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Oceanographic Investigations off West Greenland 2008

by

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Abstract

The regional hydrography in summer 2008 is presented and discussed based on data from standard sections along the west coast of Greenland and data retrieved during trawl surveys. In addition, data from five Southwest Greenland fjords are presented.

In 2008, the winter North Atlantic Oscillation (NAO) index was positive describing anomalous strong westerlies over the North Atlantic Ocean resulting in extensive cooling over the Labrador Sea / Davis Strait area (Våge et al., 2009) and extensive west-ice coverage was formed during the winter 2007/2008. Cold surface waters already in 2007 (Ribergaard et al., 2008) may have had a positive effect on the sea-ice formation. The extension of multi-year-ice ("Storis") was also high, and the two types of sea-ice meet during late winter 2008, which is seldom observed.

The general settings in the region have traditionally been presented with offset in the hydrography observed over the Fylla Bank. Here, time series of mid-June temperatures on top of Fylla Bank show below average conditions in 2008 with noticeable low salinities.

The presence of Irminger Water in the West Greenland waters were above normal in 2008. Pure Irminger Water was observed at the sections off Paamiut, Cape Farewell and Cape Desolation, and Modified Irminger Water could be traced north to the Sisimiut section. The Irminger water (water of Atlantic origin) was warmer than normal, and their salinities were above normal and even 35 or more at Cape Farewell and Cape Desolation. The mean (400–600 m) salinity and temperature west of Fylla Bank (st.4) was both above normal. However, mean temperatures and salinities for the same depth interval for Maniitsoq and Sisimiut were among the highest observed consistent with the large scale settings in the Subpolar North Atlantic (Holliday et al. 2008).

The presence of Polar Water was also above normal in 2008. The extension of multi-year-ice ("Storis") encountered during the survey was above normal. The salinity above the entire shelf were low with generally low surface and subsurface temperatures. West of Fylla Bank a clear cold Polar Water core was observed, which had very low temperature and salinity. The core is still clear further north west of "Sukkertop Banke" and "Store Hellefiskebanke". All together this suggest above normal presence of Polar Water.

1. Introduction to the west Greenland oceanography

This report describe the hydrographic conditions in West Greenland Waters in 2008 from Cape Farewell in the southeastern Labrador Sea northward to Upernavik in the Western Baffin Bay (Figure 1). After describing data and methods, the atmospheric conditions are described, then the oceanographic conditions and finally fjord observations are presented.

The ocean currents around Greenland are part of the cyclonic sub-polar gyre circulation of the North Atlantic and the Arctic region. The bottom topography plays an important role for guiding the circulation and for the distributing the water masses. Consequently, the strongest currents are found over the continental slope.

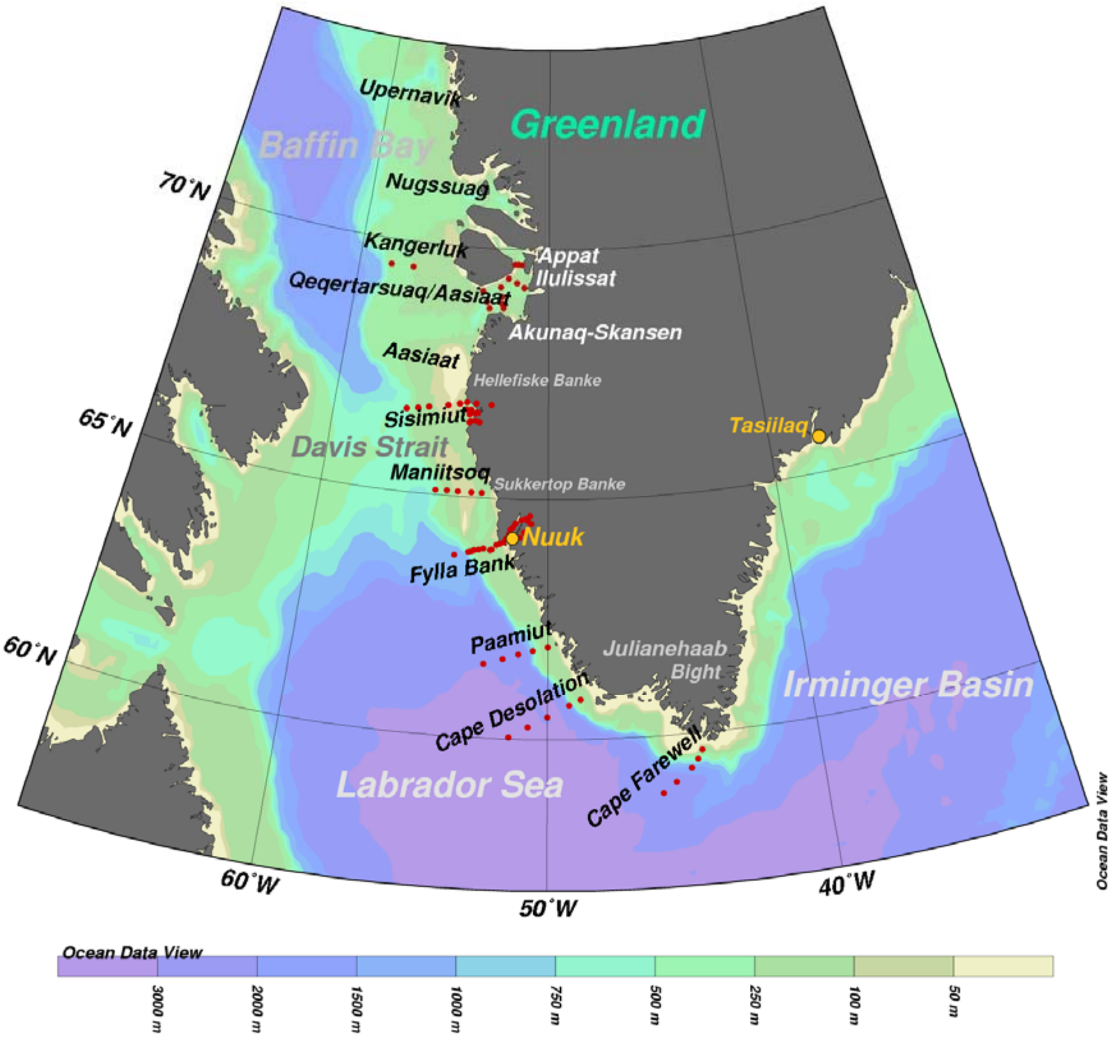

Figure 1. Position of the oceanographic sections off West Greenland where measurements were preformed in 2008 except ECOGREEN stations done onboard R/V DANA (Figure 6). The fjord sections at Sisimiut and Godthaabsfjorden are shown in Figure 4 and Figure 5. Contours shown for water depths in colours. Map produced using Ocean Data View (Schlitzer, 2007).

The surface circulation off West Greenland is dominated by the north going West Greenland Current. It is primarily composed of cold low-saline Polar Water (PW) of the Arctic region and the temperate saline Irminger Water (IW) of the Atlantic Ocean. At intermediate depths Labrador Sea Water is found, and at the bottom overflow water from the Nordic Seas are found. Only the surface circulation will be handled in this report.

The watermass characteristics in the West Greenland Current are formed in the western Irminger Basin where the East Greenland Current and the Irminger Current meets and flowing southward side by side. As they round Cape Farewell the IW subducts the PW (Figure 2b) forming the West Greenland Current (WGC). These water masses gradually mix along West Greenland, but IW can be traced all along the coast up to the northern parts of Baffin Bay (Buch, 1990). At Cape Farewell IW is found as a 500–800 m thick layer over the continental slope with a core at about 200–300 m depth. The depth of the core gradually decreases from east to west as seen in Figure 2b, whereas the depth gradually increases from south to north to below 400 m in the northern Davis Strait and Baffin Bay.

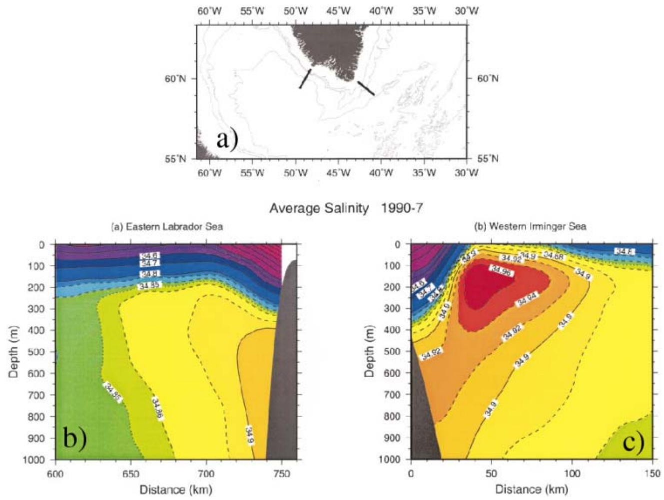

Figure 2. Mean upper-layer salinity sections for the period 1990–1997. a) Location of the two sections. Isobaths shown: 1000, 2000 and 3000 m. b) Eastern Labrador Basin. c) Western Irminger Basin. From Pickart et al. (2002).

Over the fishing banks off West Greenland a mixture of IW and PW dominates, as sketched in Figure 3. PW is continuously diluted by freshwater run-off from the numerous fjord systems. As the WGC reaches the latitude of Fylla Bank it branches. The main component turns westward and joins the Labrador Current on the Canadian side, while the other component continues northward through Davis Strait.

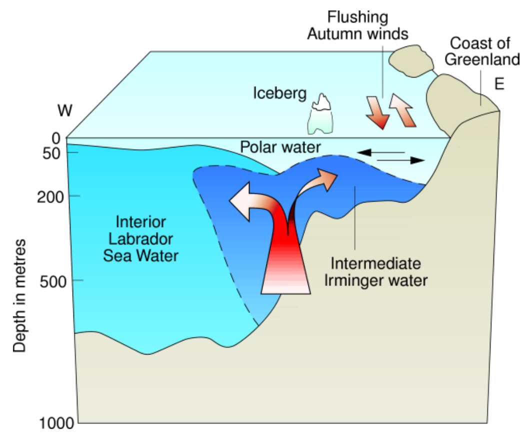

Figure 3. Sketch of the water masses off West Greenland in the Davis Strait region. From Valeur et al. (1997).

The tidal signal is significant. At West Greenland the strongest tidal signal is located close to Nuuk at 64°N. The tides are primarily semidiurnal with large difference between neap and spring (1.5 m versus 4.6 m at Nuuk, Buch, 2002). The interaction between the complicated topography and the strong tidal currents gives rise to a residual anticyclonic circulation around the banks in the Davis Strait area (Ribergaard et al., 2004).

Sea-ice is important in Greenlandic Waters. The West Greenland area is mainly dominated by 2 types of sea-ice. “Storis” is multi year ice transported from the Arctic Ocean through Fram Strait by the East Greenland Current to Cape Farewell, where it continues northward by the West Greenland Current. “Vestice” is first-year ice formed in the Baffin Bay, Davis Strait, and western part of the Labrador Sea during winter.

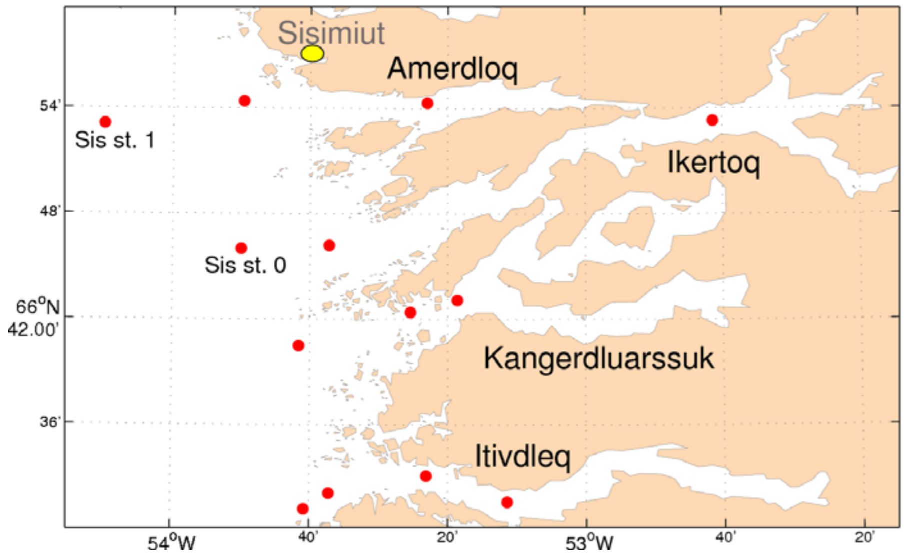

Figure 4. Position of the oceanographic stations around Sisimiut where measurements were preformed in 2008. See Figure 1 for position of all sections measured in 2008.

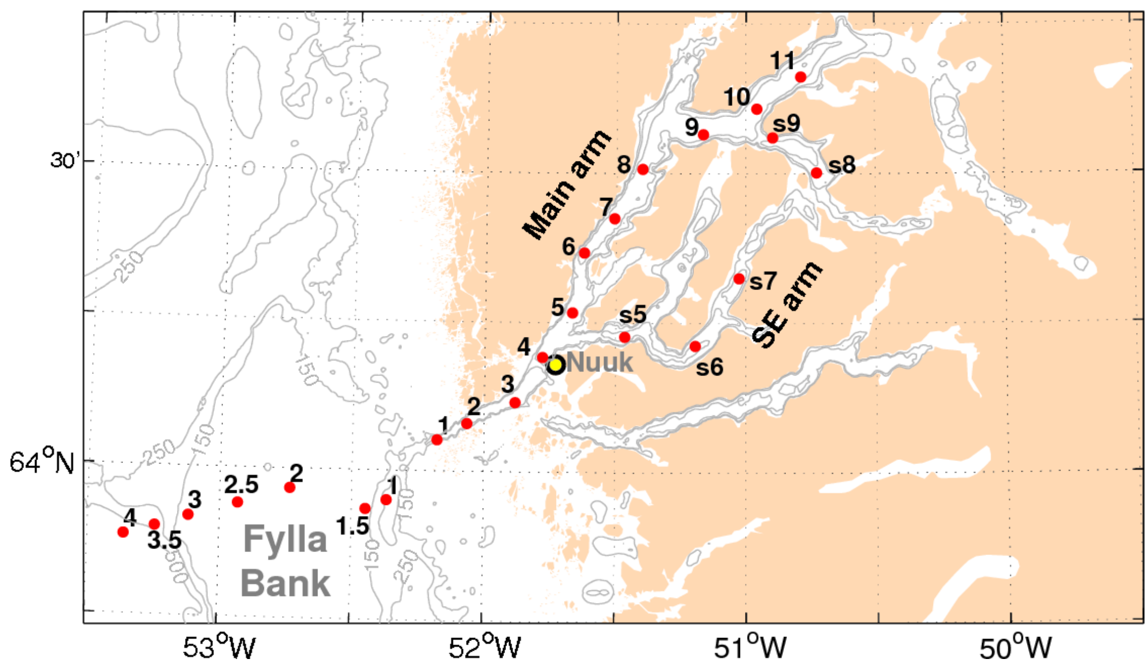

Figure 5. Position of the oceanographic stations in Godthaab Fjord and Fylla Bank where measurements were preformed in 2008 onboard I/K TULUGAQ. The numbers refeer to standard station numbers as shown in Figure 37. See Figure 1 for position of all sections measured in 2008.

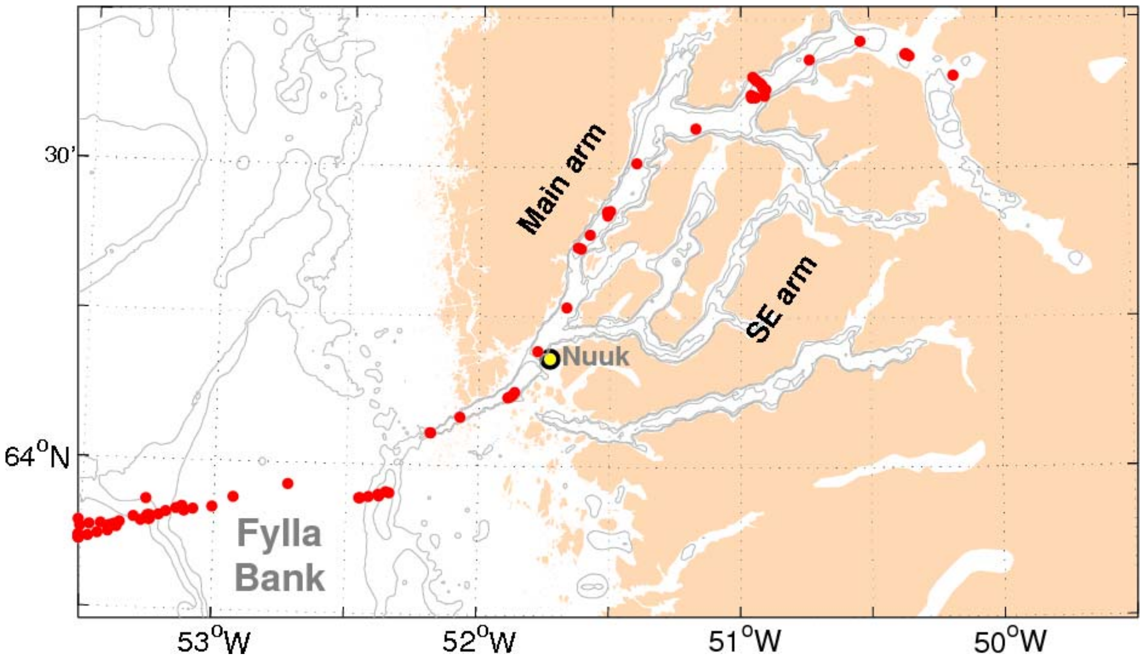

Figure 6. Position of the oceanographic stations in Godthaab Fjord and Fylla Bank where measurements were preformed in 2008 onboard R/V DANA. The data are not presented in this report.

2. Measurements

The 2008 cruise was carried out according to the agreement between the Greenland Institute of Natural Resources (GINR) and Danish Meteorological Institute (DMI) during the period June 13–23, 2008 onboard the Danish naval ship "I/K TULIGAQ"**.** Observations were carried out on the following standard stations (Figure 1):

Offshore Labrador Sea/Davis Strait:

- Cape Farewell St. 1–5
- Cape Desolation St. 1–5
- Paamiut St. 1–5
- Fylla Bank St. 1–5
- Maniitsoq St. 1–5
- Sisimiut St. 1–5 and St. 0

Fjords around Sisimiut (Figure 4):

- Amerdloq St. 2, 4
- Ikertoq St. 1, 4
- Kangerdluarssuk St. 1–3
- Itivdleq St. 1–4

Godthaab Fjord (Figure 5):

- Godthaab Fjord St. 1–11
- Godthaab Fjord south St. 5–9

Additional stations on Fylla Bank Section:

- Fylla Bank St. 1.5, 2.5, 3.5

On each station the vertical distributions of temperature and salinity was measured from surface to bottom, except on stations with depths greater than 750 m, where approximately 750 m was the maximum depth of observation. At Fylla Bank and Godthaab stations additional parameters were measured (Oxygen, Florescence, Irradiance).

Multi-year-ice (”Storis”) was presence on the innermost stations to the south and “Vestice” (first-year ice) was meet on the outermost station on the Sisimiut section (Figure 7). Nevertheless, all planned stations was occupied, expect Cape Farewell st.1, which was taken off position by about 5 nm but on the shelf.

During the period July 1–30, 2008 the Greenland Institute of Natural Resources carried out trawl survey from Sisimiut to the Disko Bay area and further North onboard “R/V PAAMIUT”. During this survey CTD measurements were carried out on the following standard stations (Figure 1):

Offshore Davis Strait/Baffin Bay:

- Sisimiut St. 1-5
- Kangerluk (Disko fjord) St. 3–4

Disko Bay:

- Qeqertarsuaq–Aasiaat (Godhavn–Egedesminde) St. 1, 3−4
- Skansen–Akunaq St. 1–4
- Ilulissat (Skansen–Jakobshavn) St. 1–3
- Appat (Arveprinsens Ejlande) St. 1–3

During the period July, 23th – August, 4th, additional 84 hydrographic measurements were done onboard R/V DANA at Fylla Bank and within Godthaabsfjorden. Besides salinity and temperature additional parameters were measured (Oxygen, Fluorescence, Irradiance). The cruise were part of the Danish IPY project ECOGREEN (Ecosystem West Greenland). These data are not presented in this report.

3. Data handling

Measurements of the vertical distribution of temperature and salinity were carried out using a SEABIRD SBE 9-01 CTD except for the Fylla Bank section and Godthaab Fjord, where a SEABIRD SBE 19plus was used. All sensors were newly calibrated in 2008. On the R/V DANA cruise two SEABIRD SBE 9-11 CTD’s were used.

For the purpose of calibration of the salinity measurements of the CTD, water samples were taken at great depth on stations with depths greater than 500 m or below sill depth in fjords. The water samples were after the cruise analysed on a Guildline Portosal 8410 salinometer.

The CTD data were analysed using SBE Data Processing version 5.37d software provided by SEABIRD (www.seabird.com). Onboard the SBE 9-01 data was uploaded using term17 in SEASOFT version 4.249 (for DOS) provided by SEABIRD. For uploading SBE 19plus and SBE 9-11 data, the SEABIRD program Seasave (for windows) was used.

All quality-controlled data are stored at the Danish Meteorological Institute from where copies have been sent to ICES and via ICES to MEDS. Data are also stored at Greenland Institute of Natural Resources.

