using surface water temperature anomaly data (Smed, 1978). Even though

1 these measurements are from the south-western side of Greenland, the continuity of the East and  
2 West Greenland Currents around Cape Farewell suggests that variability at Fylla Bank is also  
3 representative of the variability upstream by the southeast Greenland shelf and in the polar frontal  
4 zone (Bacon et al., 2008). The Shelf Index is statistically significant correlated with the Fylla Bank  
5 data (Andresen et al. 2012).  
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10 Similarities are observed between the alkenone-derived SST (Fig. 5E), the Shelf Index  
11 (Fig. 5D) and the Fylla Bank SSTs (Fig. 5C). Episodes with relatively warm conditions are  
12 recognised in the late 1930s and after 2000, as well as minor warming in the mid-1970s (red  
13 regions). During these warm periods, alkenone SSTs are slightly higher than those just outside the  
14 fjord emphasizing enhanced contribution of warmer IC waters which in summer can reach 11-12°C.  
15 The Great Salinity anomalies (GSAs), which occurred in the mid-1960/70s, 1980s and 1990s are all  
16 recognised as cooling episodes in both the alkenone SSTs, the Shelf index and the Fylla Bank data  
17 (blue stipled lines in Fig. 5). These were episodes with an increased amount of multi-year pack ice  
18 exported from the Arctic Ocean via the EGC. The episode in the mid-1960/70s was a more severe  
19 kind of a GSA, where the fresh surface water anomaly reached the northern coast of Iceland and  
20 was further transported with the WGC to the Labrador Sea and Newfoundland (Belkin, 2004).  
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30 We investigated the link between the alkenone-derived SSTs and the Shelf Index more  
31 statistically rigorously. Interannual variations are strongly damped in the proxy-based alkenone  
32 derived SST, and therefore we low-pass filtered the Shelf Index with a five year moving average so  
33 that the two series would get similar spectral characteristics. We then calculated their detrended  
34 correlation coefficient as 0.34. The two-sided 90% confidence band on this value was estimated by  
35 block-bootstrapping (Wilks, 1997) and we obtained the limits -0.04 and 0.56. Varying the block  
36 length between 5 and 15 years did not significantly change this.  
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43 The effect of uncertainties in the age model on the correlation coefficient was also  
44 considered. This was done by a Monte Carlo procedure where the age of each point in the record of  
45 alkenone SSTs was perturbed according to the uncertainties in the dating (fig 3c). From this we  
46 obtained a confidence band with limits 0.11 and 0.54. All this enable us to conclude with some  
47 justification that we have a relationship on the longer time scales between alkenone-derived SSTs  
48 and the Shelf Index.  
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54 Thus, comparison of the alkenone SSTs with the seal-derived SSTs and with the Shelf  
55 Index suggests that alkenones from Sermilik Fjord sediment reflect mainly SST changes outside  
56 Sermilik Fjord and to a lesser degree also further upstream of the warmer waters of the IC. Our  
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1 results thus show that the observed alkenone SSTs variability is linked, to a certain degree, with  
2 shelf water property and variability caused by changes in the IC and EGC current systems.  
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#### 8 ***5.4 Comparing reconstructed ocean temperature with glacier changes in Greenland*** 9

10 The correspondence between climatic and oceanographic changes and the variability in the  
11 reconstructed changes in iceberg calving from Helheim Glacier was previously investigated  
12 (Andresen et al., 2012a). However, due to a lack of data from local hydrographical surveys, the  
13 calving record was compared with SST data from south of Iceland, the Storis Index and the Shelf  
14 Index assuming that the heat content of the waters reaching the glacier and its mélange may be  
15 linked to regional variability. It was found that on multi-decadal timescales, calving is linked with  
16 synchronous changes in the Northern Irminger Sea SSTs. SSTs in this region reflect the Atlantic  
17 Multi-decadal Oscillation (AMO), which is a multi-decadal mode of variability (oscillation of 65-70  
18 years) occurring in the North Atlantic Ocean and is usually defined from patterns of SST  
19 variability; i.e. a positive (negative) mode is characterized by relatively high (low) SSTs  
20 (Schlesinger and Ramankutty, 1994). Furthermore, short-term (3-10 years) calving peaks were  
21 coincident with short-term episodes of positive Shelf Index indicating that increased IC inflow  
22 and/or warming along with decreased flow of Storis and EGC are associated with enhanced calving.  
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34 The alkenone SST data strengthens the link between oceanographic variability and  
35 Helheim Glacier calving (Andresen et al., 2012) with a detrended correlation coefficient of 0.37 and  
36 90% confidence band with limits 0.09 and 0.56. Also the limits of the confidence band associated  
37 with uncertainties in the age model was estimated at 0.02 and 0.48 (see 5.3. for statistical method).  
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41 A new and interesting finding is that the alkenone SST data show a *record* peak in the  
42 late 1930s at the culmination of the so-called Early 20<sup>th</sup> Century Warming (Wood and Overland,  
43 2010) and that it is broadly concordant with a calving maximum in 1940 (Fig. 5E and F). The  
44 upstream SSTs from south of Iceland do not show a *record* of high SST at this time – rather they  
45 resemble the AMO pattern with generally high SSTs in 1925-1965 (Fig. 5A). A possible  
46 explanation is that during the 1950s and 1960s the warm IC waters may have been mixed and  
47 cooled more intensively by the EGC upon reaching Southeast Greenland than during the 1930s and  
48 1940s, when sea ice was less abundant and the EGC weaker (Schmith and Hansen, 2005, Fig. 5B).  
49 The same pattern of decreased ocean temperatures in the 1950-1960s is observed in West Greenland  
50 (Lloyd et al., 2011, Fig. 5G). In this study, benthic foraminifera assemblage changes in sediment  
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1 cores obtained from Disko Bay by Jakobshavn Isbrae were used to reconstruct temperature  
2 variability at 300 m water depth. According to aerial images, a relatively rapid retreat of the  
3 Jakobshavn Isbrae glacier front occurred in 1930-1950, at the time of the subsurface water  
4 temperature maximum in 1920-1945 (peak in 1940). The glacier subsequently attained a stable  
5 position 1950-2000 and this stagnation was accompanied by a cold WGC in 1950-1980. Overall,  
6 these proxy-based ocean water temperature reconstructions document a markedly warm peak in  
7 subsurface water by West and surface water by Southeast Greenland in the late 1930s, possibly  
8 caused by less mixing of cold EGC waters at this time. Proxy-based temperature reconstructions of  
9 Greenland shelf waters detailing the past 100 years are restricted to the study presented here and the  
10 data set from Jakobshavn (Lloyd et al. 2011), but on the basis of these we suggest a period of  
11 markedly increased ocean heat content around 1940 impacted Greenland glacier stability to an  
12 extent that was only matched after 2000.  
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## 25 **6. Conclusion**

26 The alkenone SST record obtained from core ER07 provides evidence of repeated mixing of warm  
27 IC Water throughout the past 100 years into Sermilik Fjord. The temperature range of 8-12°C  
28 suggests that alkenones were produced outside the fjord and in the IC, and that production in the  
29 uppermost surface waters in the fjord was minor. The resemblance of alkenone SST variability with  
30 the Shelf Index emphasizes the regional character of this signal and its link to IC and EGC  
31 variability. Our results confirm previous finding on the important role of regional ocean forcing on  
32 outlet glacier stability, particularly the marked calving episode of the late 1930s. They also provide  
33 valuable information on the role of ocean and its heat content to Greenland Ice Sheet melting and  
34 succeeding sea level rise and emphasize the need to better account for ocean/sea ice interactions in  
35 modelling studies.  