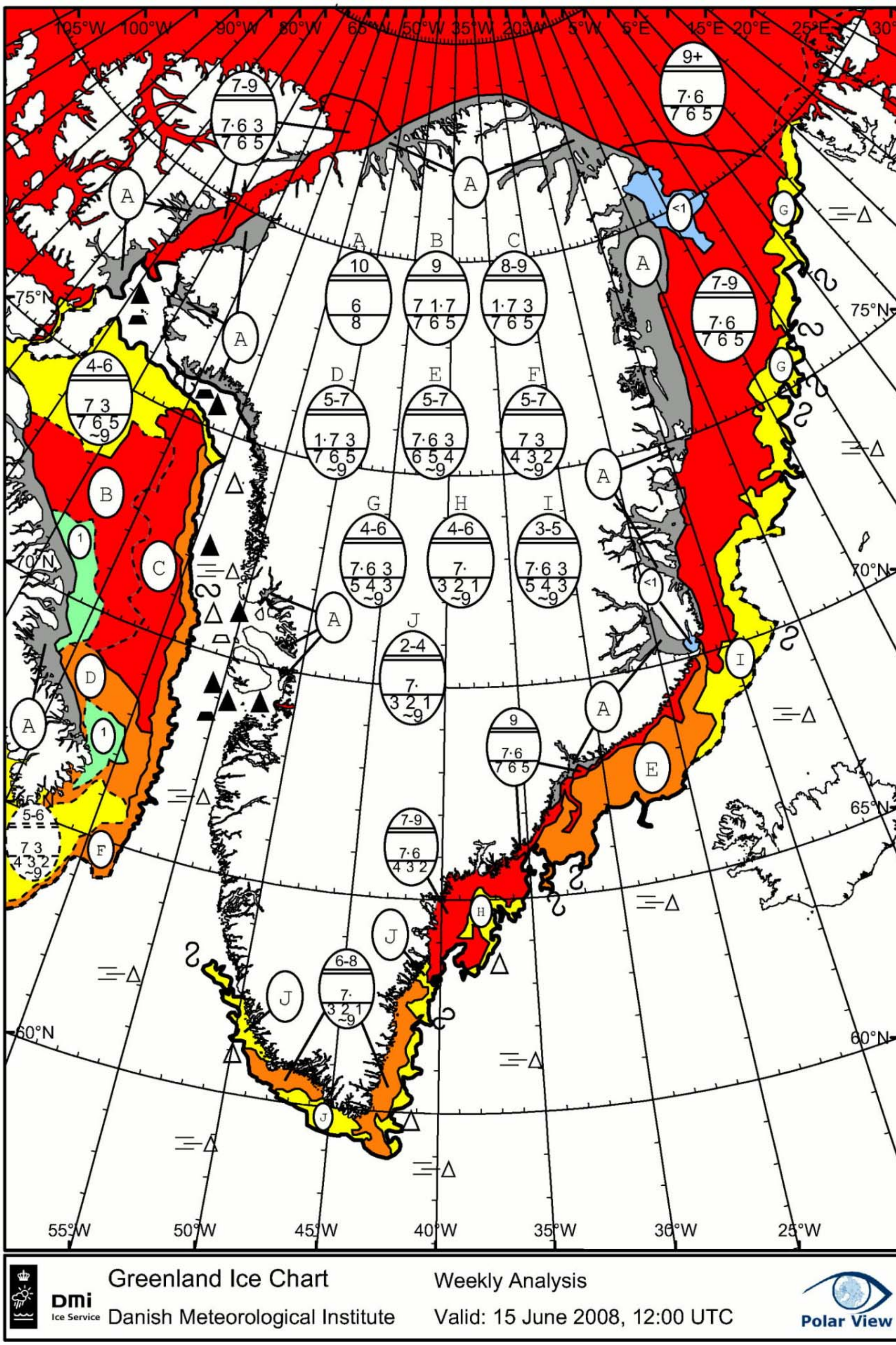

Figure 7. Distribution of sea ice in Greenland Waters valid for 15. June 2008.

Atmospheric conditions in 2008

The North Atlantic marine climate is to some extend controlled by the so-called North Atlantic Oscillation (NAO), which is a measure of the strength of the westerlies driven by the pressure difference between the Azores High and the Iceland Low pressure cells. We use wintertime (December–March) sea level pressure (SLP) difference between Ponta Delgada, Azores, and Reykjavik, Iceland, and subtract the mean SLP difference for the period 1961–1990 to construct the NAO anomaly. The winter NAO index during winter 2008/09 was positive[1] (Figure 2) and among the 15% highest observed in the past 143 years. The Icelandic Low was during the winter months (December–Marts) centred over the northern Irminger Basin (Figure 9), which is close to normal position (Figure 10). Both the Icelandic Low and the Azores High was strengthen (Figure 10) resulting in an increased pressure difference over the North Atlantic sector compared to normal conditions.

The pressure difference has the effect that the westerlies over the North Atlantic Ocean was strengthened with anomalous[2] winds towards west centred in a belt across the North Atlantic from the Labrador Sea/Davis Strait to the North Sea (Figure 12). Over the East Greenland shelf, especially between Jan Mayen and Greenland, the mean wind direction was towards south (Figure 11). Over the Labrador/Davis Strait area, the wind anomaly was increased significantly, i.e. strengthened/intensified winds from Canada onto the ocean. These cold and dry airmasses from the Canadian landmasses play a central role in the extensive formation and coverage of first-year-ice (“westice”) during winter 2007/2008 (Figure 7 and Våge et al., 2009).

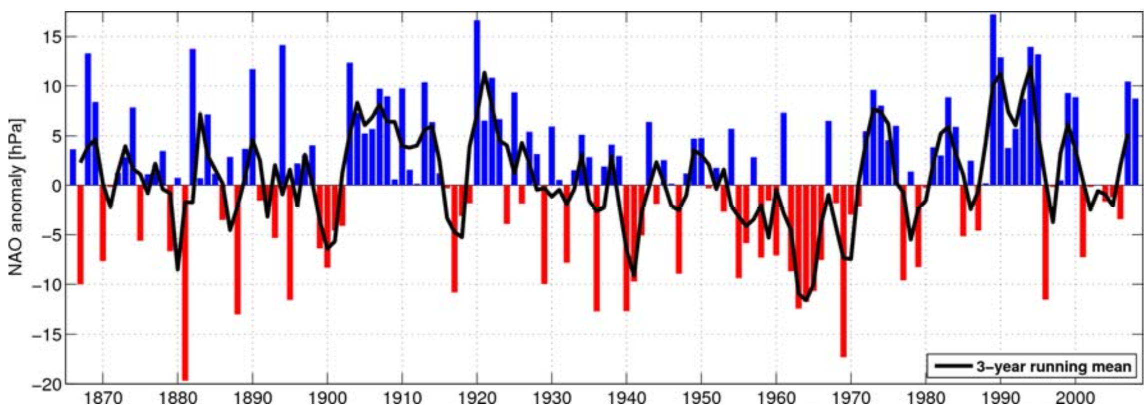

Figure 8. Time series of winter (December–March) index of the NAO from 1865/1866–2008/2009. The heavy solid line represents the NAO index smoothed with a 3-year running mean filter to remove fluctuations with periods less than 3 years. In the figure the winter 1865/1866 is labelled 1866 etc.. The mean and standard deviation is 0.9 ± 7.3 hPa. Data updated, as described in Buch et al. (2004), from http://ww.cru.uea.ac.uk/cru/data/nao.htm.

West Greenland lies within the area which normally experiences cold conditions when the NAO index is positive. Nevertheless, as can be seen from Figure 13 the annual mean air temperature for 2008 in Nuuk[3] was -1.36°C which is close to average, despite of a positive NAO index. However it was 0.7°C colder than recent years. The mean annual air temperature for 2008 was only slightly above normal for almost the entire North Atlantic region including the southern Greenland with positive anomalies at about 0–1°C. However, north of Davis Strait and Denmark Strait higher positive anomalies of about 1–2°C were found (Figure 14).

Sea surface temperatures in West Greenland often follow those of the air temperatures, major exceptions are years with great salinity anomalies i.e. years with extraordinary presence of Polar Water. In 2008 the mean temperature (1.64ºC) and salinity (33.09) on top of Fylla Bank in the middle of June was below normal conditions – especially the salinity was low (Figure 15 and Table 1), despite air temperatures in Nuuk and Tasiilaq was slightly higher than average (Figure 13) suggesting higher than normal presence of Polar Water in 2008.

[1] The NAO index using December − February was also positive.
[2] Anomaly defined as the difference from normal conditions relative to the period 1968–1996.
[3] Nuuk temperature for October 2007 and November 2008 was taken from the Nuuk airport synop station 04254 due to failure on the instrument on synop station 04250 (Nuuk) for more than half of the months.

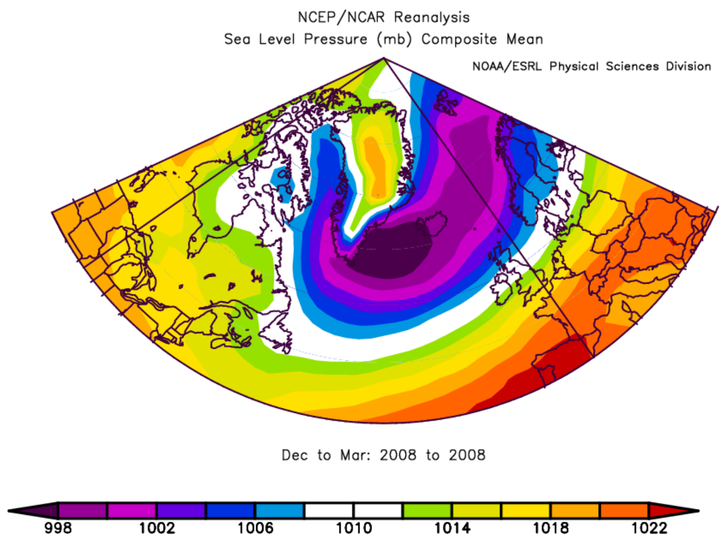

Figure 9. Winter (DJFM) sea level pressure for 2007/2008 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

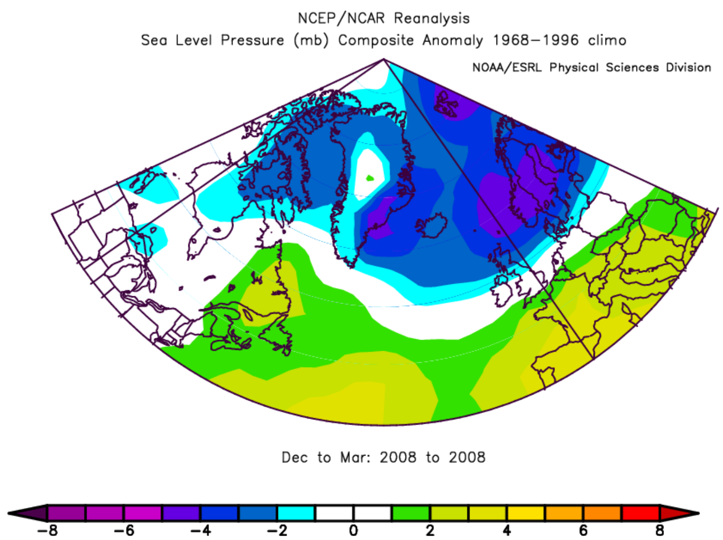

Figure 10. Winter (DJFM) sea level pressure anomaly for 2007/2008 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

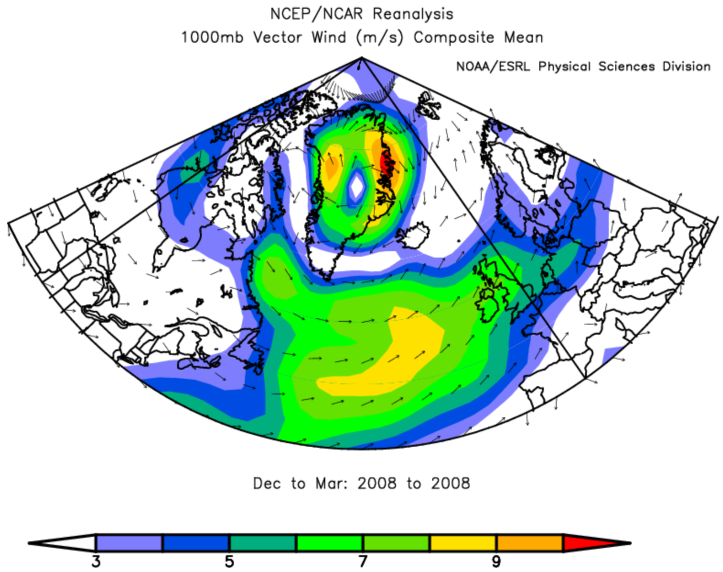

Figure 11. Winter (DJFM) wind for 2007/2008 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

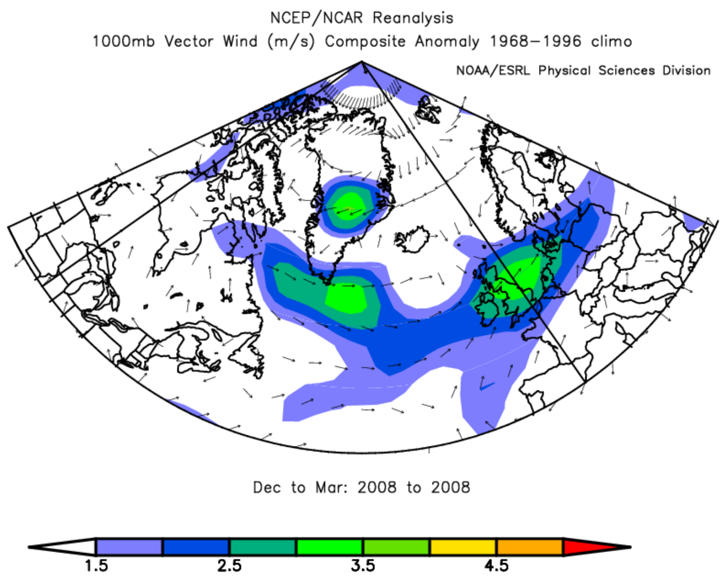

Figure 12. Winter (DJFM) wind anomaly for 2007/2008 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

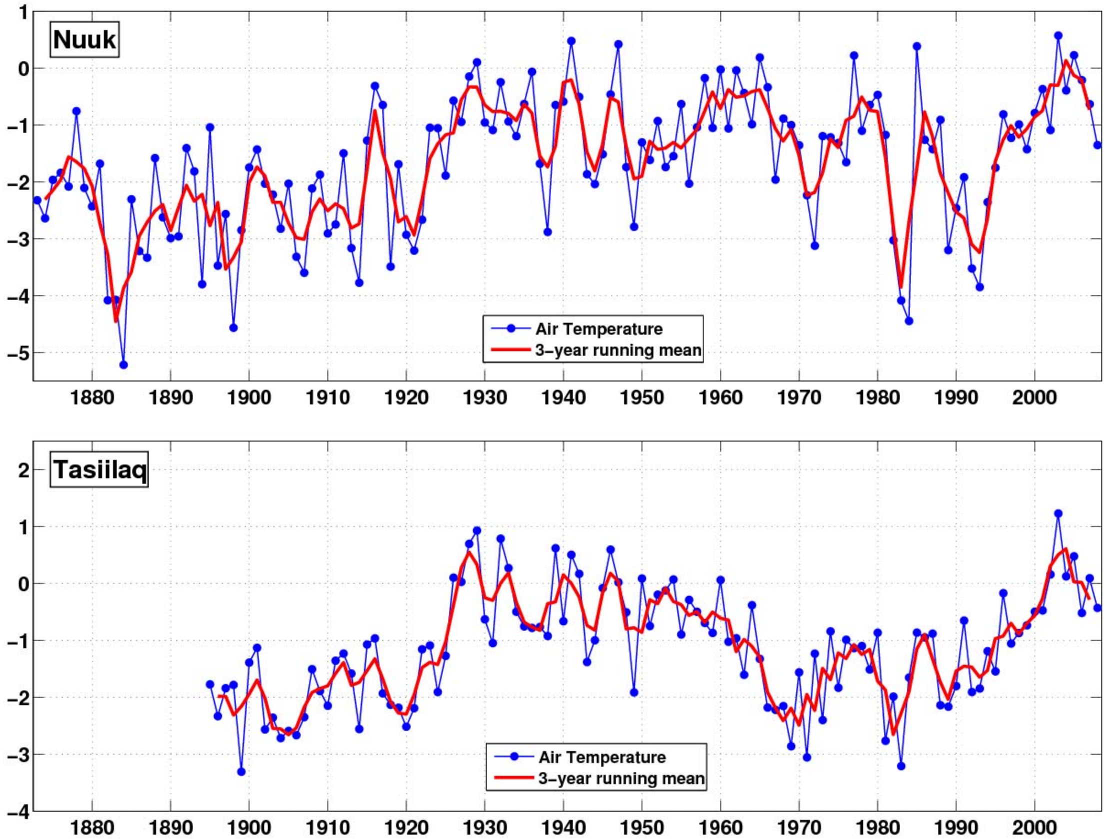

Figure 13. Annual mean air temperature observed at Nuuk and Tasiilaq for the period 1873–2008. The mean and standard deviation is -1.68 ± 1.21 °C for Nuuk and -1.14 ± 0.99 °C for Tasiilaq. Nuuk temperature for October 2007 and November 2008 was taken from the Nuuk airport synop station 04254 due to a failure on the instrument (synop 04250) for more than half of the respective months.

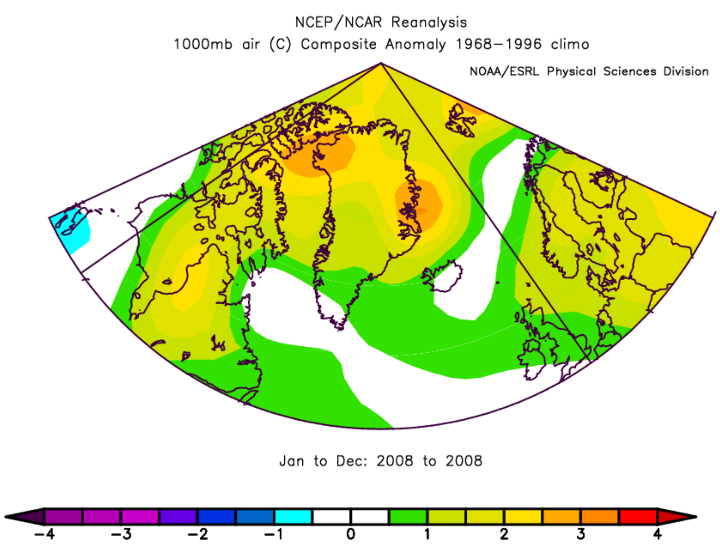

Figure 14. Anomalies of the mean air temperature for 2008 in the North Atlantic region. NCEP/NCAR re-analysis (from http://www.cdc.noaa.gov).

Table 1. Statistics for potential temperature and salinity Fylla Bank st. 2. The timeseries are corrected for annual variations in order to get the temperature in mid-June. Smed data are not included for the statistics.

Fylla Bank St. 2	Temperature [°C] Mean ± std	Salinity Mean ± std	2008 Tpot	2008 S
0–40 m	1.78 ± 0.75°C	33.40 ± 0.25	1.64°C	33.09

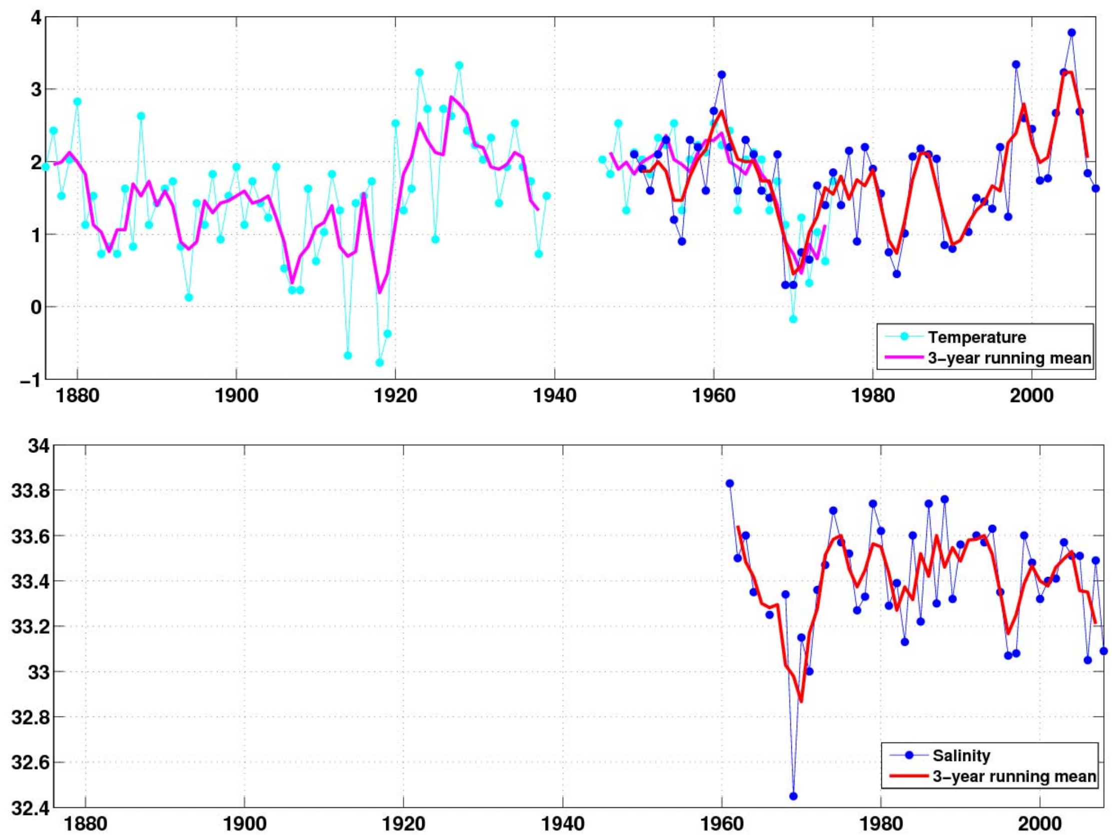

Figure 15. Timeseries of mean temperature (top) and mean salinity (bottom) on top of Fylla Bank (0–40 m) in the middle of June for the period 1950–2008. The red curve is the 3 year running mean value. Statistics is shown in Table 1. The timeseries for temperature (top, magenta/purple) is extended back to 1875 using Smed-data for area A1 (Smed, 1978). See Ribergaard et al. (2008) for details.

4. Oceanographic conditions off West Greenland in 2008

The surface temperatures and salinities observed during the 2008 cruise are shown in Figure 16. The cold and low salinity conditions observed close to the coast off Southwest Greenland reflect the Polar Water carried to the area by the East Greenland Current. Water of Atlantic origin (T>3^{o}C; S>34.5) is normally found at the surface at the three outermost stations on the Cape Farewell and Cape Desolation sections (Figure 25 and Figure 26). The salinities was lower than normal and the extension of multi-year-ice ("Storis") and especially first-year-ice in the Baffin Bay/Davis Strait ("Vestice") was higher than normal. During early 2008 they even meet at about the latitude of Nuuk, which is seldom observed. Last time this happened was in the early 1990s.

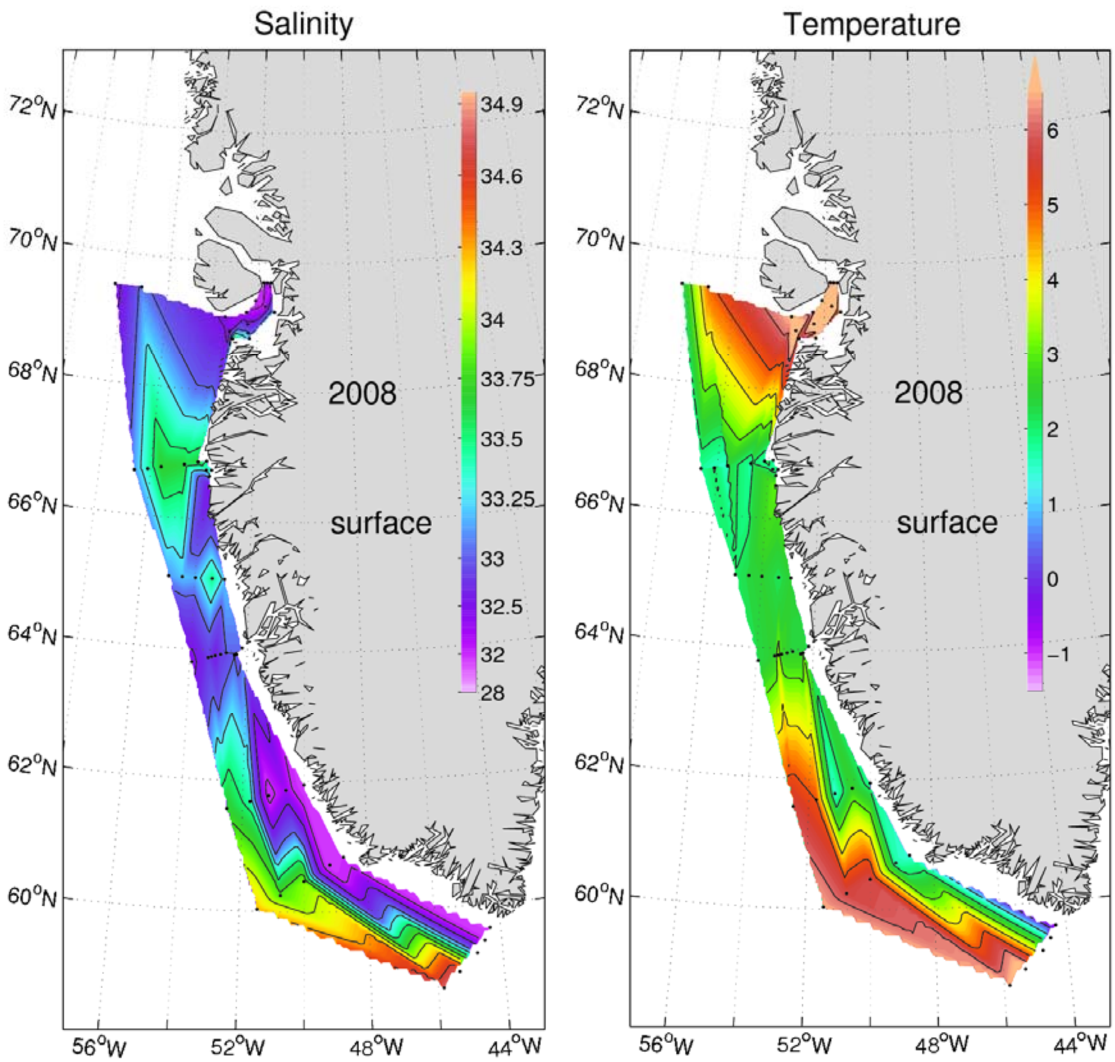

Figure 16. Salinity (left) and temperature (right) observed in 2008 at the surface (mostly 2–6 m). The data are all from June (south of Sisimiut) and June/July (north of Sisimiut).

In the Baffin Bay the low surface salinities, generally below 33, originate from the large outlet glaciers but also from melting of sea-ice during summer. Highest salinities of about 33.5–34 reflect the core of the West Greenland Current, which is slightly modified by Atlantic Water. The warm surface waters in and around the Disko Bay was caused by solar heating of the 20–30 m thin low-saline surface layer. Therefore it is not seen at 34 m, but only at the surface. The cold waters <0°C observed offshore in the subsurface of the Baffin Bay (Figure 17) is the top of the layer of previous winter convected waters. Above (Figure 16), a thin low-saline surface layer is found formed by melting of sea-ice. This layer is heated due to solar radiation.

A vertical section of salinity, temperature and density over the shelf break from Cape Farewell to Sisimiut is shown in Figure 23 and over the shelf in Figure 24. The vertical distribution of temperature, salinity and density at sections along the West Greenland coastline is shown in Figure 25 – Figure 32 and within the Disko Bay in Figure 33 – Figure 36.

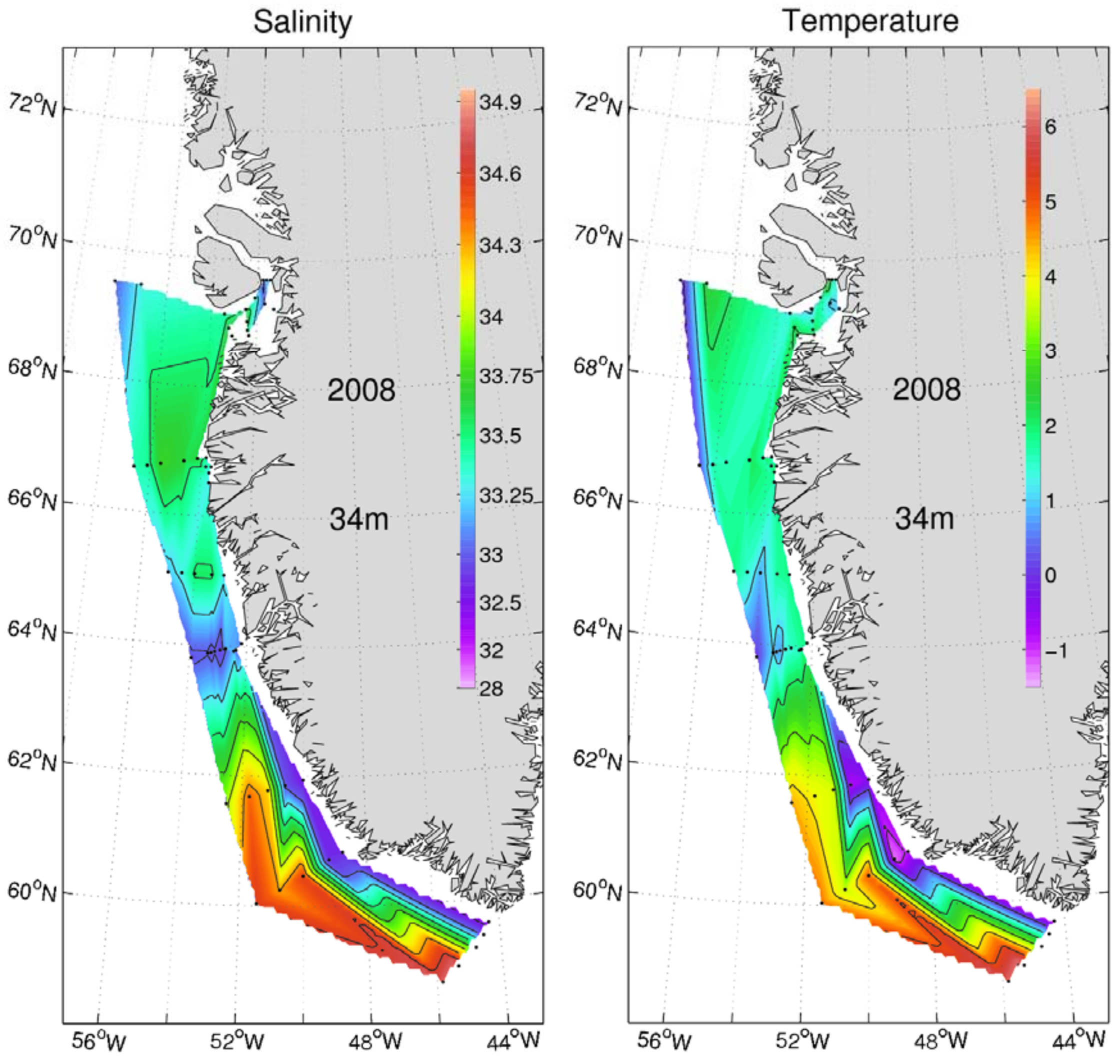

Figure 17. As Figure 16, but for 34 m depth.

At intermediate depths pure Irminger Water (T ≥ 4.5°C; S ≥ 34.95) was traced north to the Paamiut section. Modified Irminger Water (T ≥ 3.5°C ; 34.88 ≤ S < 34.95) was observed all the way north to Sisimiut section. The northward extension of Irminger Water may indicate intensified inflow of water of Atlantic origin to the West Greenland area. The temperature of the Irminger Water was in general higher than normal but not as pronounced as in 2007 (Ribergaard et al., 2008) . As the Irminger Water is not in direct contact with the atmosphere in West Greenland waters, local heat gain is not a likely explanation, instead elevated temperatures may be linked to the recent maximum of heat in the North Atlantic currents feeding the Irminger current (Holliday et al 2008) in addition to slightly warmer air temperatures than normal over the North Atlantic (Figure 14).

The average salinity and temperature at 400–600 m depth west of Fylla Bank (st. 4), which is where the core of the Irminger Water normally is found, is shown in Figure 18 (red curves). The temperature of this layer was 4.31°C which is only 0.15°C higher than normal and the average salinity of 34.84 was above normal by 0.03 (Table 2). Temperatures and salinities above normal may indicate, that the presence of Irminger Water was higher than normal, which is also seen in the heat transport calculated by Myers et al. (2009).

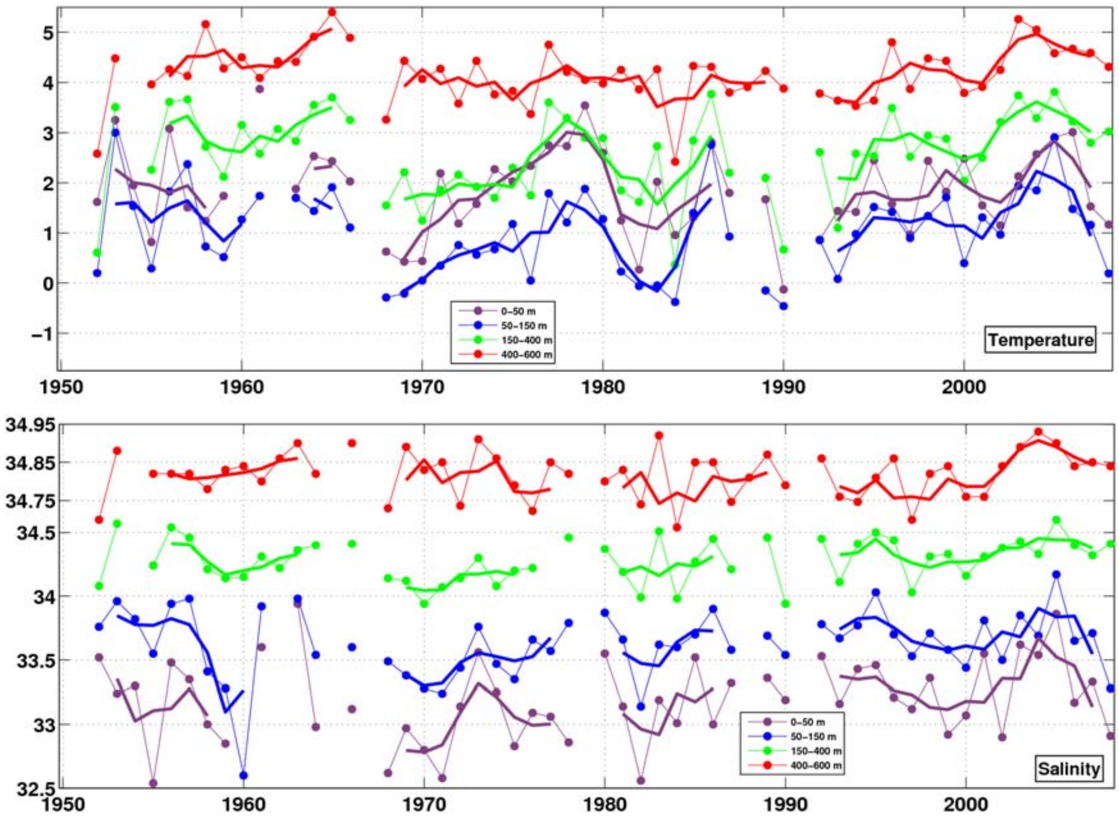

Figure 18. Timeseries of mean June-July temperature (top) and salinity (bottom) for the period 1950–2008 averaged in four different depth intervals west of Fylla Bank (st.4) over the continental slope. Thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics are shown in Table 2.

Table 2. Statistics for potential temperature and salinity at Fylla Bank st. 4. and values for 2008.

Fylla Bank St.4	Temperature [°C]	Salinity	2008	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.85 ± 0.86°C	33.19 ± 0.32	1.17°C	32.91
50–150 m	1.02 ± 0.85°C	33.63 ± 0.27	0.19°C	33.28
150–400 m	2.57 ± 0.85°C	34.28 ± 0.17	3.02°C	34.41
400–600 m	4.17 ± 0.57°C	34.81 ± 0.08	4.31°C	34.84

Similar timeseries west of the banks for further north at Maniitsoq st.5 (Figure 20) and Sisimiut st.5 (Figure 21) confirm, that the Irminger Water component of the West Greenland Current still brings heat and salt to the area. Temperatures and salinities measured in 400–600 m was high at both Sisimiut and Maniitsoq. However, contrary the Fylla Bank st.4 (Figure 18), Maniitsoq st.5 and Sisimiut st.5 are only regular measured since 1970, while the former "warm period" in the 1950s–1960s is only sporadically measured. Consequently the statistical means are less certain. Similar, high bottom temperature are seen within the Disko Bay at a location just outsite Ilulissat ("Jakobshavn") at station Skansen-Ilulissat st.3 (SJA3), updated from Holland et al. (2008), whereas the salinity was just above normal. However, the timeseries are quite short compared to the three above mentioned timeseries.

The bottom salinities and temperatures in 400–600 m at Maniitsoq st.5 and Sisimiut st.5 was higher than observed further south at Fylla Bank st.4. This was also the case in 2007 (Ribergaard et al., 2008). As the warm and saline water can only enter from south, the bottom waters at Sisimiut and Maniitsoq is likely waters from former years. The maximum could thereby be a remaining of former years maximum presence of Irminger Water.

In general, the surface salinity over the shelf was low and the multi-year-ice "Storis" was present off the southeast coast of Greenland extending well north of the Julianehaab Bight (Figure 7) both indicating higher than normal presence of Polar Water.

In 2008, a well defined core of Polar Water, revealed by its low temperature, was observed west of Fylla Bank at 50–150 m depth. It was much more pronounced than in 2003–2005 (Ribergaard and Buch, 2004; Ribergaard and Buch, 2005; Ribergaard, 2006) and even more pronounced than in 2006 and 2007 (Ribergaard, 2007; Ribergaard et al., 2008). The Polar Water core was also remarkably well defined on both the Maniitsoq and Sisimiut section indicating high presence of Polar Water.

At the outermost station (st.5) of Sisimiut, very low salinities were observed in the surface due to melting of the sea-ice, which was present at station, and the temperature of the top 100 m was below 0°C. This water is most likely Polar Water transported southward by the Baffin Current, as indicated by the slope of the isopycnals.

At the Disko fjord ("Kangerluk") offshore section, a distinct Polar Water core was absent. Instead a colder layer was found with temperatures below 1°C (below -1°C at its core) centeed at depth at about 75 m. This layer was most likely formed during winter by convection. Brine rejection increases the low surface (0–50 m) salinities, so it can overcome the strong upper halocline which is created during summer by melting of sea-ice and run-off of fresh water from land. The top of this layer can be seen in Figure 17. Below the cold subsurface layer, a relative warm (> 3°C) watermass was found below 150–200 m. This water is the extension of the Irminger Water component of the West Greenland Current.

West of Fylla Bank (st.4, Figure 18), the temperature and salinity was above normal in both the interval 150-400 m and below 400 m (Table 2). Contrary, above 150 m depth, both the salinity and temperature was much lower than normal. Generally, the same conditions is seen further to the northwest, off the "Sukkertop banke" and "Store Hellefiskebanke" (Figure 20 and Figure 21), with high salinities and temperatures observed at the bottom and low salinities and temperatures in the upper 150 m, i.e. a larger vertical gradient than normal. This suggest higher than normal presence of both Irminger Water and Polar Water. The extraordinary low salinity and surface temperatures in the surface mixed layer (0–50 m) at Sisimiut st.5 in June (Figure 30) could also be explained by the presence or nearby presence of west-ice and are not seen in July (Figure 31)

Surface temperatures below normal despite of anomalous positive air temperatures over the Davis Strait (Figure 14) and low temperatures in the core of the Polar Water indicates above normal presence of Polar Water. The presence of both multi-year-ice and west-ice (Figure 7) likely also has the effect, that the surface temperatures remain lower than normal.

Noticeably, since the mid-1990s, the temperature west of and on top of Fylla bank seems to be relative warm without sudden particular cold periods as has happen in the late 1960s, the early 1980s and the early 1990s (Figure 15 and Figure 18). Likewise, since the early 2000s, the mean salinity at 400–600 m depth west has increased which may indicate increased strength of the Irminger Current as suggested by Ribergaard (2004). Similar high property values are observed further northwest of "Sukkertop banke" and "Store Hellefiskebanke", with the two exceptions, that relative cold surface waters is also observed in the late 1990s and the increase in temperature are more gradually during the late 1990s and remains high in the 2000s below 150m (Figure 20 and Figure 21). Using more advanced analytical methods, Myers et al. (2007, 2009) also reported increased strength of the Irminger Water component on the Cape Farewell, Cape Desolation and Paamiut sections, which is likely linked to the North Atlantic subpolar gyre circulation (Hátún et al., 2005). Similar findings was also reported by Stein (2005). Not surprisingly, similar increase in salinity and temperature are observed in the Atlantic Water in the eastern North Atlantic and the Nordic Seas (Holliday et al., 2008), suggesting that the recent changes in the Irminger Water property is an outcome of changes in the circulation in the North Atlantic subpolar gyre circulation.

For a more comprehensive study of the hydrographic conditions off West Greenland, the reader is refereed to the work done by Myers et al. (2009, 2007). They calculated volume, heat and fresh water transport for the 6 southern sections for the time period up to 2008. They also concluded, that the inflow of Polar Water was high in 2008 and that the heat transported to the area within the Irminger Water is still high.

As earlier noted, the extension of particular "Westice" in the Baffin Bay, Davis Strait and Northern Labrador Sea were much higher than normal in winter 2007/2008. This was partly due to wind anomaly from Canadian over the Labrador

Sea (Figure 12), which contributed to the intensive formation of "vest ice" (Våge et al., 2009). Moreover, surface water temperatures on the northern sections were also low in 2007 (Ribergaard et al., 2008). Thereby the surface waters were "preconditioned" for local sea-ice formation which also likely have contributed to the extraordinary formation and extension of "Westice".

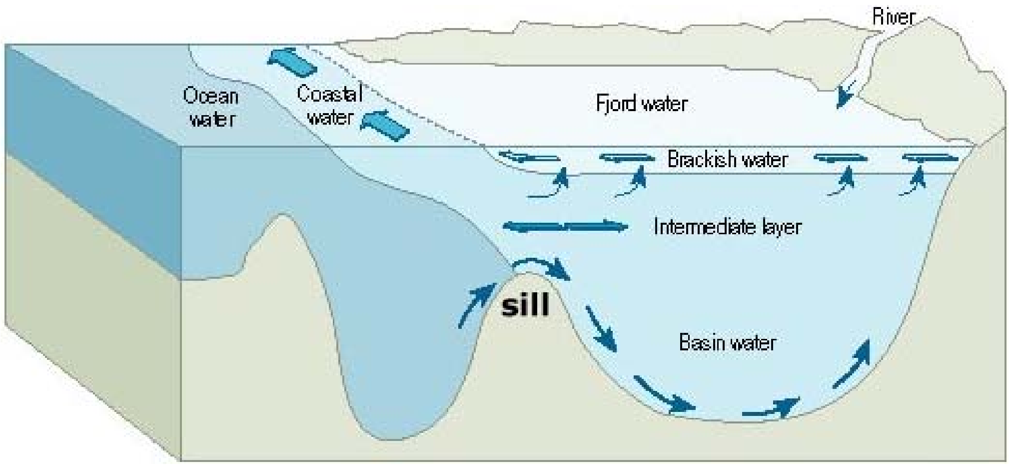

Figure 19. Sketch of the circulation in a fjord (modified from AMAP Assessment Report: Arctic Pollution Issues, Figure 3.20, http://www.amap.no/maps-gra/show.cfm?figureId=58).