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## 45 **Acknowledgements**

46  
47 This study has been supported by Geocenter Denmark in financial support to the SEDIMICE  
48 project, the Danish Council for Independent Research | Nature and Universe (Grant no. 09-  
49 064954/FNU) and the Danish Agency for Science, Technology and Innovation as part of the  
50 Greenland Climate Research Centre. The alkenone data presented here have been produced within  
51 the NAIV project supported by LEFE program of the Institut National des Sciences de l'Univers  
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1 (INSU) of the Centre national de la Recherche Scientifique. FS and DS were supported by NSF  
2 funded projects. We are very grateful to our reviewers for their help in improving this manuscript.  
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## 57 **Figure captions**

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1 Fig 1. A. Main currents in the North Atlantic Ocean (Straneo et al., 2012) and location of Helheim  
2 Glacier (HG), Kangerdluqssuaq Glacier (KG), Disko Bay (DB), Jakobshavn Isbrae (JI),  
3 Scoresbysund (SU), Fyllas Banke (FB) and region south of Iceland from where SSTs of the IC were  
4 obtained. B. Helheim Glacier and Sermilik Fjord with position of core ER07 (bathymetry from  
5 Schjøth et al., 2012) and the pathways of the EGC/EGCC system and the IC (Straneo et al., 2010).  
6 Box 1 indicates the region in which the alkenone-derived SST reconstruction is interpreted to record  
7 variability.  
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16 Fig. 2. Profiles of temperature versus depth taken inside Sermilik Fjord during the summers of  
17 2008, 2009, 2010 and 2011 (blue) via ship-based hydrography (the 2008 and 2009 are those  