West Greenland fjords 2008

The hydrography in fjords is to a large extent determined by the land runoff of fresh water in the surface and at the inflow near the bottom at the mouth of the fjord (see Figure 19). Often fjords have a sill at the opening to the open ocean and it is the depth of this sill that determinate which watermasses are allowed to enter near the bottom. Above sill depth water can freely flow either in or out of the fjord. At the surface the current are often directed out of the fjord caused by the runoff of fresh water, which on average cause a slight increase in the sea level towards the head of the fjord. Thereby a pressure gradient is established and surface water will flow out of the fjord. This surface water will entrain water from below and to compensate for this entrainment, inflow is taking place at the bottom as sketched in Figure 19. Besides, West Greenland fjords experience a large tidal signal which cause extensive vertical mixing and significant horizontal ventilation which by far dominate the fluxes of freshwater to the fjords over shorter timescales.

Most fjords in West Greenland are sill fjords i.e. resulting in strong limitations of the exchange of water between the deeper parts of the fjord and the open ocean. Mainly three different watermasses can be found in the West Greenlandic fjords:

- Relative warm and saline waters of Atlantic origin (mixed Irminger Water).
- Cold and relative fresh water of polar origin (mixed Polar Water).
- Fresh surface water from land, either as melting of the Greenland Ice Sheet or from precipitation (surface water).

The flux of fresh surface water from land is highly variable on a seasonal scale. When exported out of the fjords, this brackish water is mixed with the surrounding surface waters, which is Polar Water. Mixing continues along the coast, and the watermass stays close to the coast. In the following this water is named Coastal Polar Water.

4.1. Godthaabsfjorden

Godthaabsfjorden (Nuuk fjord) were measured twice in 2008, however only shown once for June (Figure 37, Figure 5). The fjord system has a sill depth of about 200 m close to Godthaabsfjord station GF1. Another major sill exists northwest of Nuuk town just offshore station GF4. Between these two sills the water depth is about 400 m in a narrow channel. Strong tidal forcing mix the water column especially inshore station GF2, which can be seen in especially the temperature profiles but also the salinity profiles, where the isolines becomes almost vertical.

The main fjord system consists of three “arms”. Within these arms, several of “sub-sills” exists, as a result of the movement of the glacier back in time. The northwestern arm (“main arm”) is the deepest of more than 600 m with a sub-sill just offshore station GF6 of 350 m. The southestern arm is also deep in the outermost part, but between Godthaabfjord station GFs6 and GFs9 the bottom raise to about 350 m which efficient reject the deepest water to enter the inner part though that arm. This can be seen by following the isopycnal $\sigma_0 = 26.8$ kg/m^3 and isohaline 33.5. Note, that the densest water is actually found in the northeast arm (“main arm”), even in the offshore part of the arms. The middle arm is shallower especially at its inner part and no deep waters are allowed to pass.

The inner part of the fjord (st.10−st.11 and further inside) ends in a floating glacier and some side braches which supply the surface layers with a significant amount of fresh water and ice growlers. This fresh water supply set up a horizontal pressure gradient along the fjord which is a main driver of the general fjord circulation.

The deep sills (200m/250m) permit “warmer” water masses to enter the fjord, which is part of the reason for ice-free conditions during wintertime except for the inner parts. The bottom water was about 1−2°C and has salinities of about 33.55−33.60 - warmest and most saline in the inner part (st.10−13). This water is partly a mixture of Atlantic origin (Irminger Water) and Polar Water that enter the fjord from outside through the Fylla Bank Channel. Maximum temperature in the bottom water is found in the depth interval of about 300−400 m with decreasing temperatures towards the bottom.

4.2. Fjords south of Sisimiut

Hydrographic data were obtained from four fjords around Sisimiut in 2008 (Figure 38–Figure 41). They represent two very different types of fjords: two with deep sills (Amerdloq, Ikertoq), one with shallow sills (Kangerdluarssuk). Itivdleq fjord has an intermediate sill depth, and somewhat confusing, this categorizes it as a fjord with a shallow sill, which however occasionally show properties resembling a fjord with a deep sill depth. None of the fjords are directly connected to the Greenland ice sheet, as can be seen directly on a topographic map, and so the fresh water supply added are limited to runoff from land.

In the deep sill fjords, Amerdloq and Ikertoq fjord (Figure 38 and Figure 39), the sill depth is about 150–180 m. These sill depths allow relative warm and saline waters of Atlantic origin to enter the fjords close to the bottom. The density of this bottom water is higher than the Coastal Polar Water above, even at the freezing point of the Coastal Polar Water. Thereby winter convection to the bottom is prevented unless driven by brine rejection during sea-ice formation. The bottom water up to about sill depth remains saline and “warm” (1-3°C, >2°C in 2008). Above sill depth the salinities are almost homogenous whereas the temperature is coldest just above the interface between the diluted Irminger Water and the Coastal Polar Water. This cold water could be a result of winter convection of Coastal Polar Water, or it is just the core of the Polar Water. Close to the surface a thin warm layer was found caused by the sun heating of runoff water from land.

Kangerdluarssuk fjord (Figure 40) can be considered as a fjord with shallow sill. Kangerdluarssuk fjord has a sill depth of about 50 m. The whole bottom layer below sill depth is filled with Coastal Polar Water and the salinity is very homogeneous. During winter the Coastal Polar Water are cooled and undergoes convection. As the water inside the fjord have homogenous salinities the whole water column are gradually cooled by winter convection and the water become totally homogenous (neutral stability). Therefore cold temperatures are measured below sill depth. The bottom temperature is below 0°C and the bottom salinity is around 33.4–33.6. The low salinity at depth indicates that the winter cooled water is actually Coastal Polar Water. At the surface relative warm water is found caused by the solar radiation during spring and summer. In the top a thin warm solar heated fresh water cap was found caused by runoff from land.

Itivdleq fjord (Figure 41) has a sill depth about 70–100 m, largely prohibit warm and saline water of Atlantic origin to enter the fjord. However, occasionally, the deep water is influenced by water from outside the fjord, which is denser and more saline than the water found in the fjord above sill depths. The bottom salinities are about 33.75 and temperatures below 1°C and often below 0°C (not in 2008). Increasing salinity with depth below sill depth indicates, that winter convection to the bottom has not taken place in the last few years. In 2007, the density of the bottom water was only marginally higher than the calculated density of the Coastal Polar Water found just above sill at its freezing point indicating, that the total heat loss during winter 2008 was almost enough to create deep convection (Ribergaard et al., 2008). However this was not the case in 2008, there deep convection was prohibited. This could be due to relative low surface salinities in the Surface Polar Water. In the top near the mouth of the fjord, a thin warm solar heated fresh water cap is found caused by runoff from land.

Figure 42 and Figure 43 shows the temporal evolution in the properties in the Amerdloq/Ikertoq fjords. Between 2003 and 2005 (no measurements in 2004) the bottom water has become slightly more saline (and denser) indicating increased influence of mixed Irminger Water. This is in agreement with the findings by Ribergaard and Buch (2005) showing record high salinities in 2004 west of Fylla Bank in 400–600m and with Ribergaard (2006) showing lower, but still high, salinities in 2005. From 2005 to 2006 the salinity (and density) decreased slightly, which is to be expected, as the sub-surface salinities in 2006 west of Fylla Bank was lower than in 2005 (Figure 18) indicating that no inflow right to the bottom has taken place since. However, in 2008 the bottom temperature has increased with maximum just below sill depth suggesting renewal of the upper bottom water during autumn/winter 2007/2008. Since 2007 a marked cold water tongue is seen close to the sill depth. This is most likely the remaining water from previous winter convection, as the cold waters are not seen outside the fjord (Figure 38 and Figure 39).

Bottom temperatures in the Kangerdluarssuk fjord has become colder and slightly less saline than previous years with coldest bottom temperatures in 2007 (Figure 44). This is likely due to a combination of colder atmospheric winter temperatures in 2007 and 2008 than previous years resulting in a larger surface heat flux. The slightly decrease in bottom salinity could be due to increased influence of Polar Water since 2006 (Ribergaard, 2007; Ribergaard et al., 2008) compared to earlier, leaving lightly fresher waters in the surface, which undergoes convection during winter.

Itivdleq fjord was only observed in 2005−2008 (Figure 45). The bottom salinity has become less saline and the density has decreased throughout the water-column below sill depth and the temperature has become colder. In 2008 the bottom waters has again become only slightly more saline but also slightly warmer and less dense below sill depth. The lower salinities in 2007 and 2008 compared to earlier is a sign of increased influence of Polar Water.

Conclusions

Atmospheric and oceanographic conditions off West Greenland during the summer 2008 were characterised by:

- Positive NAO index.
- Strengthen westerlies over the North Atlantic.
- Increased wind anomaly from Canadian over the Labrador Sea, which contributed to the intensive formation of “Westice” during winter 2007/2008 (Våge et al., 2009). Besides surface water temperatures on the northern sections were also low in 2007 (Ribergaard et al., 2008) which probably also play a role for the intensified local sea-ice formation.
- Air temperatures over most of the North Atlantic sector was only about 0–1°C warmer than normal.
- Mean annual air temperature in Nuuk was close to normal.
- Water temperature on top of Fylla Bank was slightly below average in June whereas the salinity was very low.
- Above normal presence of Polar Water and Irminger Water indicated by:
    - Above normal concentration of multi-year-ice (“Storis”).
    - Low salinities in the surface over the shelf and shelfbreak and generally low surface and subsurface temperatures.
    - Well defined cold Polar Water core was observed west of Fylla Bank with very low temperature and salinity. The core is well defined further north west of “Sukkertop Banke” and “Store Hellefiskebanke”.
    - Water temperature on top of Fylla Bank was slightly below average in June despite normal to slightly higher air temperatures over the Davis Strait region, whereas the salinity was well below average.
    - High Irminger Water salinities (≥35) at Cape Farewell and Cape Desolation.
    - Pure Irminger Water was observed north to the Paamiut section and Modified Irminger Water could be traced north to the Sisimiut section.
    - West of Fyllas Bank (st.4) the mean temperature and salinity in 400–600 m depth was above average.

- West of “Sukkertop Banke” and “Store Hellefiskebanke”, the observed temperatures and salinities were among the highest observed in 400–600 m depth. However the time series are not as complete as the Fylla Bank st.4.
- Increased vertical stratification with above normal salinities and temperatures in the deeper waters and low salinities and temperatures in the upper 100–150m waters.

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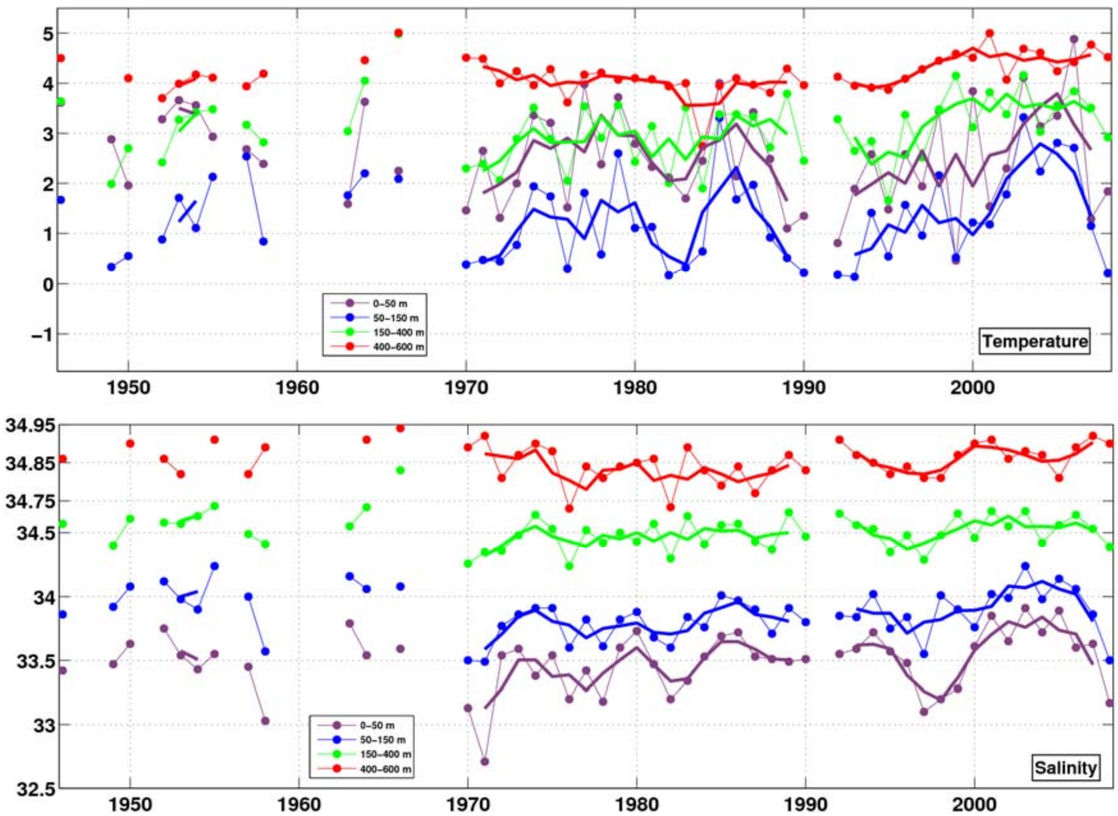

Figure 20. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2008 in four different depth intervals west of "Sukkertop Banke" (Maniitsoq, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in Table 3.

Table 3. Statistics for potential temperature and salinity at Maniitsoq (Sukkertoppen) st. 5. and values for 2008.

Maniitsoq St.5	Temperature [°C]	Salinity	2008	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	2.55 ± 0.98°C	33.49 ± 0.23	1.84°C	33.17
50–150 m	1.30 ± 0.87°C	33.87 ± 0.19	0.21°C	33.50
150–400 m	3.09 ± 0.67°C	34.51 ± 0.13	2.92°C	34.39
400–600 m	4.18 ± 0.37°C	34.85 ± 0.05	4.52°C	34.90

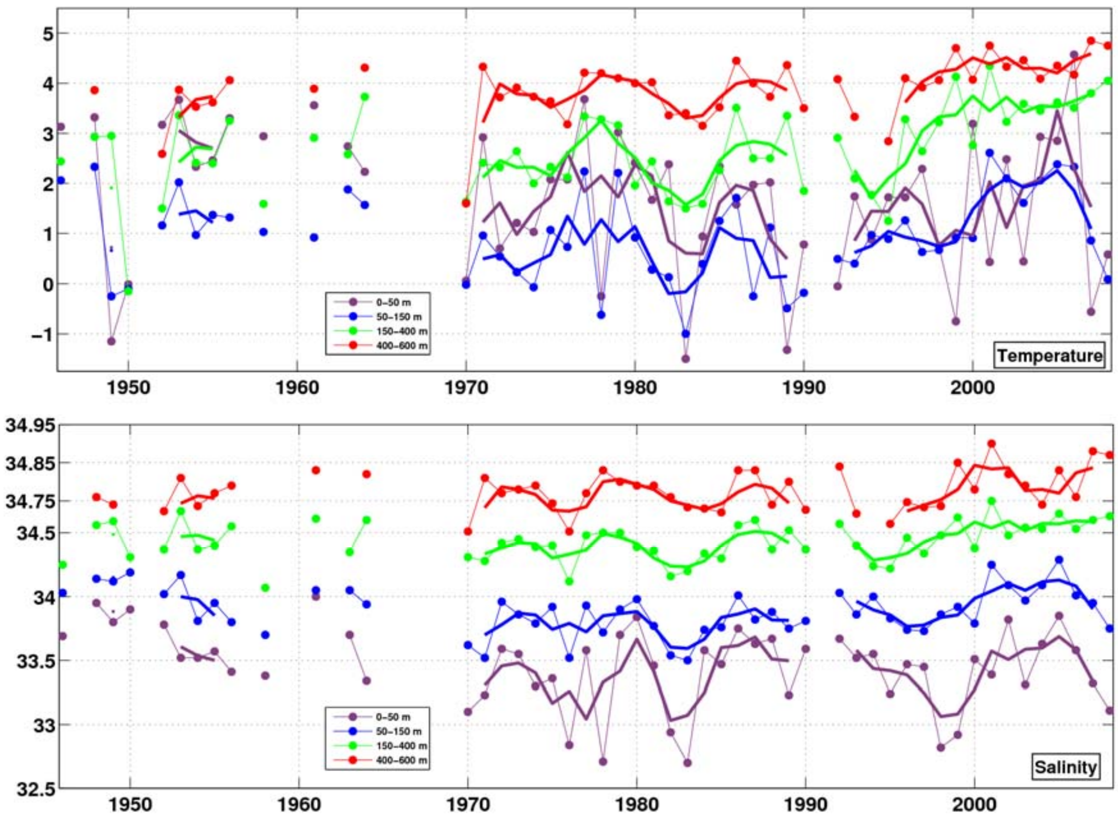

Figure 21. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1946–2008 in four different depth intervals west of "Store Hellefiskebanke" (Sisimiut, st.5) over the continental slope. The thick curves are the 3 year running mean values. Note the change in scales at 34.75 for salinity. Statistics is shown in Table 4.

Table 4. Statistics for potential temperature and salinity at Sisimiut (Holsteinsborg) st. 5. and values for 2008.

Sisimiut St.5	Temperature [°C]	Salinity	2008	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.70 ± 1.44°C	33.46 ± 0.31	0.58°C	33.11
50–150 m	0.95 ± 0.88°C	33.89 ± 0.19	0.09°C	33.75
150–400 m	2.66 ± 0.87°C	34.43 ± 0.15	4.05°C	34.63
400–600 m	3.88 ± 0.60°C	34.76 ± 0.09	4.75°C	34.87

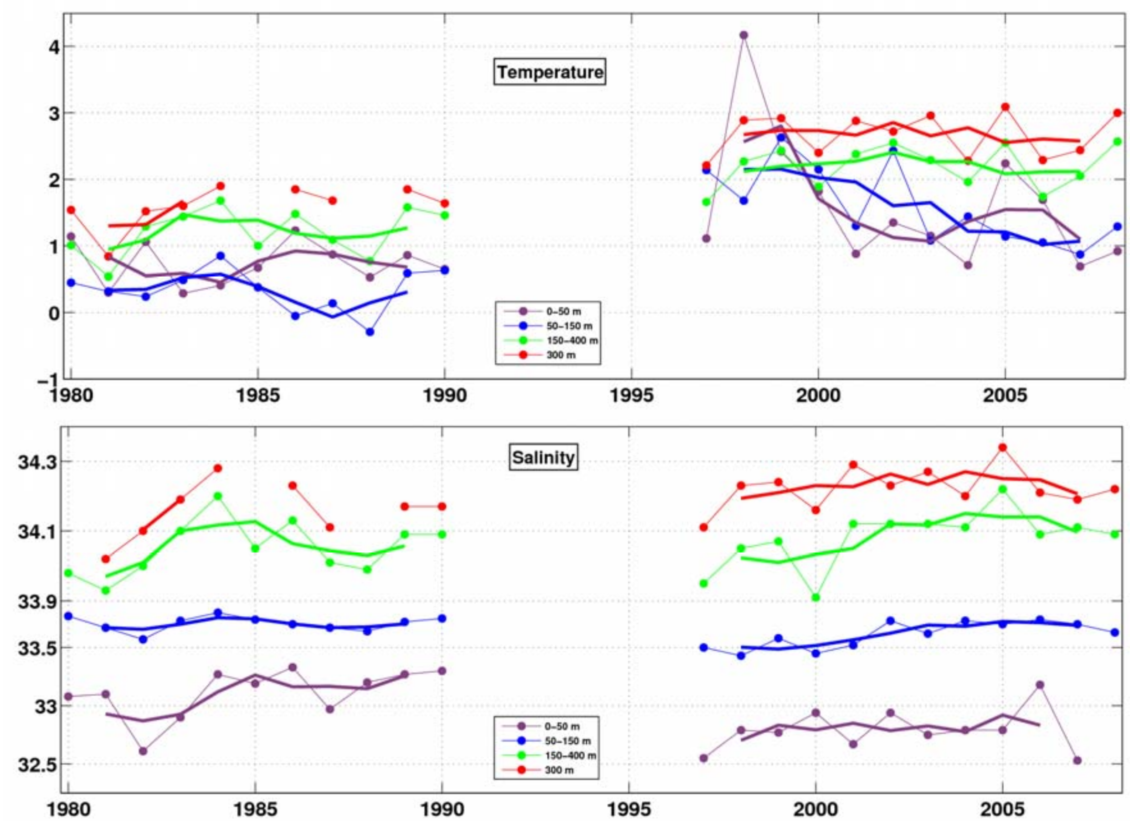

Figure 22. Timeseries of mean temperature (top) and mean salinity (bottom) for the period 1980–2008 in four different depth intervals west of "Jakobshavn-Skansen" (Ilulissat-Skansen) st.3 in the Disko Bay close to Jakobshavn Isbræ. The thick curves are the 3 year running mean values. Note the change in scales at 33.9 for salinity. Statistics is shown in Table 4.

Table 5. Statistics for potential temperature and salinity at Ilulissat-Skansen (Jakobshavn-Skansen) st. 3. and values for 2008. Note: In 2008 temperature were used as potential temperature in 0–50m because the salinity measurements were bad in the surface.

Sisimiut St.5	Temperature [°C]	Salinity	2008	
	Mean ± std	Mean ± std	Tpot	S
0–50 m	1.26 ± 0.92°C	32.98 ± 0.28	0.92°C	-
50–150 m	0.99 ± 0.78°C	33.66 ± 0.10	1.29°C	33.63
150–400 m	1.71 ± 0.60°C	34.07 ± 0.08	2.57°C	34.09
300 m	2.20 ± 0.62°C	34.20 ± 0.07	3.00°C	34.22

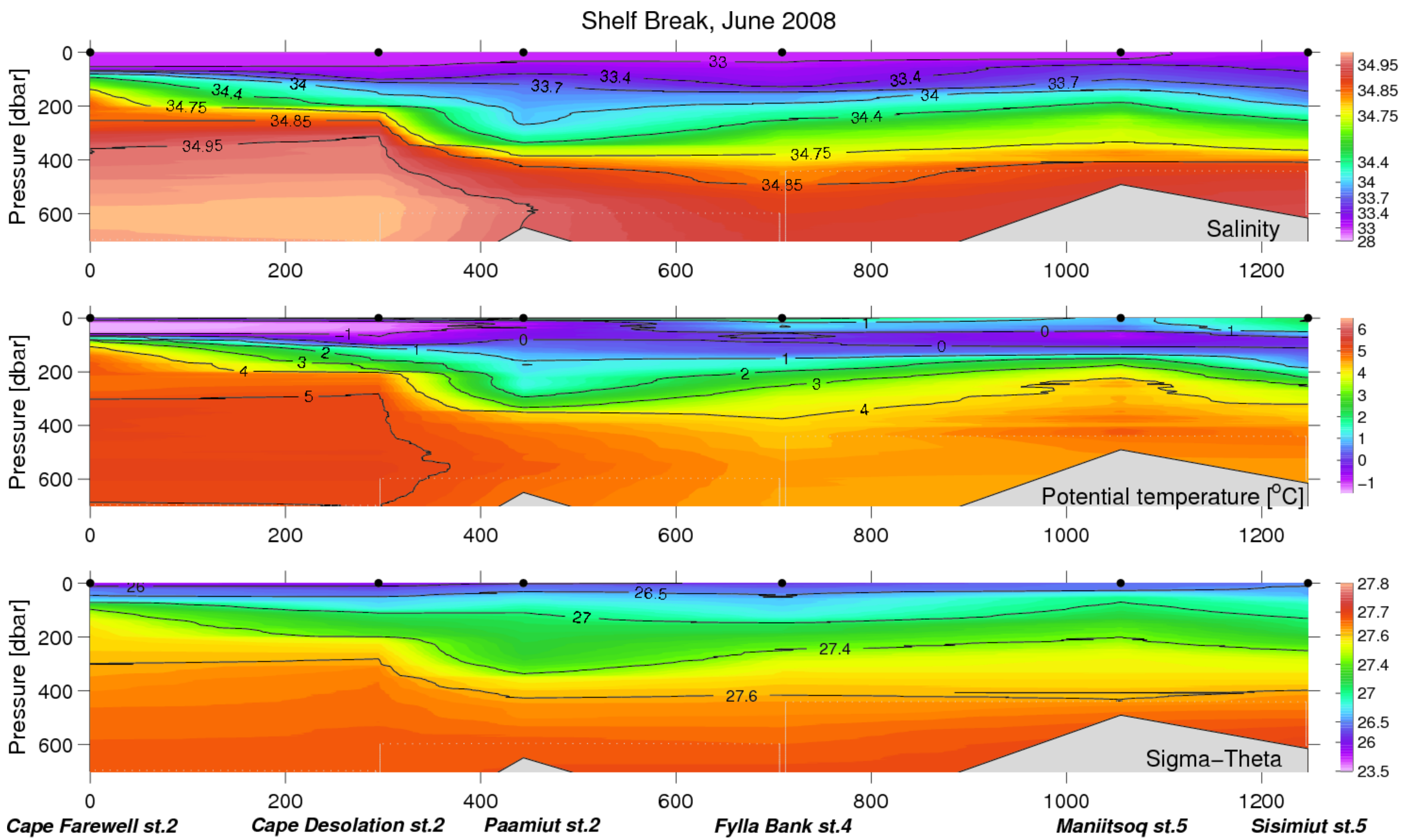

Figure 23. Vertical distribution of temperature, salinity and density over the continental shelf break from Cape Farewell to Sisimiut, June 14–22, 2008.

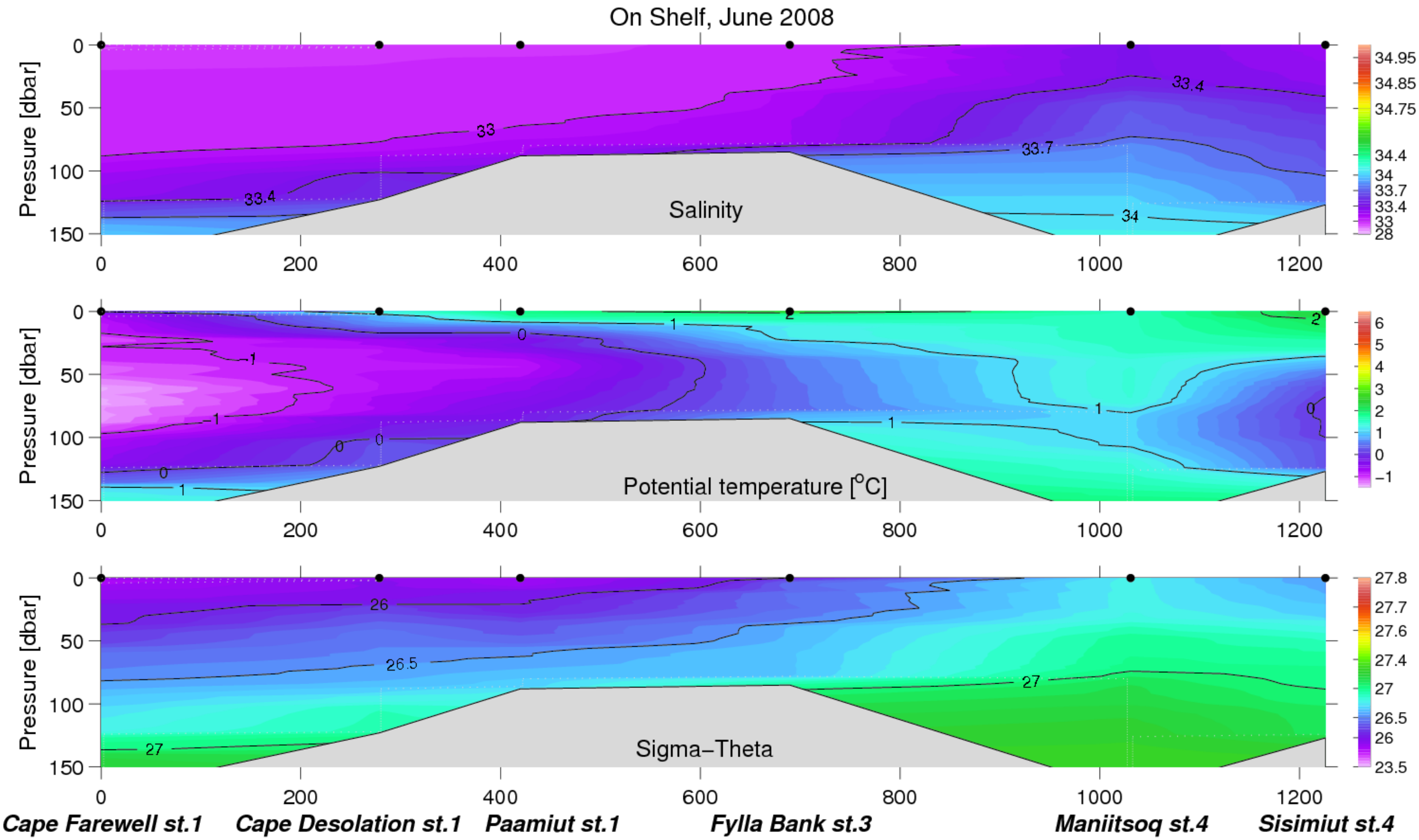

Figure 24. Vertical distribution of temperature, salinity and density over the shelf banks from Cape Farewell to Sisimiut, June 14–23, 2008.

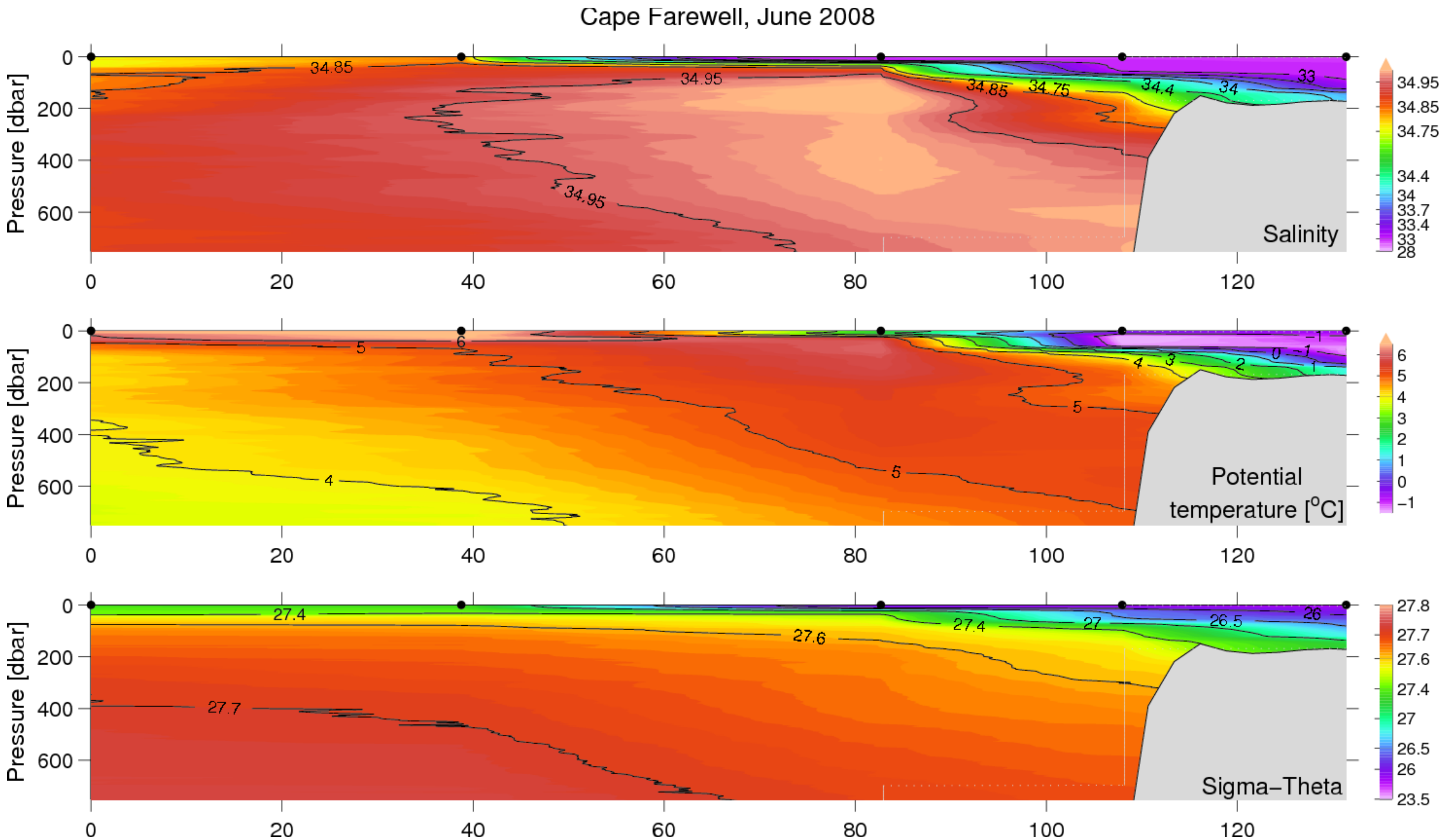

Figure 25. Vertical distribution of temperature, salinity and density at the Cape Farewell section, June 22–23, 2008.

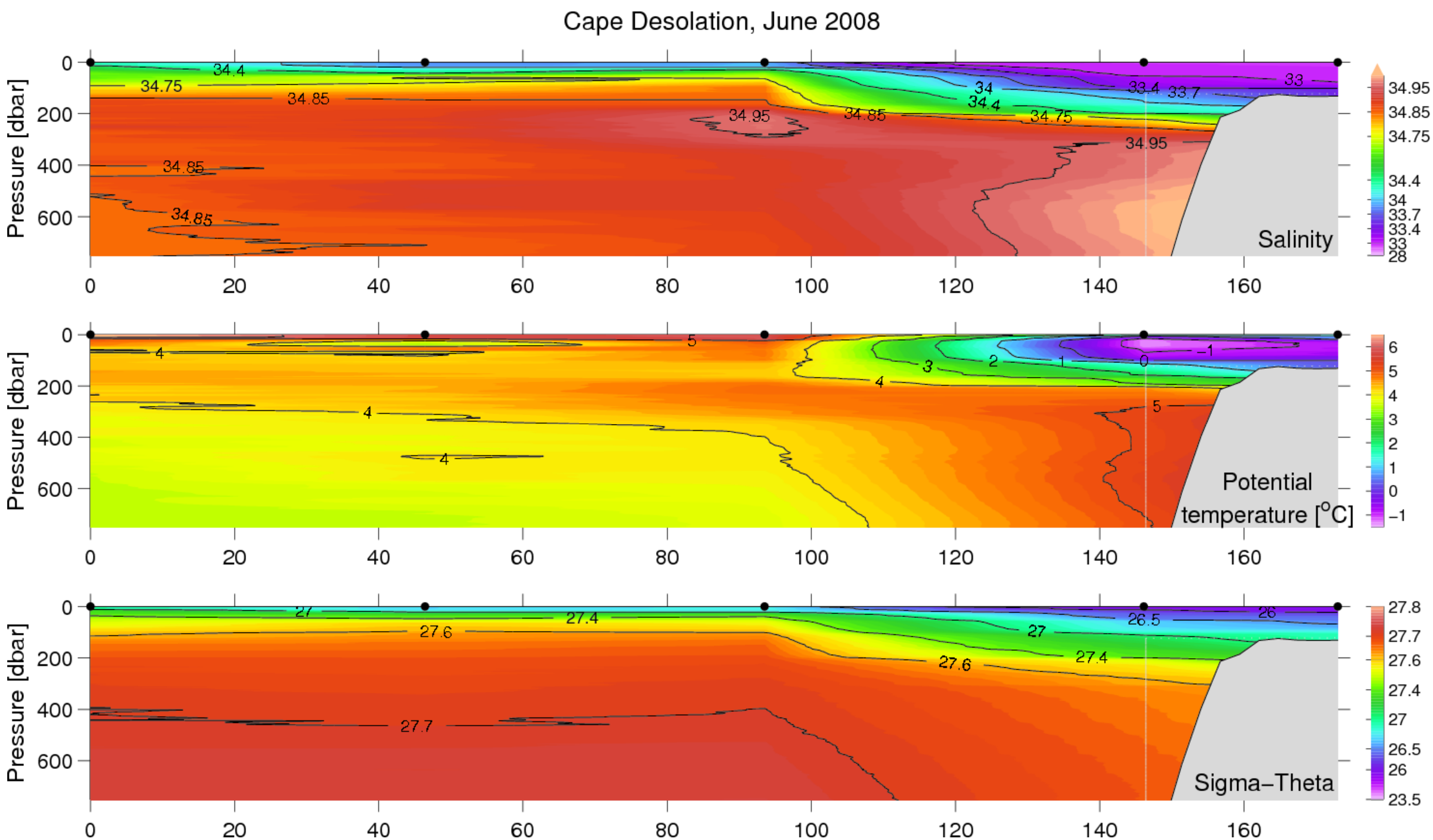

Figure 26. Vertical distribution of temperature, salinity and density at the Cape Desolation section, June 21, 2008.

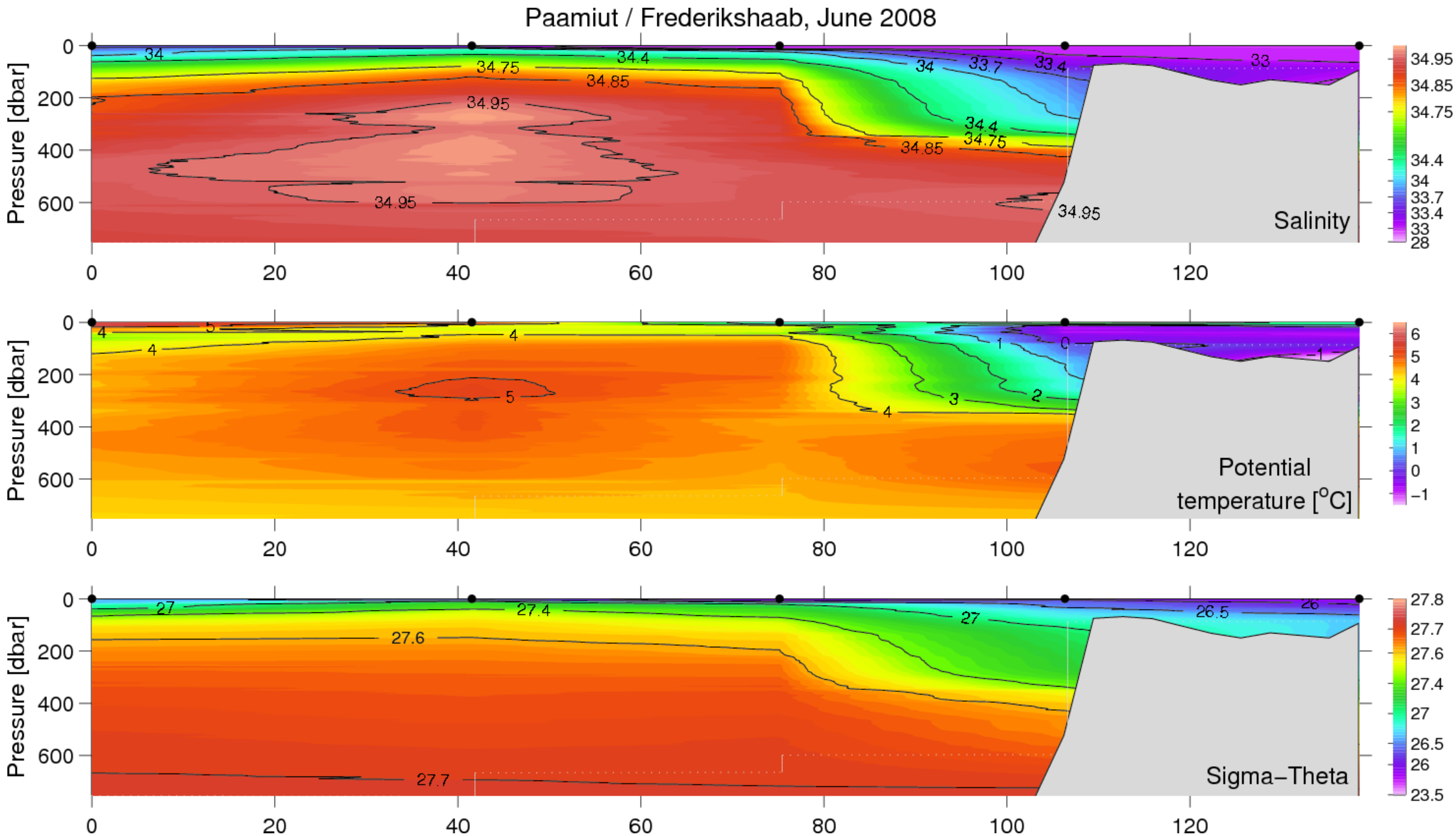

Figure 27. Vertical distribution of temperature, salinity and density at the Paamiut (Frederikshaab) section, June 20, 2008.