18 described in Straneo et al. 2010; 2011) and outside the fjord via tagged seals (red, see Box 1 in Fig.  
19 1B). The seal-derived temperatures represent summer/fall conditions when Irminger Sea water was  
20 present (29% of all profiles) over the time period 2004—2010 (Sutherland et al. 2013).  
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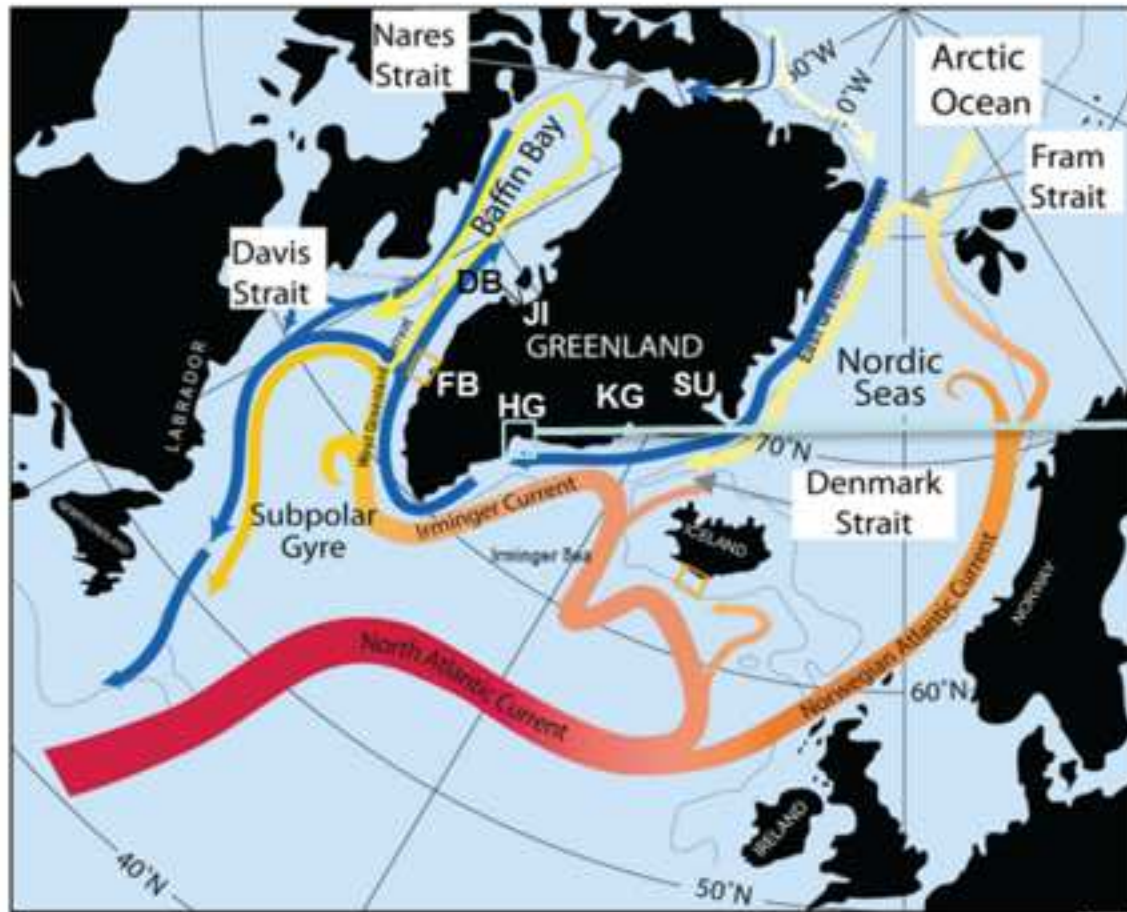
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27 Fig. 3. Core ER07 sedimentology and chronology (Andresen et al., 2012). A. Grain size distribution  
28 (wt%) of clay, silt and sand. B. Unsupported  $^{210}\text{Pb}$  and  $^{137}\text{Cs}$ . C. Age model based on  $^{210}\text{Pb}$  and  
29  $^{137}\text{Cs}$  dating (one sigma error bars).  
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34 Fig. 4. Core ER07  $\text{U37k}'$  values (left axis) and alkenone-derived SST data (right axis). Internal  
35 precision is estimated to  $0.5^\circ\text{C}$ .  
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39 Fig. 5. Comparison with other records. A. SST from offshore South Iceland (black line 3 point  
40 running mean). The AMO Index (from Enfield et al. 2001) is shown above (3 point running annual  
41 mean). Red (blue) scrapings indicate positive (negative) Index. B. The Storis Index (black line 3  
42 point running mean). C. The shelf Index (black line 3 point running mean). D. Fylla Banke SST  
43 (black line 3 point running mean) (Ribergaard et al., 2011). E. ER07 alkenone-derived SST (black  
44 line 3 point running mean). F. Reconstructed calving variability of Helheim Glacier. Data in A-C  
45 and F from Andresen et al., 2012. G. % Warm water foraminifera in Egedesminde Dyb by Disko  
46 Bay (Lloyd et al., 2012). Warm SST episodes in alkenone data highlighted with red boxes. Blue  
47 stipled lines indicate Great Salinity Anomalies (GSAs).  