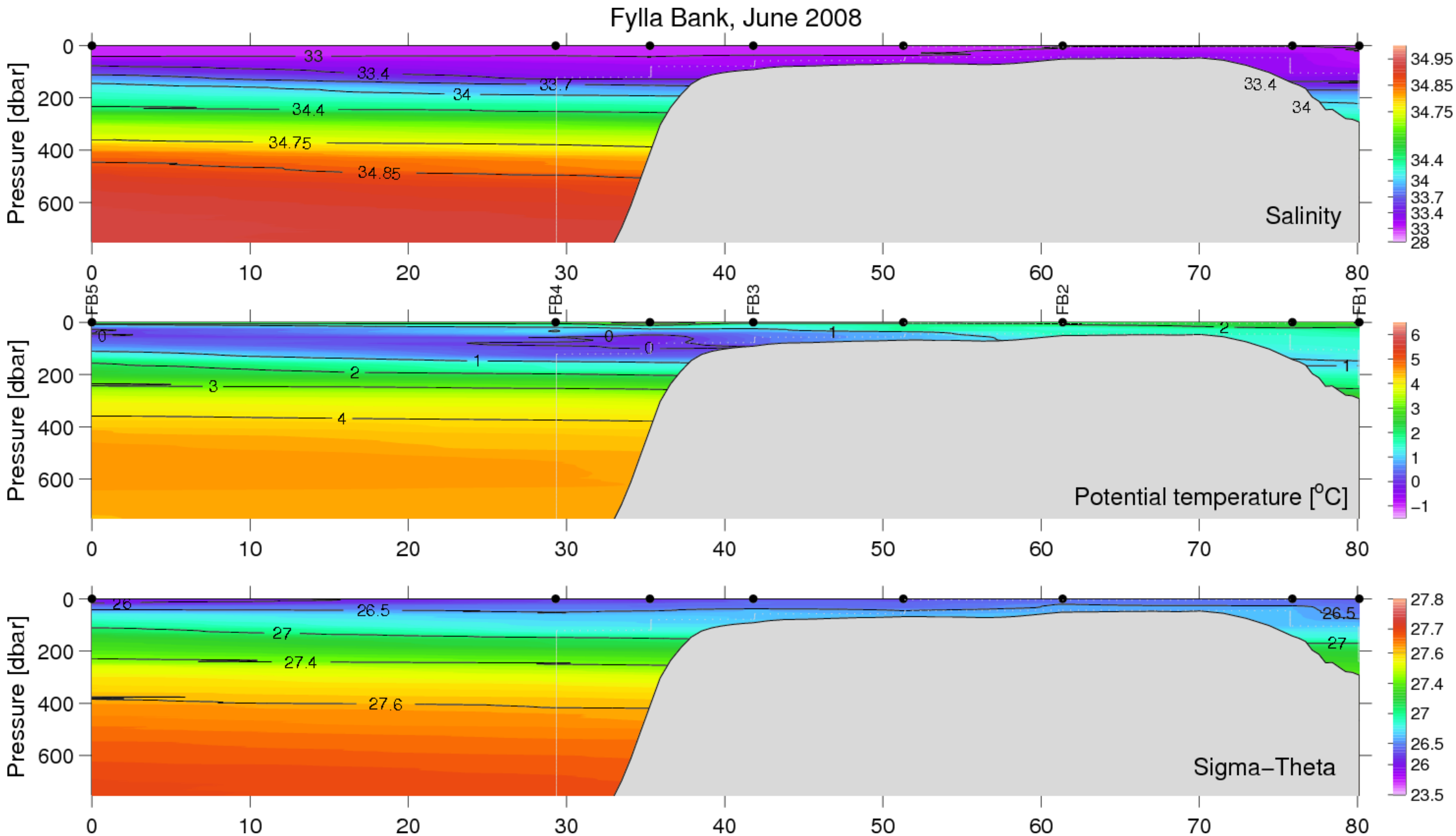

Figure 28. Vertical distribution of temperature, salinity and density at the Fylla Bank section, June 17, 2008. Three intermediate stations were taken too.

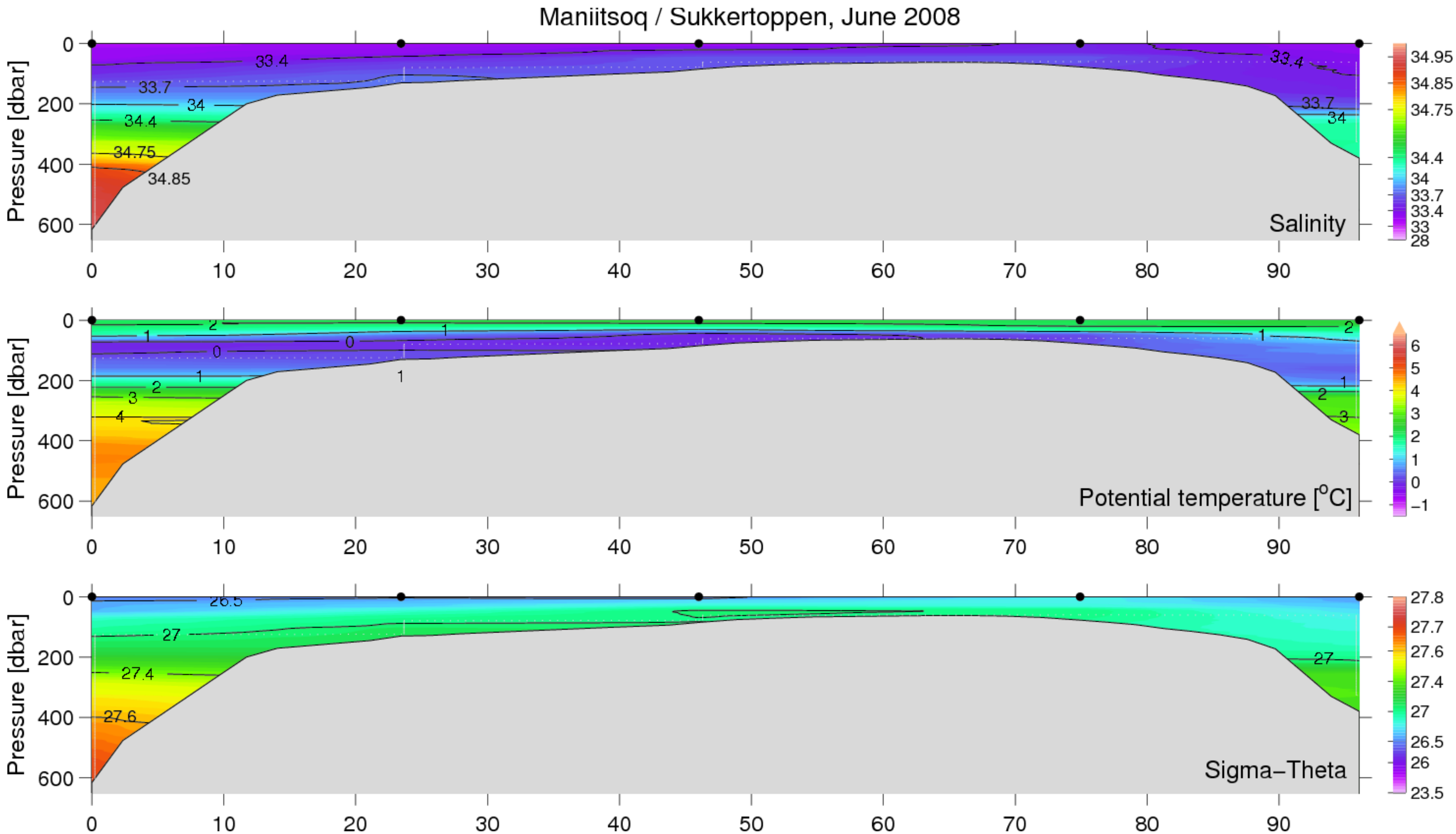

Figure 29. Vertical distribution of temperature, salinity and density at the Maniitsoq (Sukkertoppen) section, June 15, 2008.

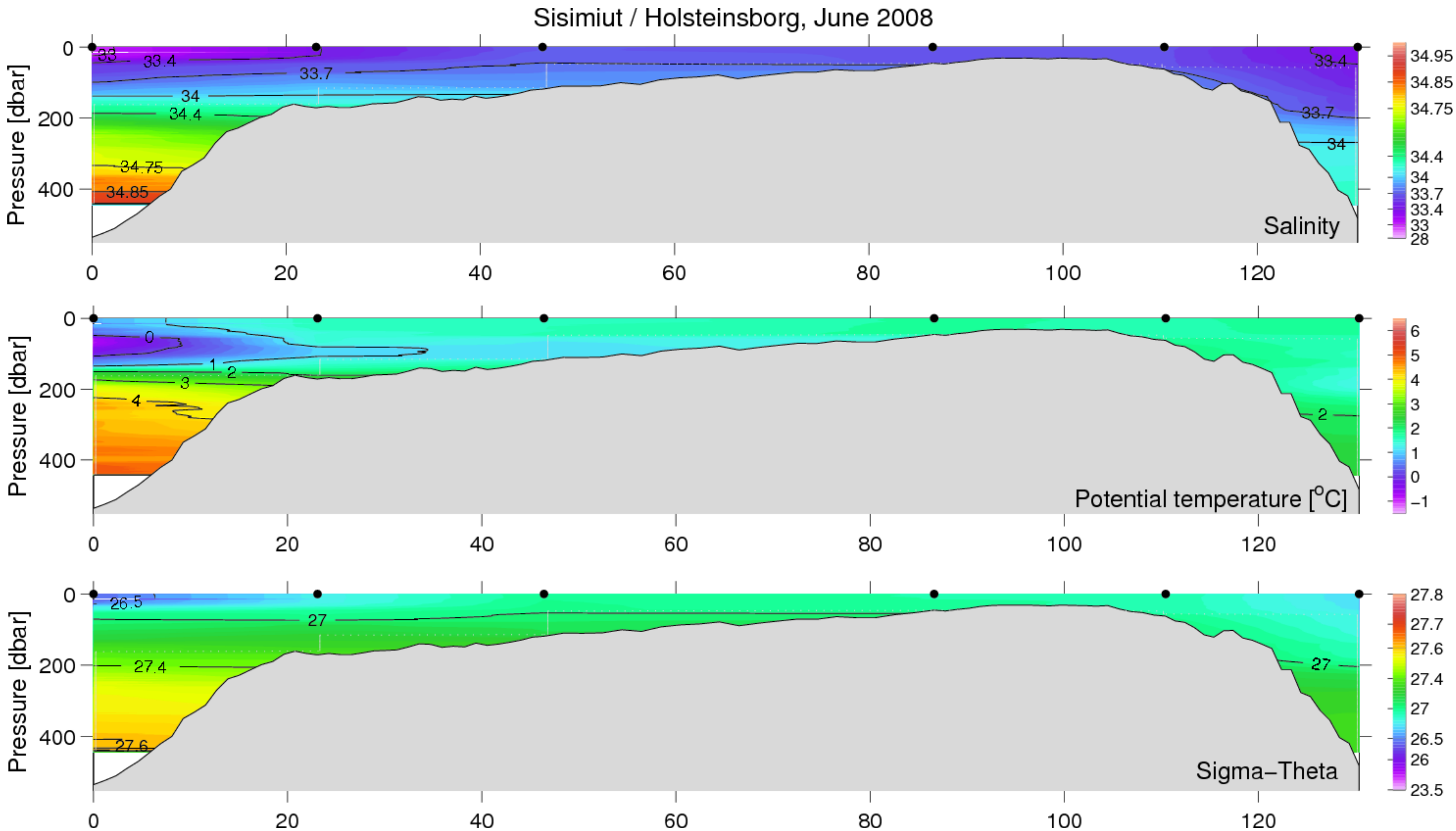

Figure 30. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, June 13–14 2008. Sisimiut st. 0 right.

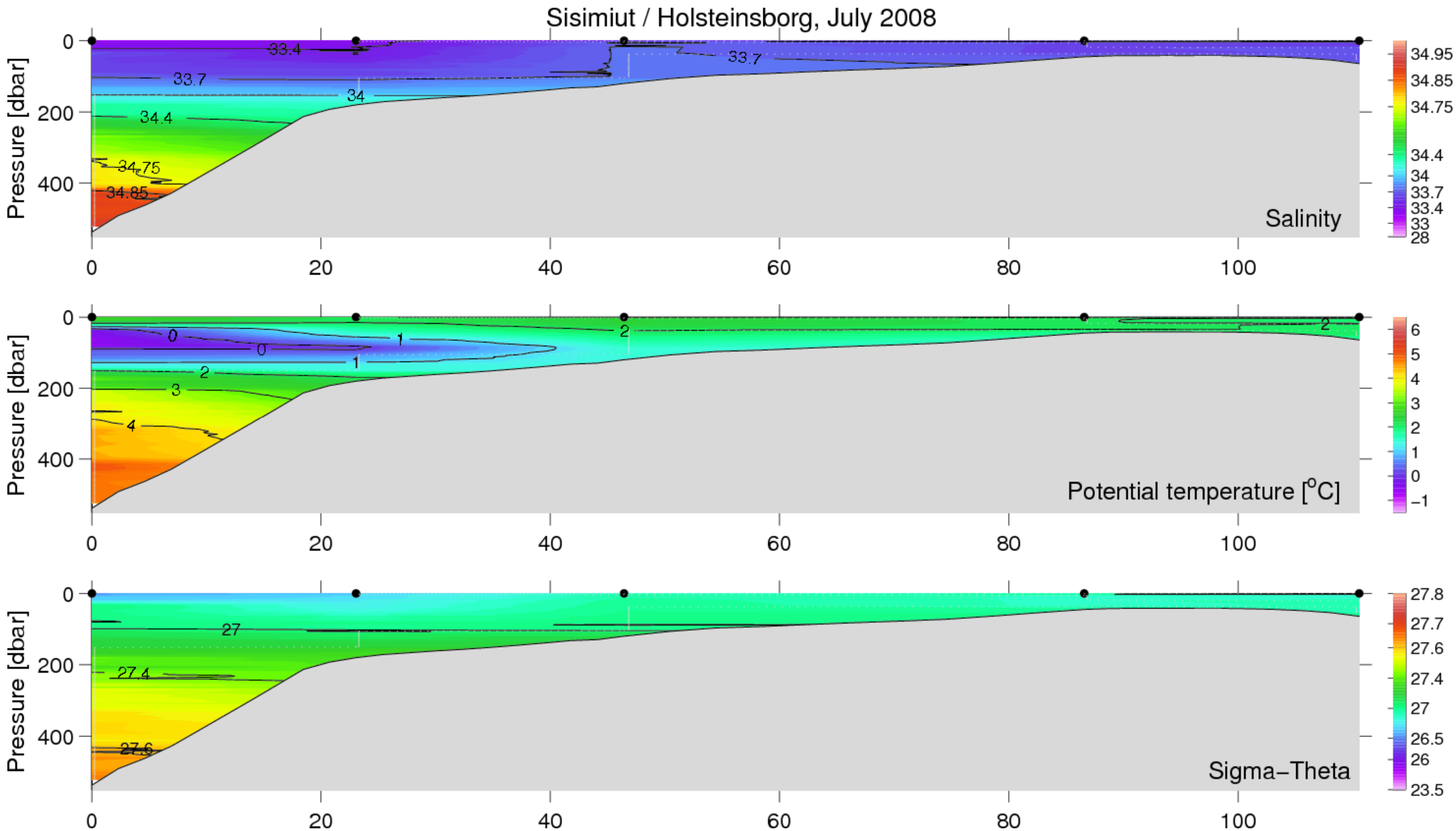

Figure 31. Vertical distribution of temperature, salinity and density at the Sisimiut (Holsteinsborg) section, July 21–22, 2008.

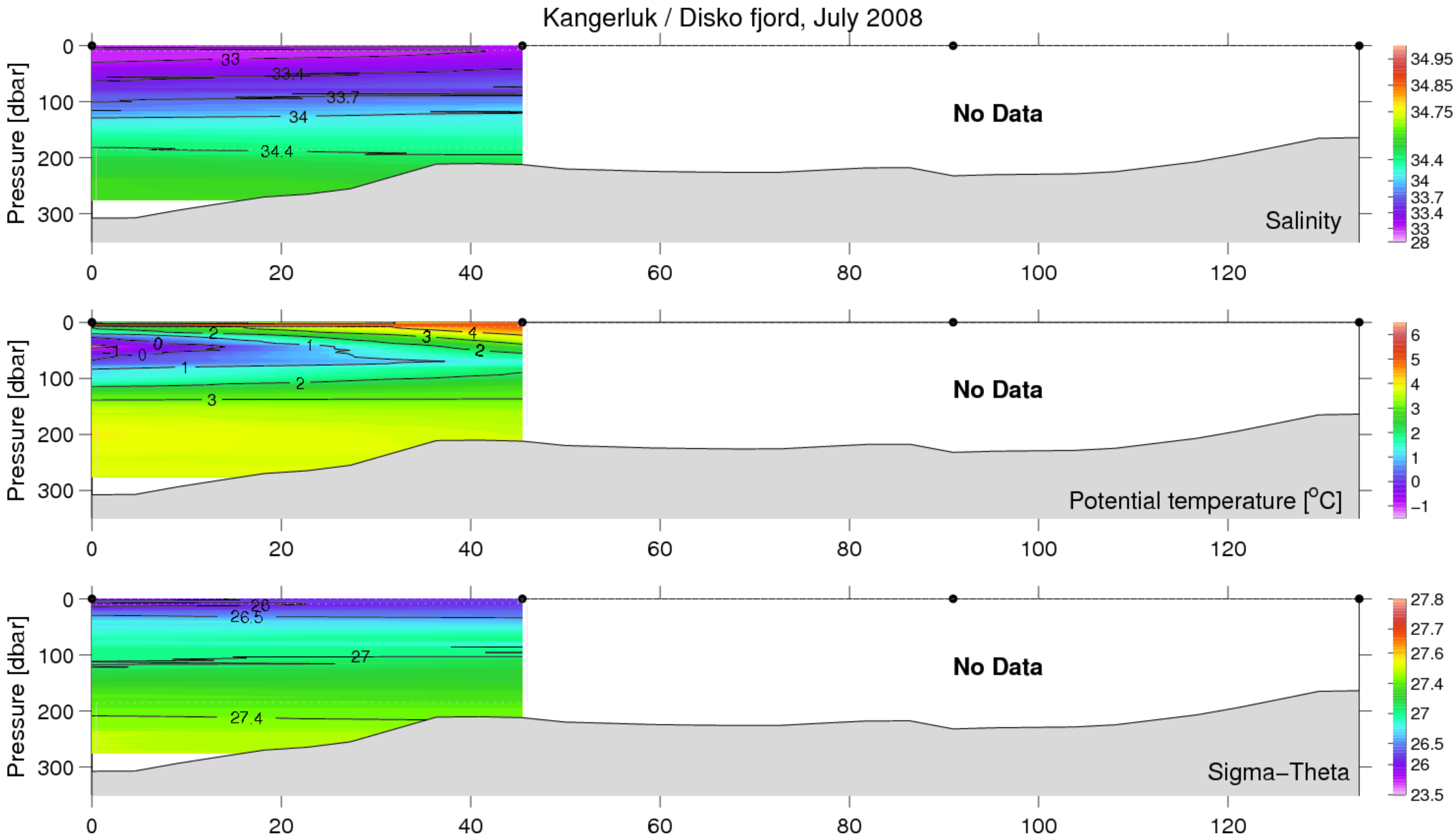

Figure 32. Vertical distribution of temperature, salinity and density at the Kangerluk (Disko Fjord) section, July 28, 2008.

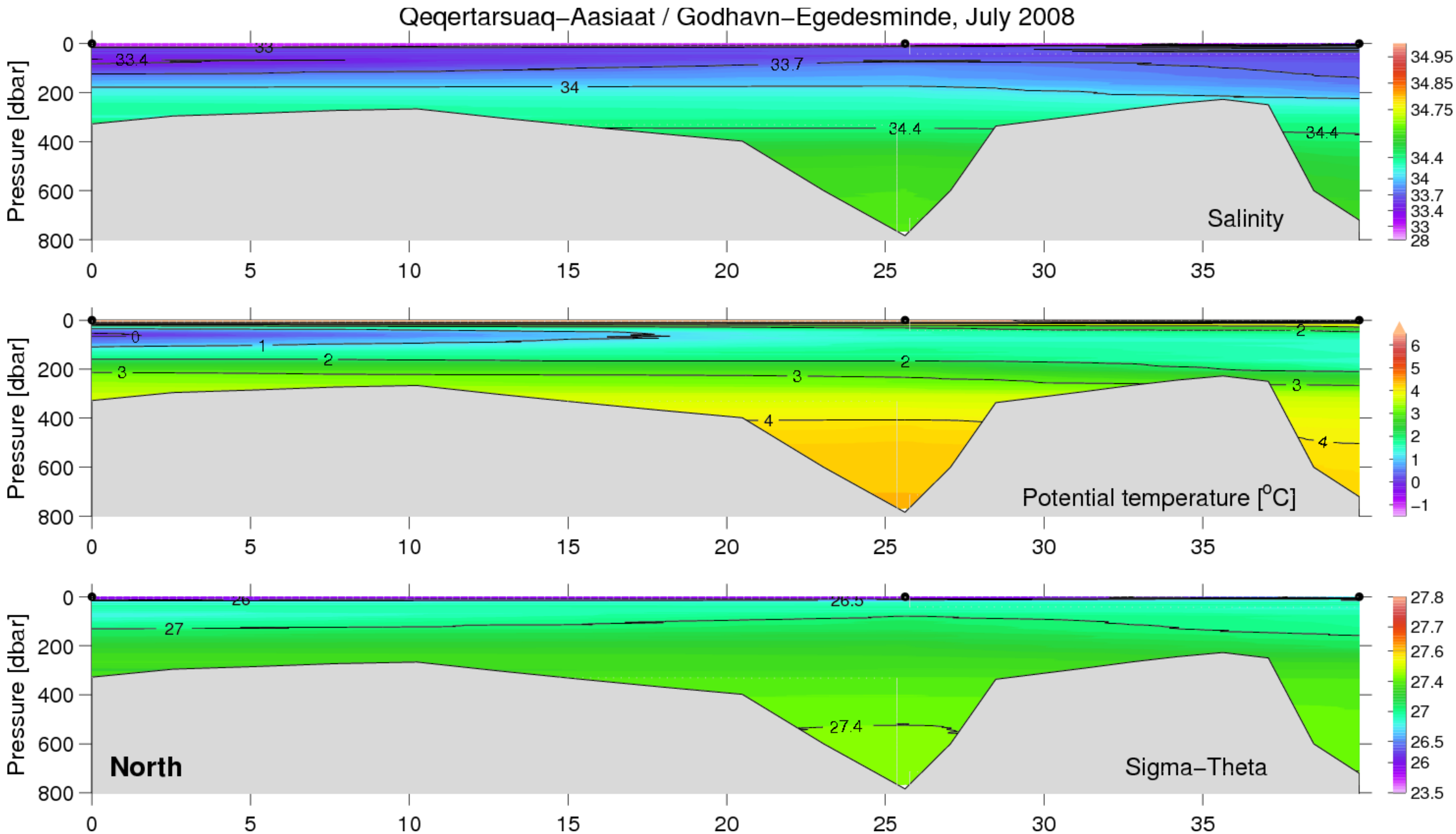

Figure 33. Vertical distribution of temperature, salinity and density at the Aasiaat–Qeqertarsuaq (Egedesminde–Godhavn) section, July 1, 2008.

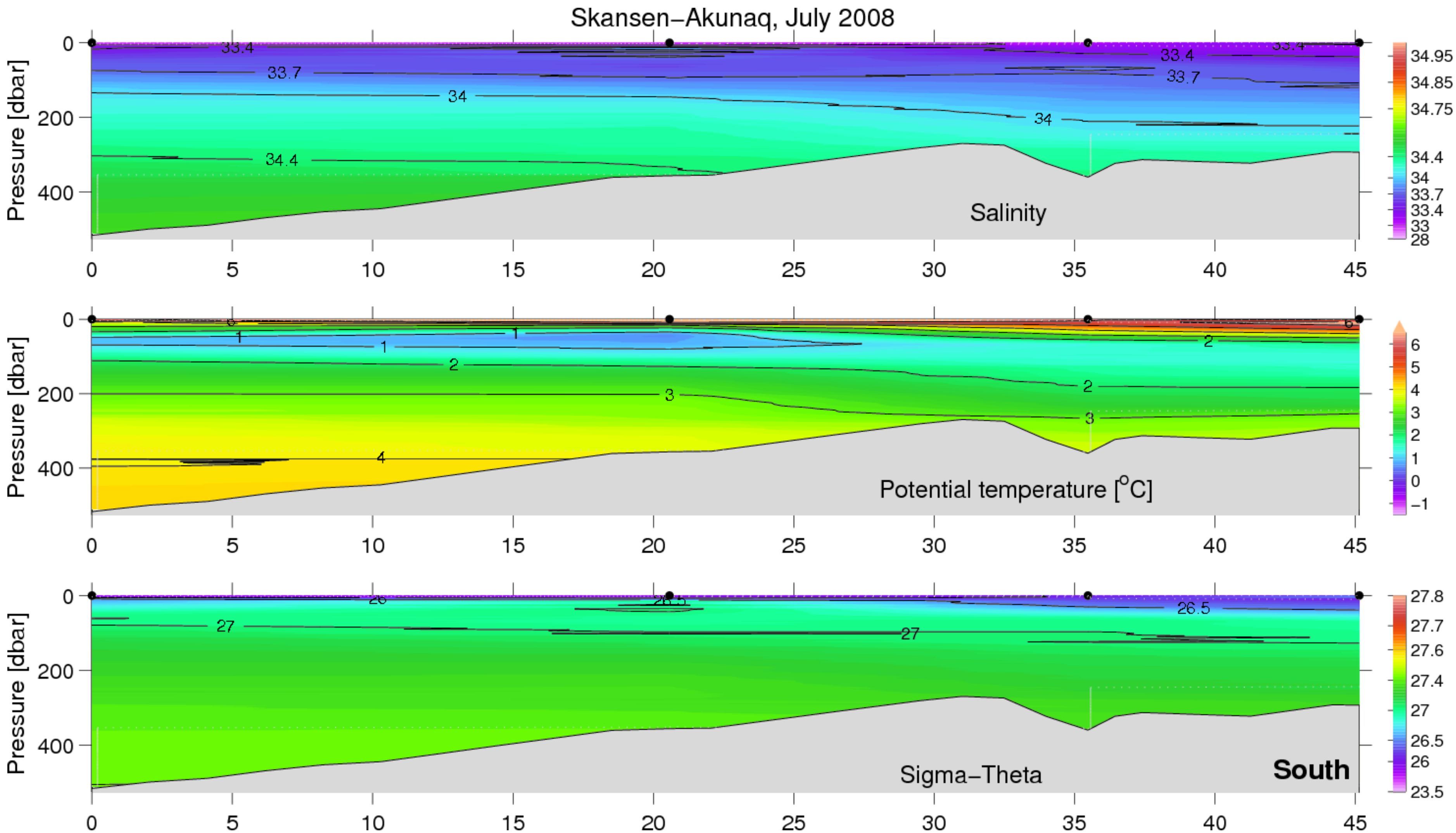

Figure 34. Vertical distribution of temperature, salinity and density at the Skansen–Akunaq section, July 30, 2008.

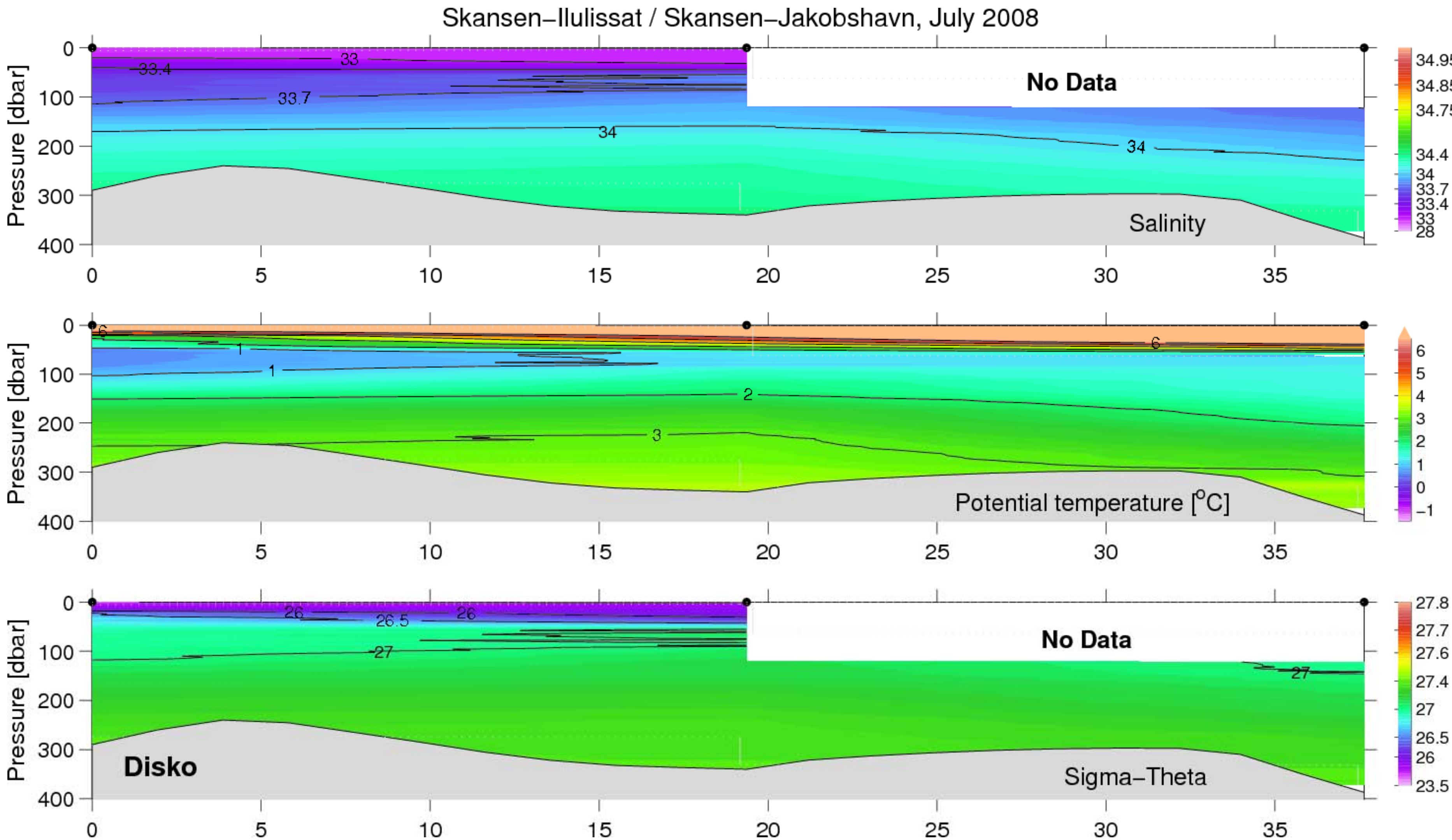

Figure 35. Vertical distribution of temperature, salinity and density at the Skansen–Ilulissat (Skansen–Jakobshavn) section, July 2, 2008. Note, temperature used instead of potential temperature where salinity are missing.

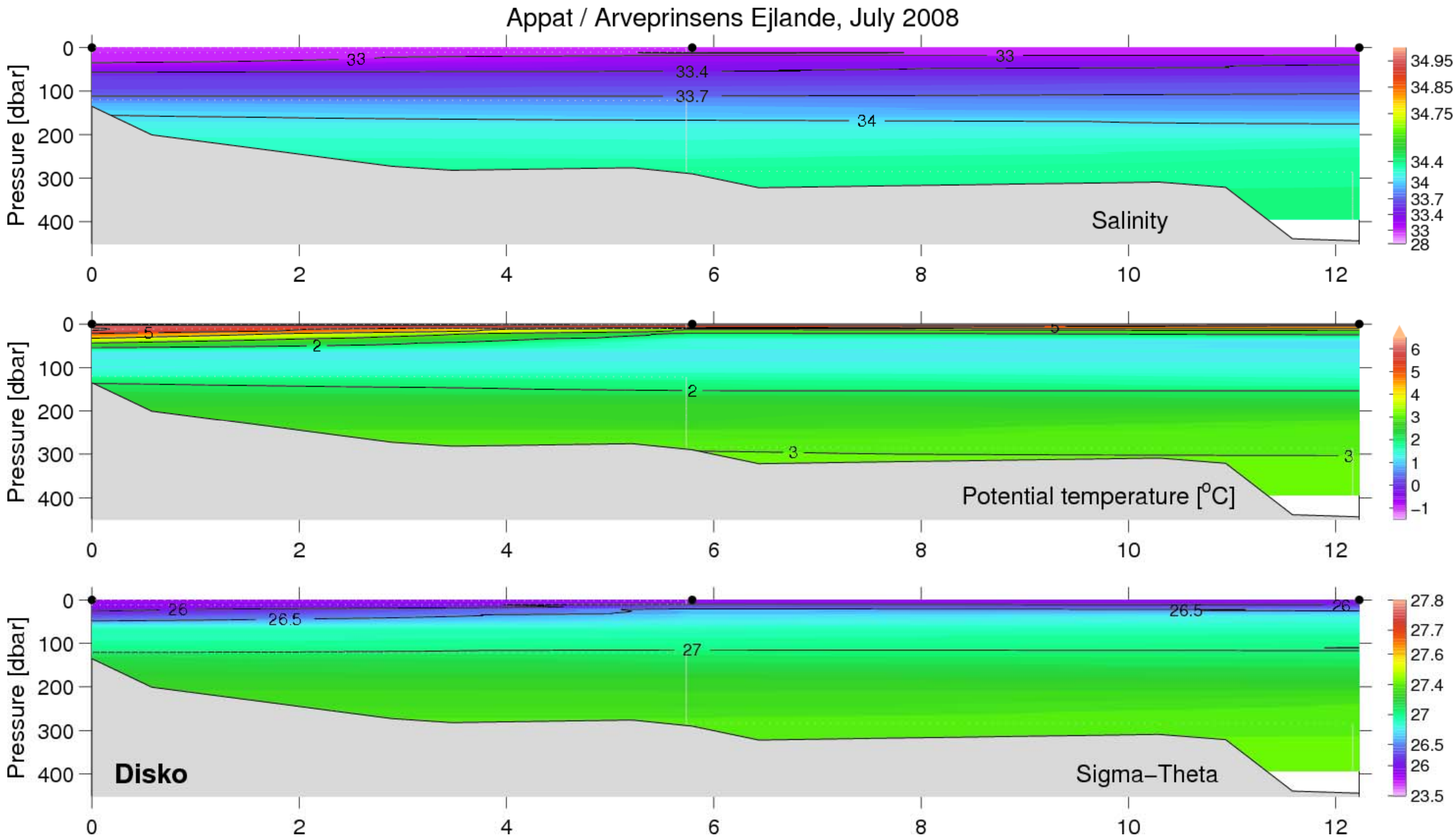

Figure 36. Vertical distribution of temperature, salinity and density at the Appat (Arveprinsens Ejlande) section, July 5, 2008.

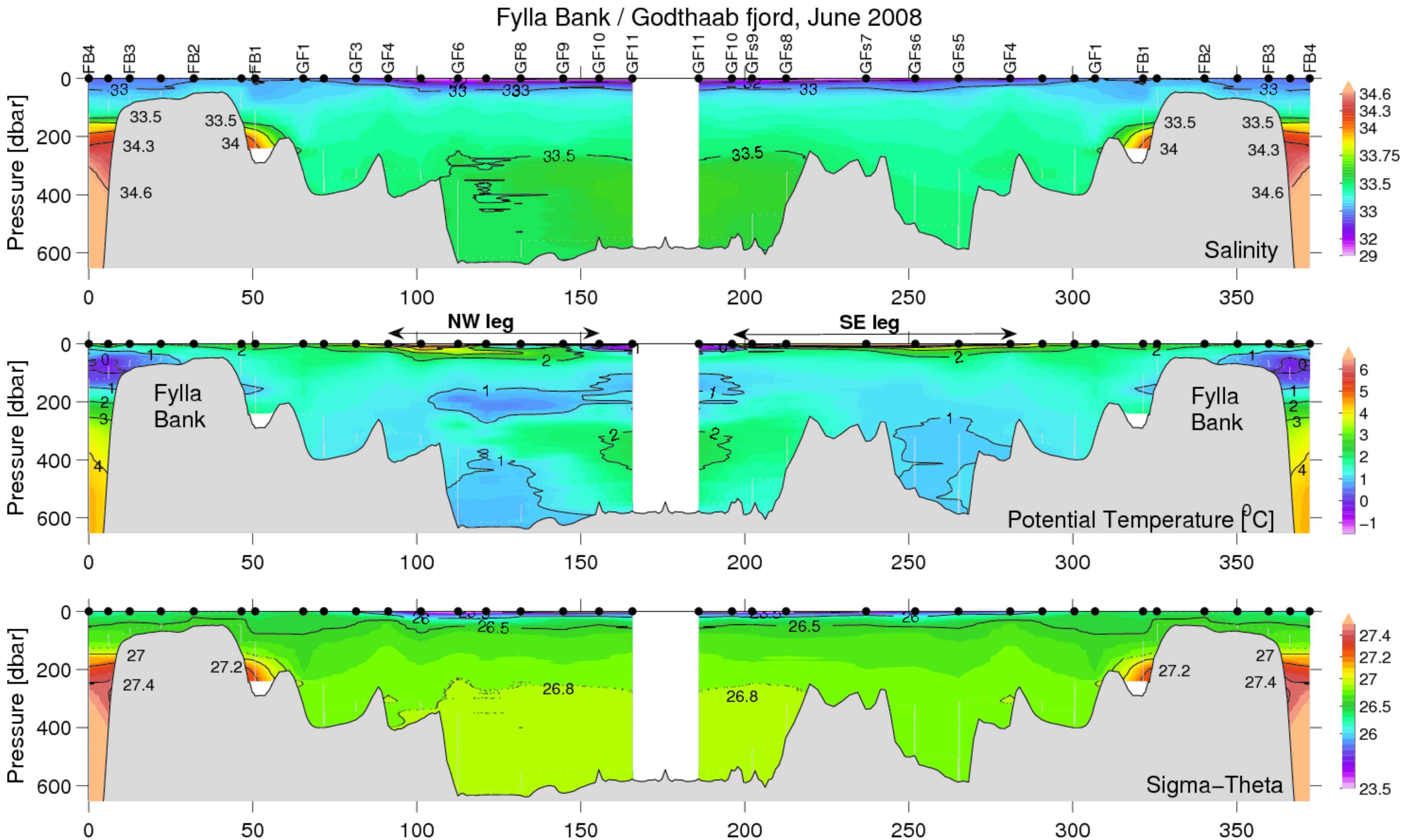

Figure 37. Vertical distribution of temperature, salinity and density at the Fylla Bank / Godthaab fjord section, June 17–18, 2008. From left to middle is show Fylla Bank and northwest leg (main leg) of Godthaab fjord. From middle to right is shown southeast leg of Godthaab fjord and Fylla Bank. Location of stations shown in Figure 5. The Fylla Bank section is found left and right in the figure (identical to Figure 28).

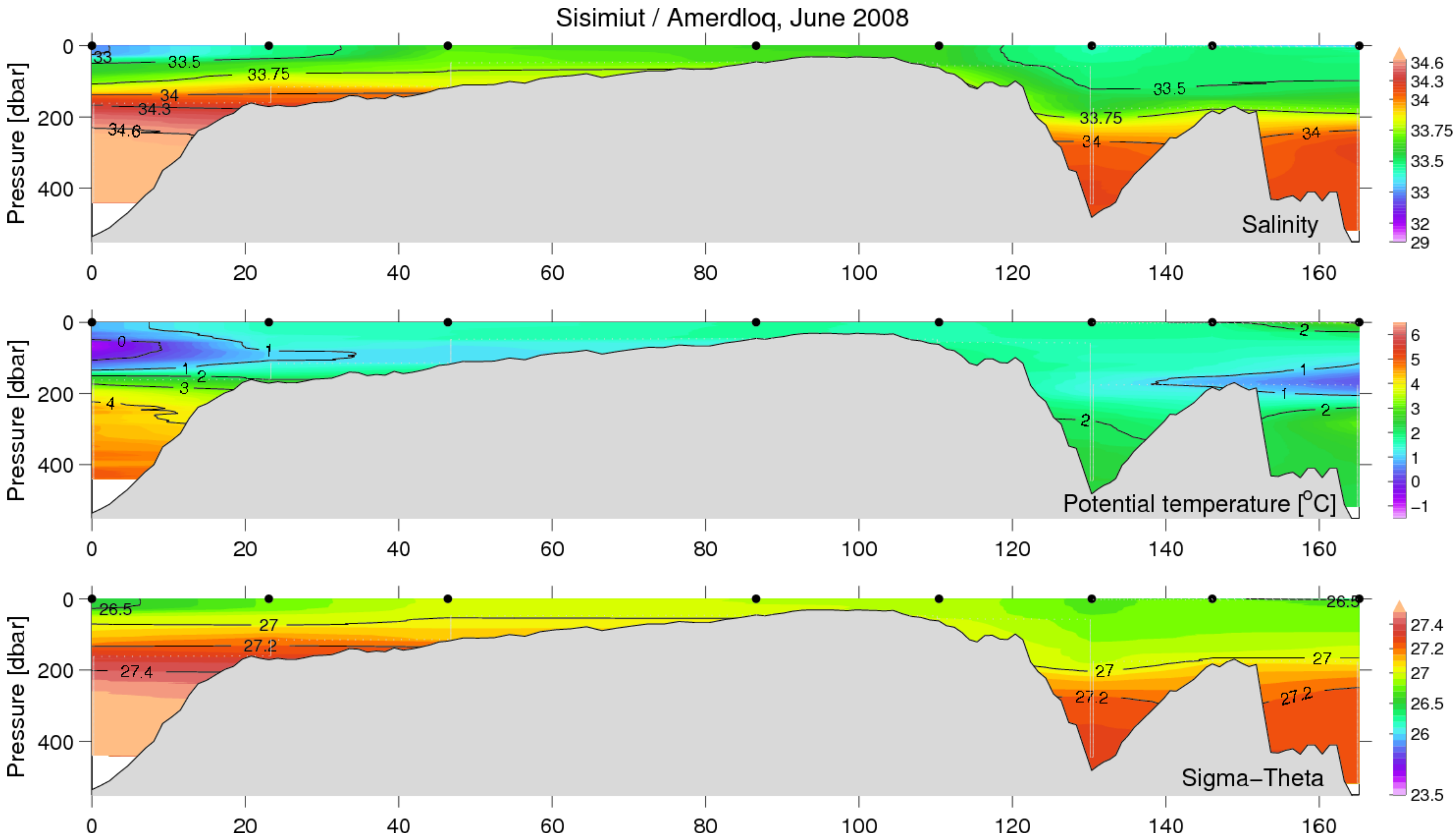

Figure 38. Vertical distribution of temperature, salinity and density at the Amerdloq fjord, June 13–14, 2008. Sisimiut section left (identical to Figure 30).