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**A**



**B**

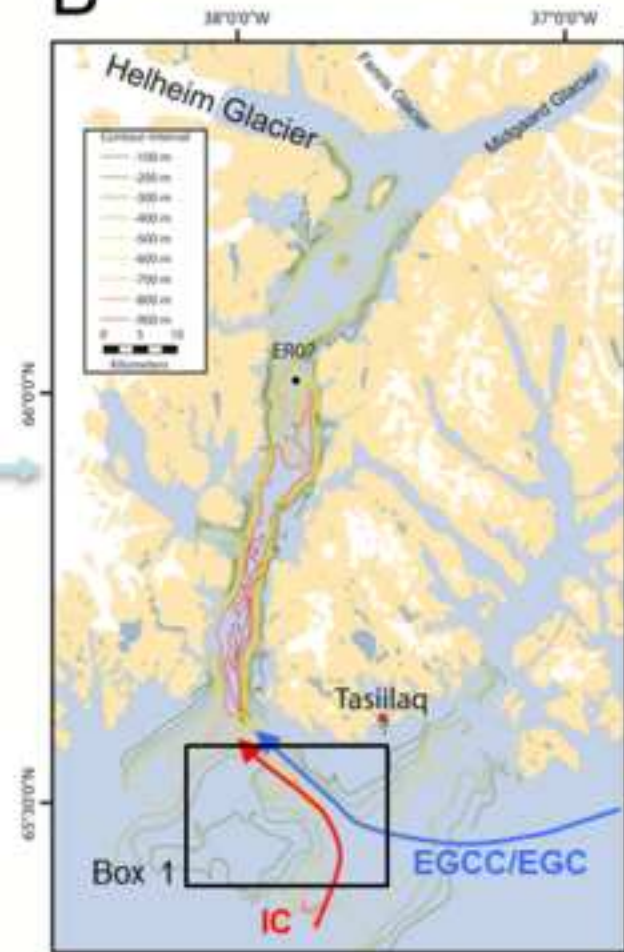




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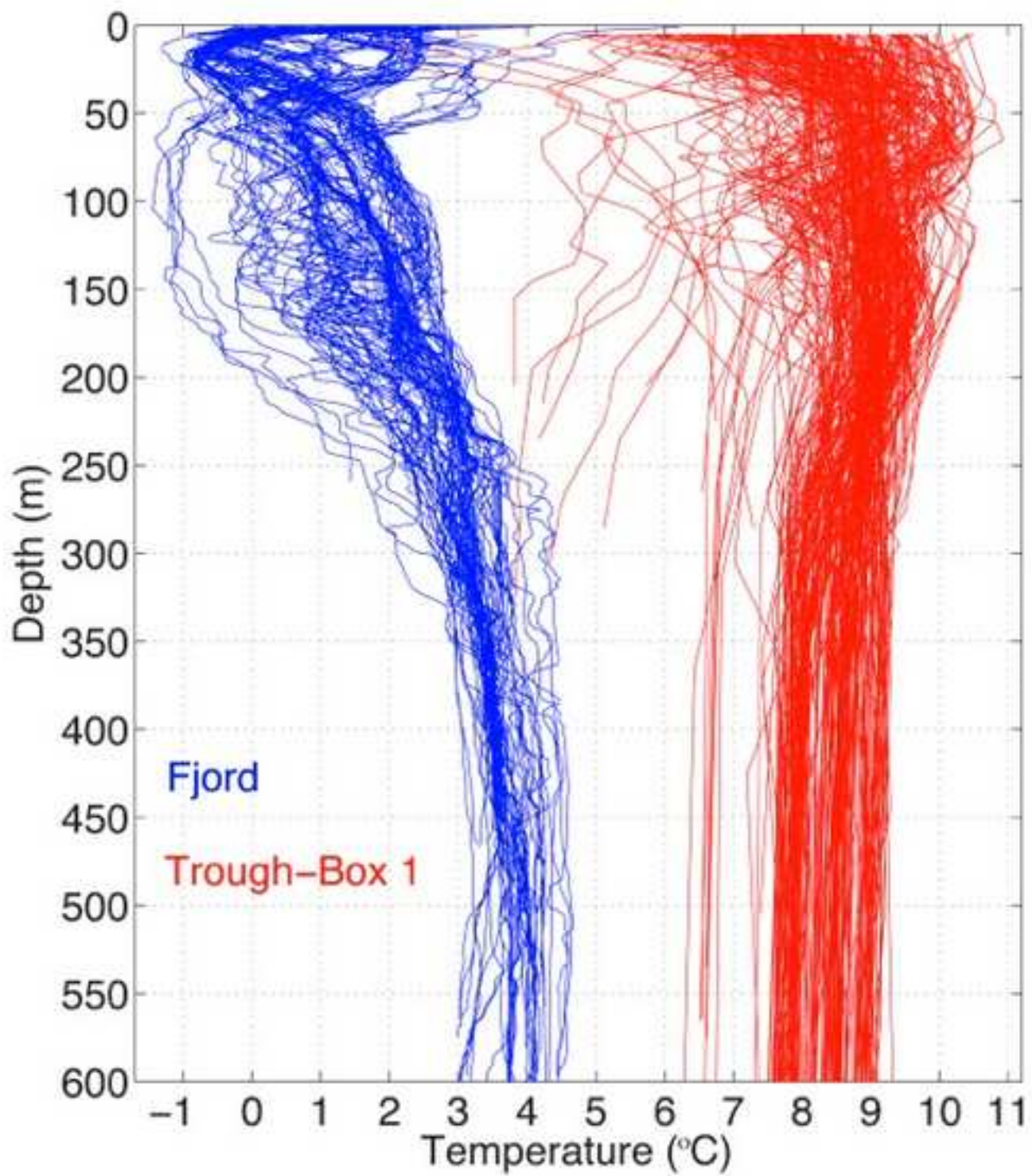
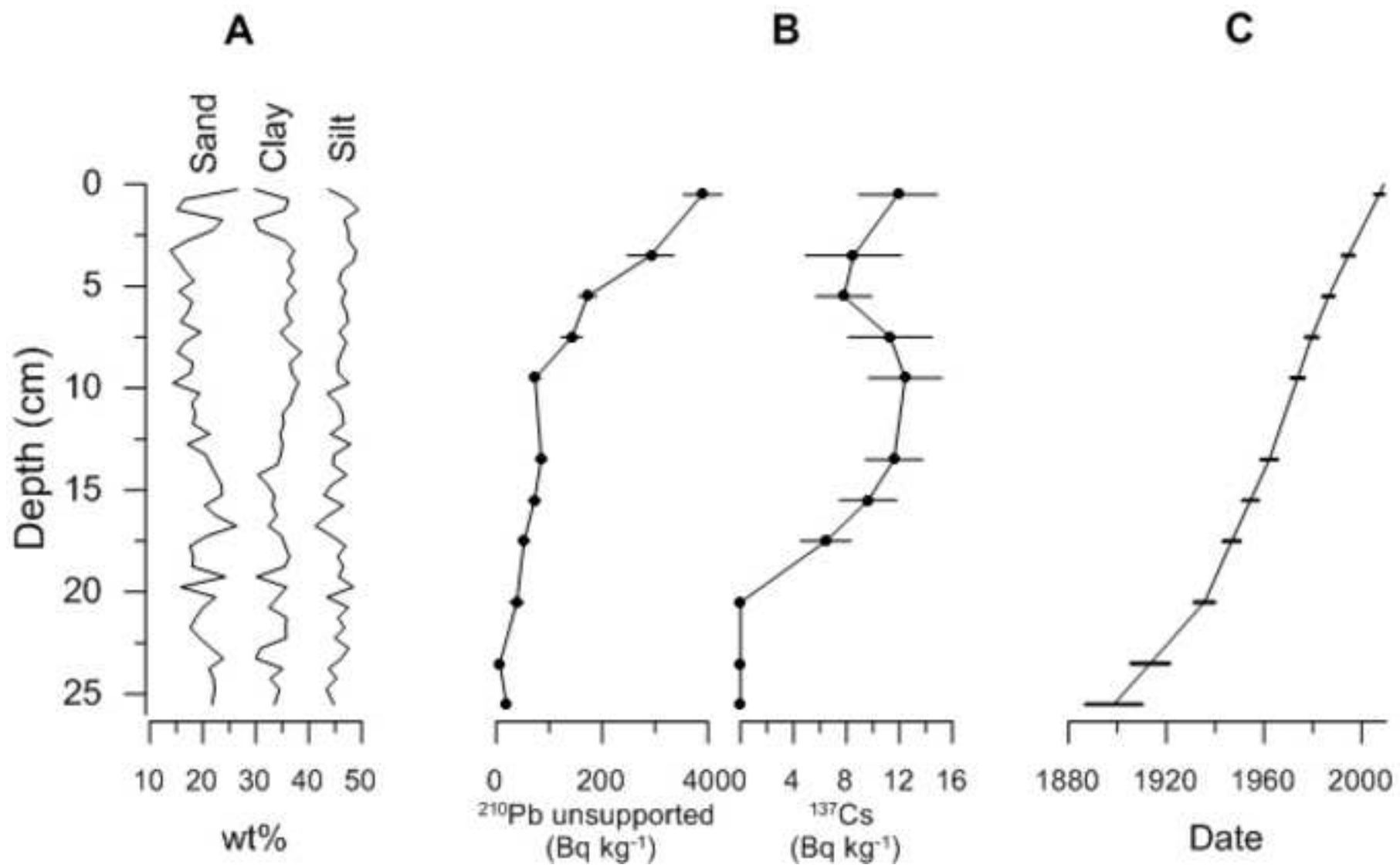


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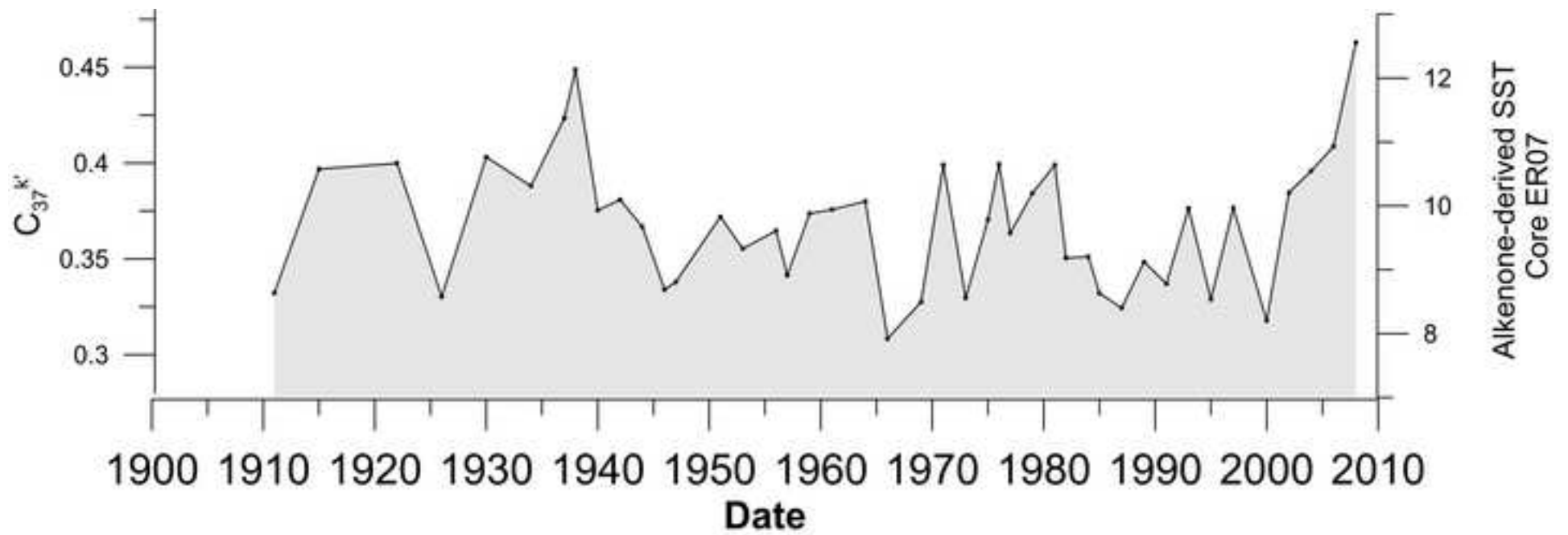


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