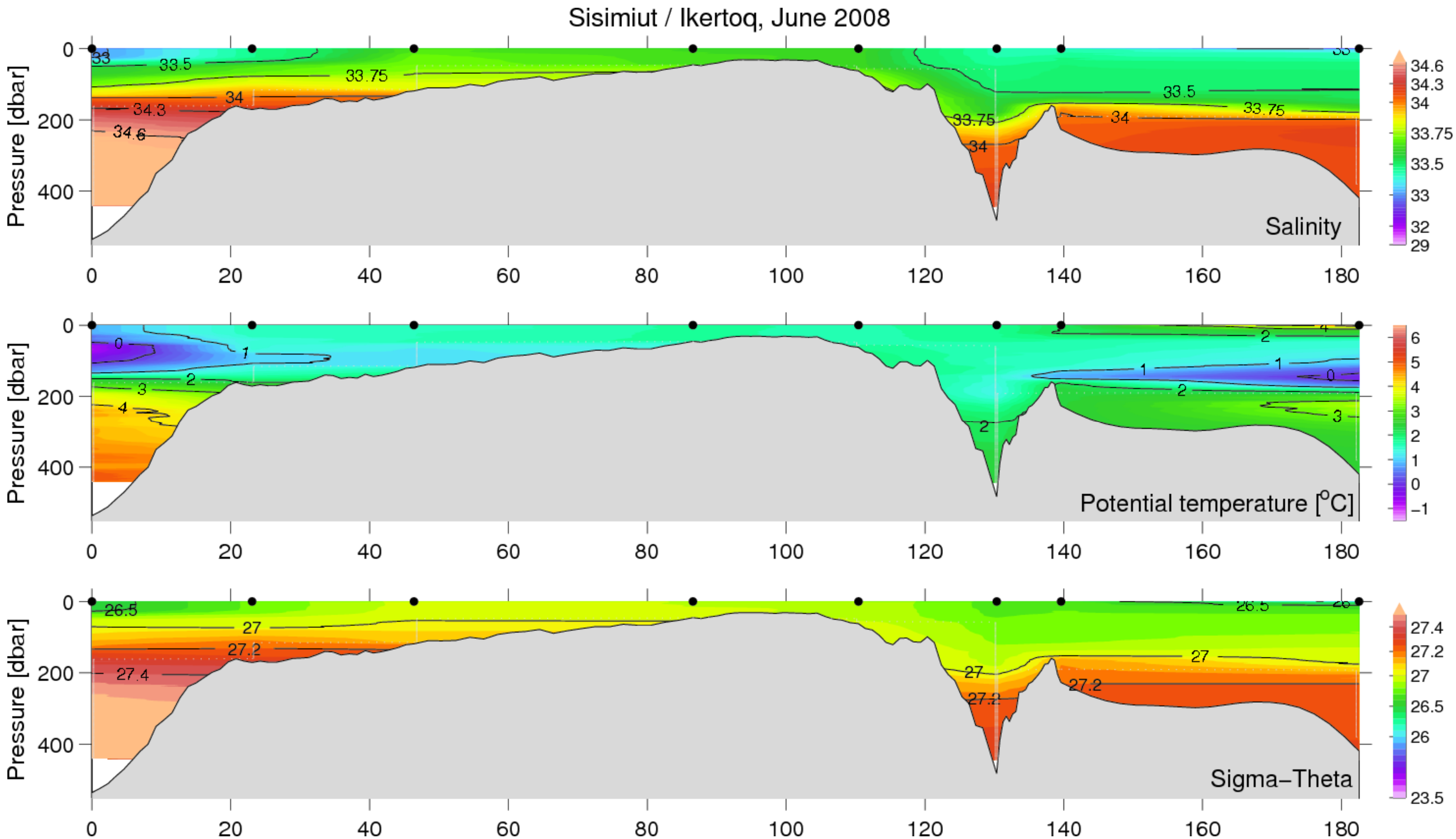

Figure 39. Vertical distribution of temperature, salinity and density at the Ikertoq fjord, June 13–14, 2008. Sisimiut section left (identical to Figure 30).

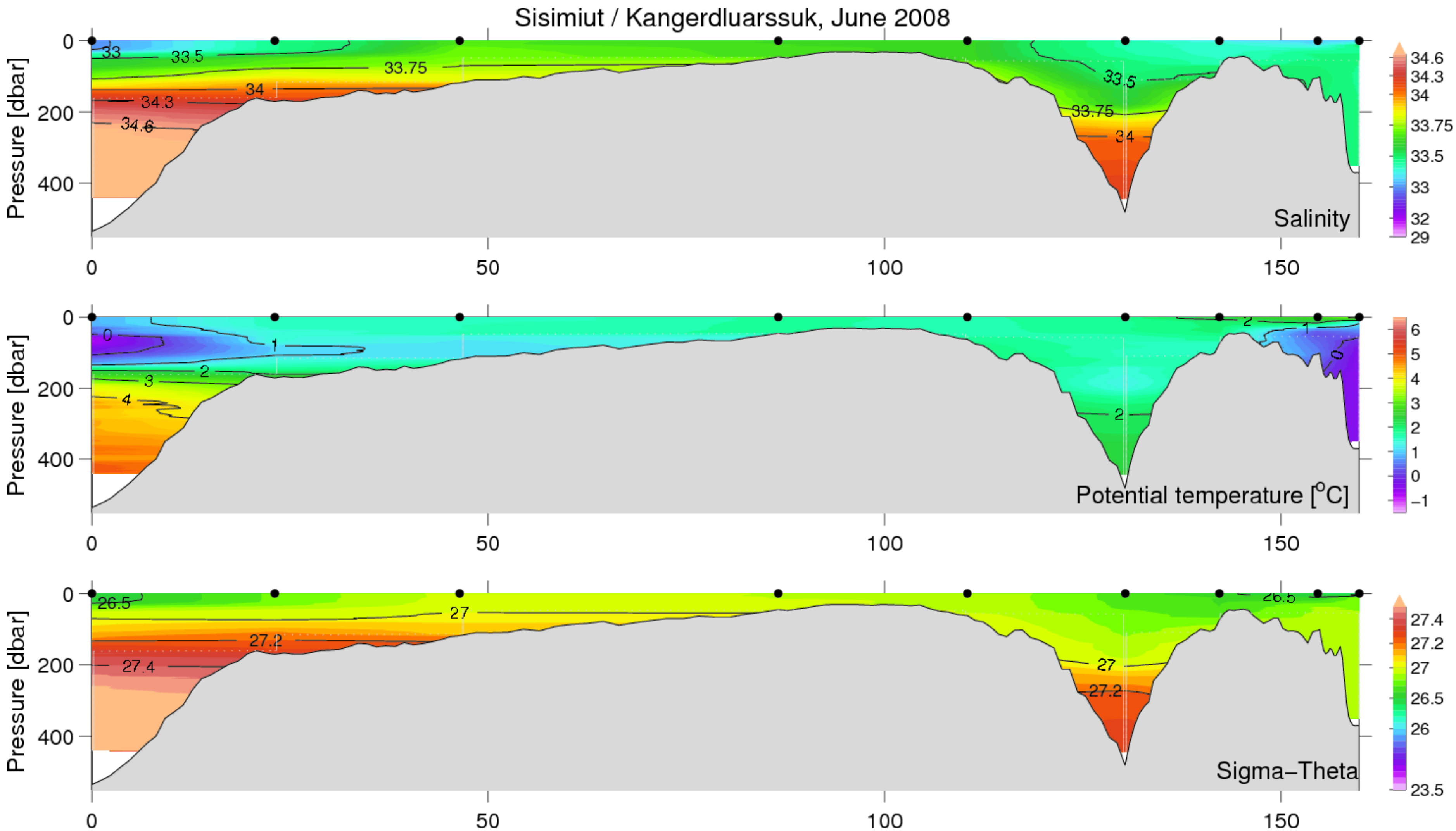

Figure 40. Vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord, June 13–14, 2008. Sisimiut section left (identical to Figure 30)

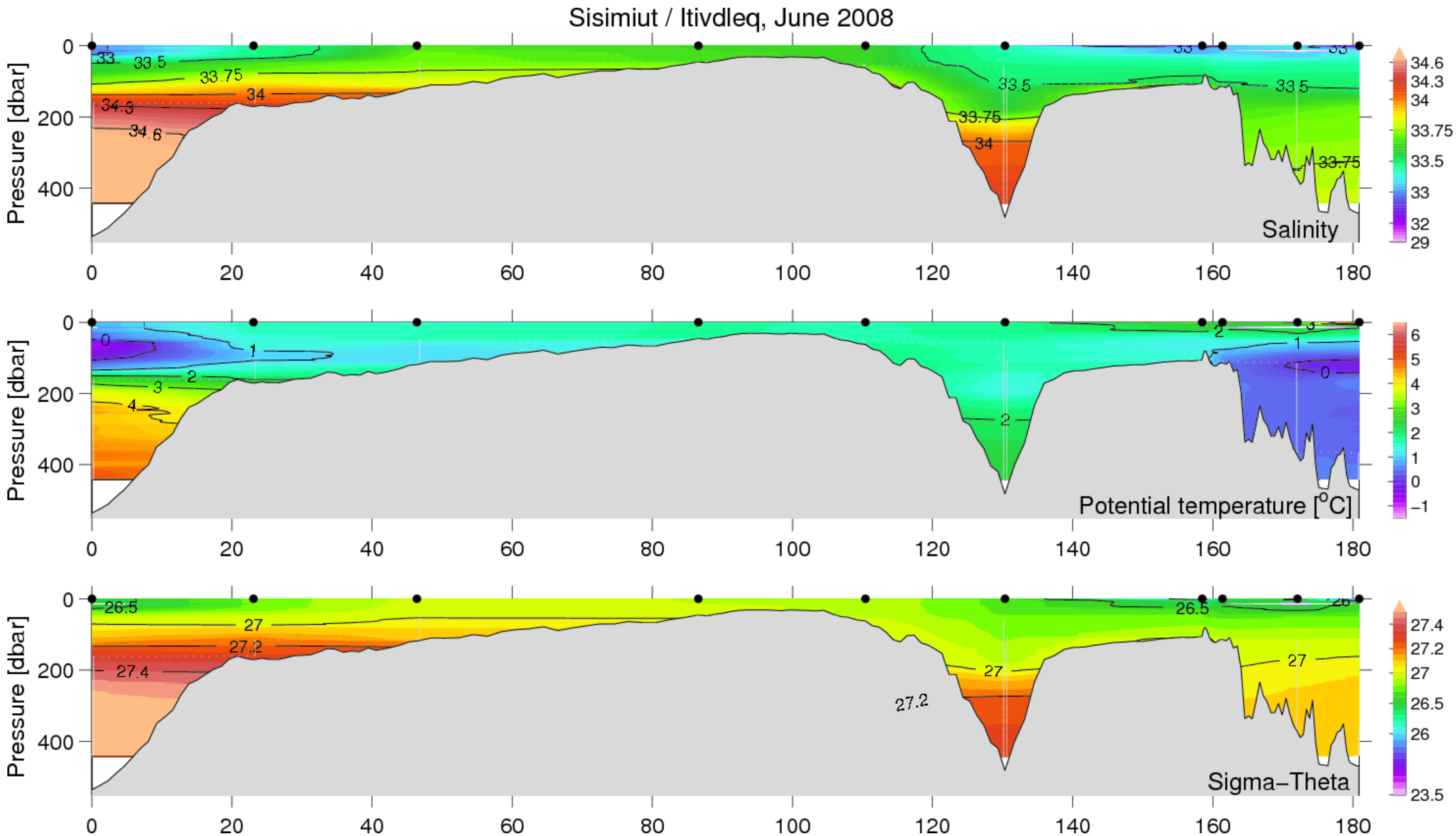

Figure 41. Vertical distribution of temperature, salinity and density at the Itivdleq fjord, June 13–14, 2008. Sisimiut section left (identical to Figure 30).

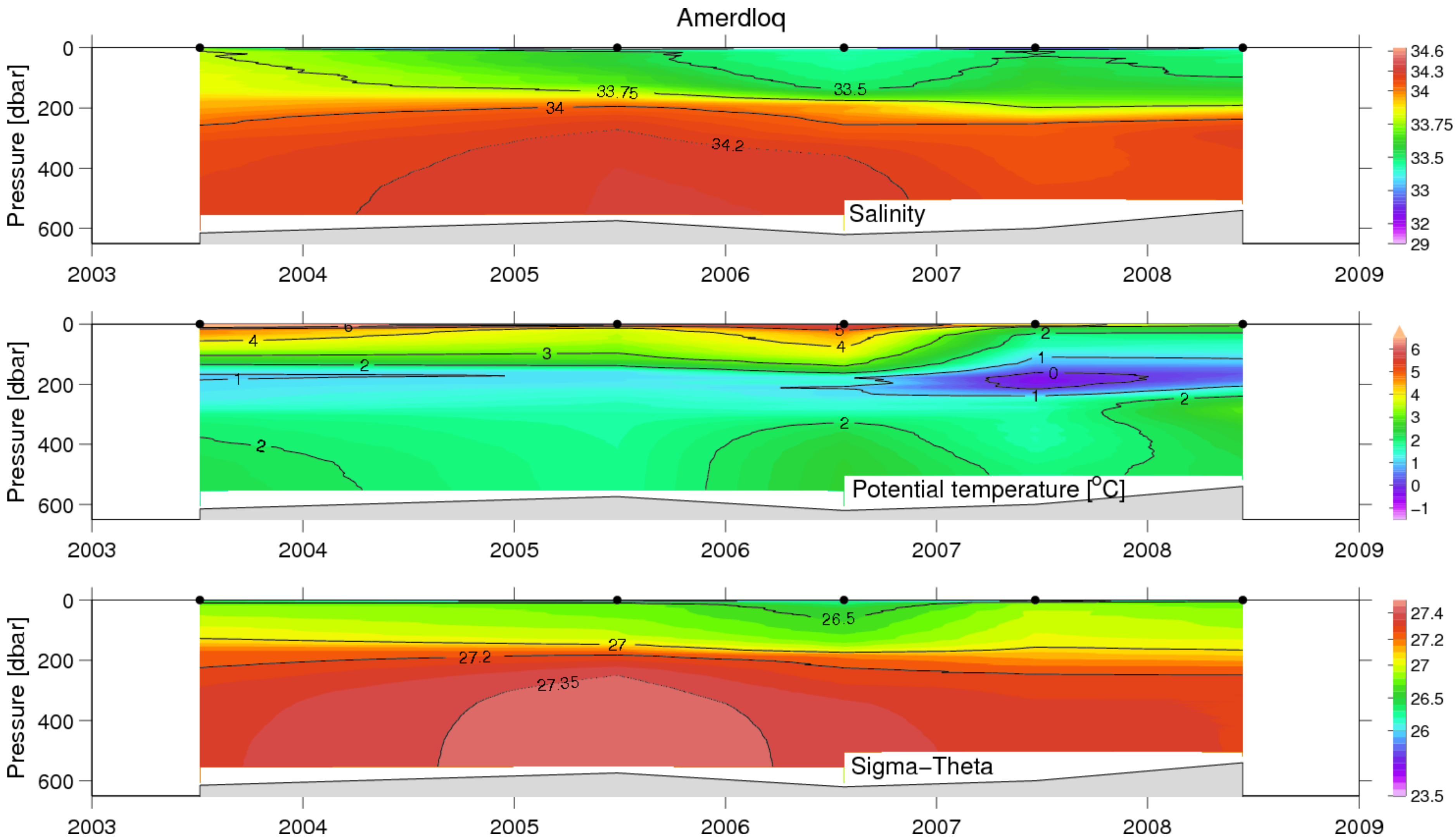

Figure 42. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Amerdloq fjord st.4, late June/July 2003, 2005–2008.

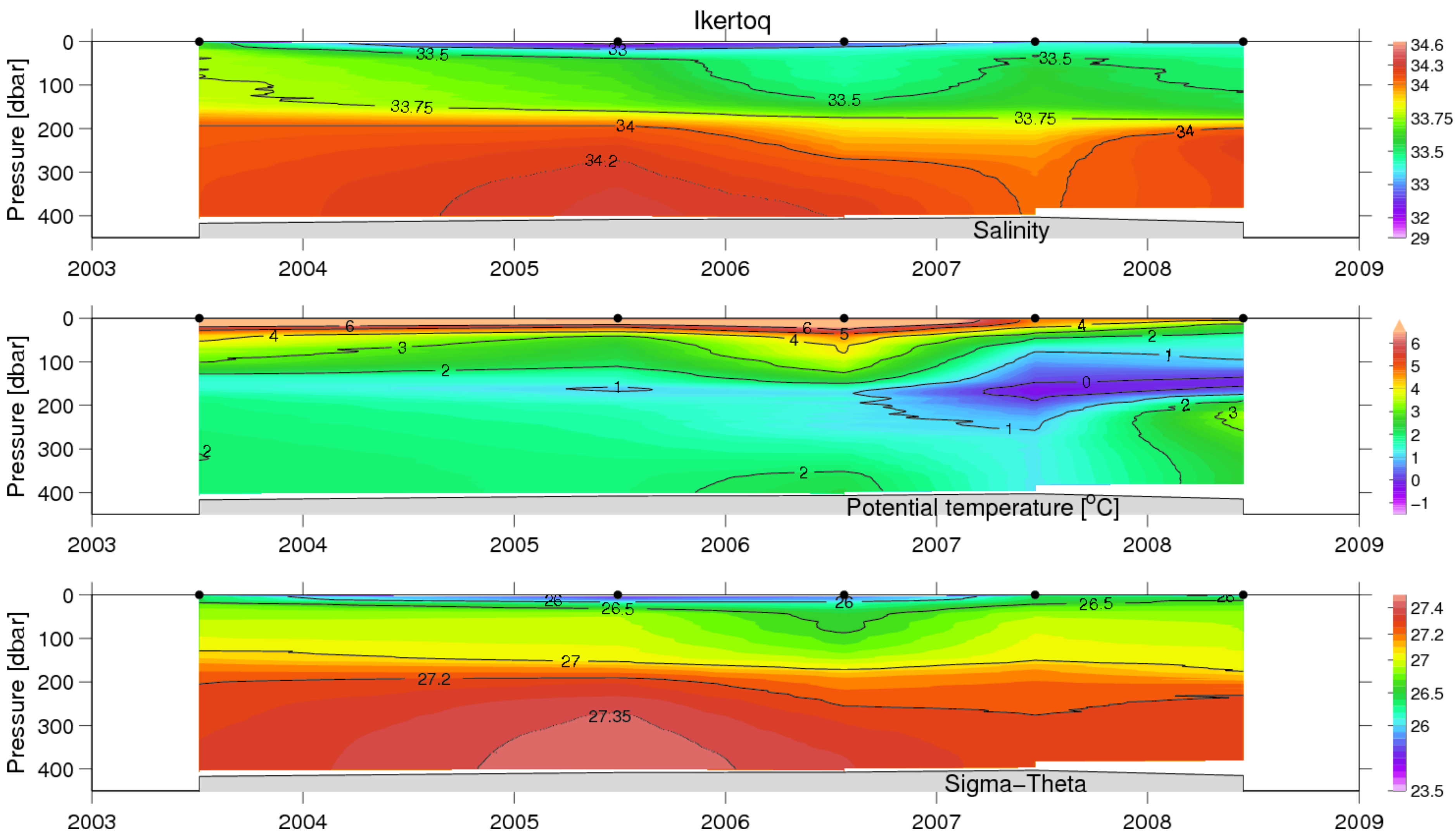

Figure 43. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Ikertoq fjord st.4, late June/July 2003, 2005–2008.

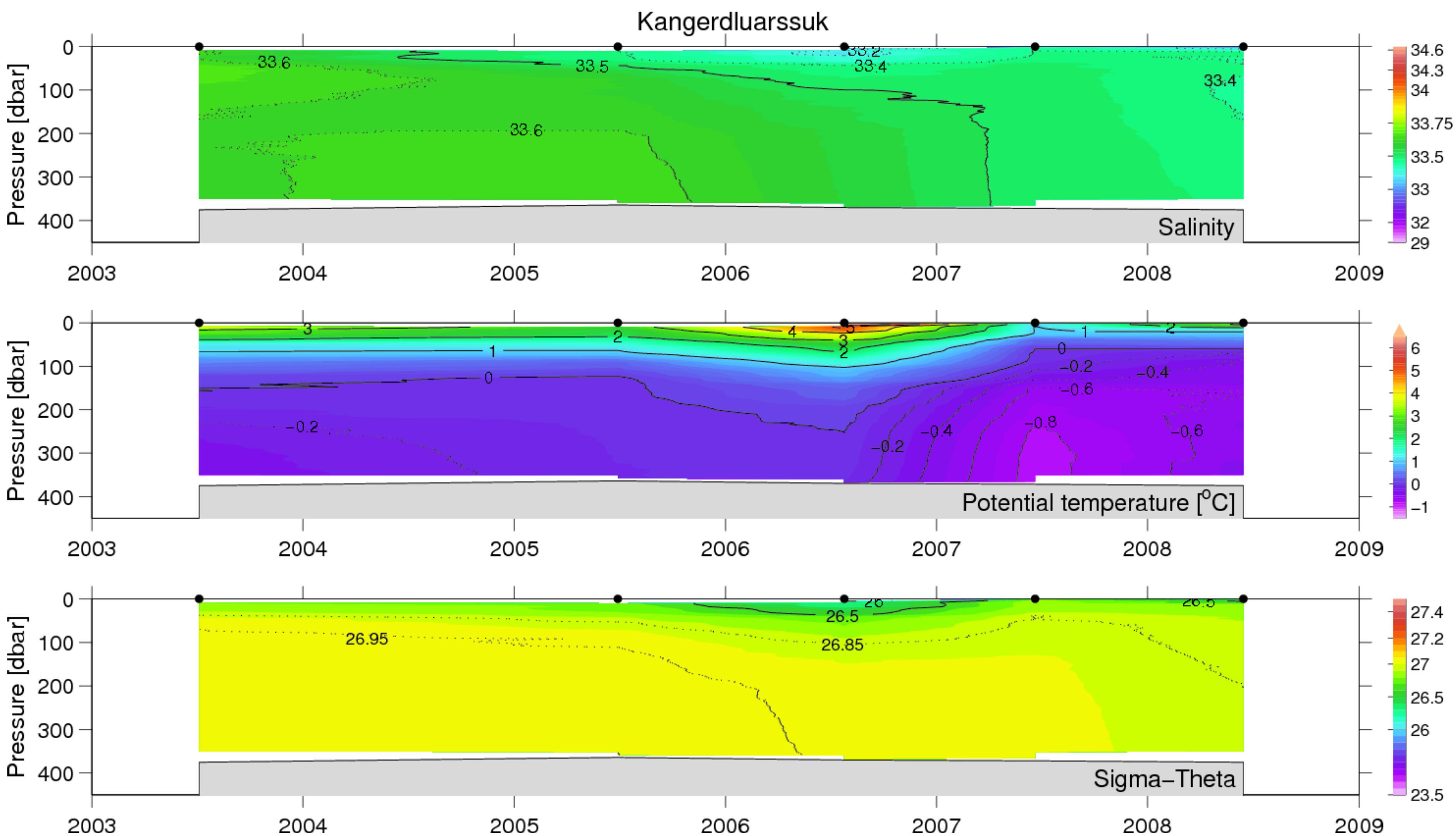

Figure 44. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Kangerdluarssuk fjord st.3, late June/July 2003, 2005–2008.

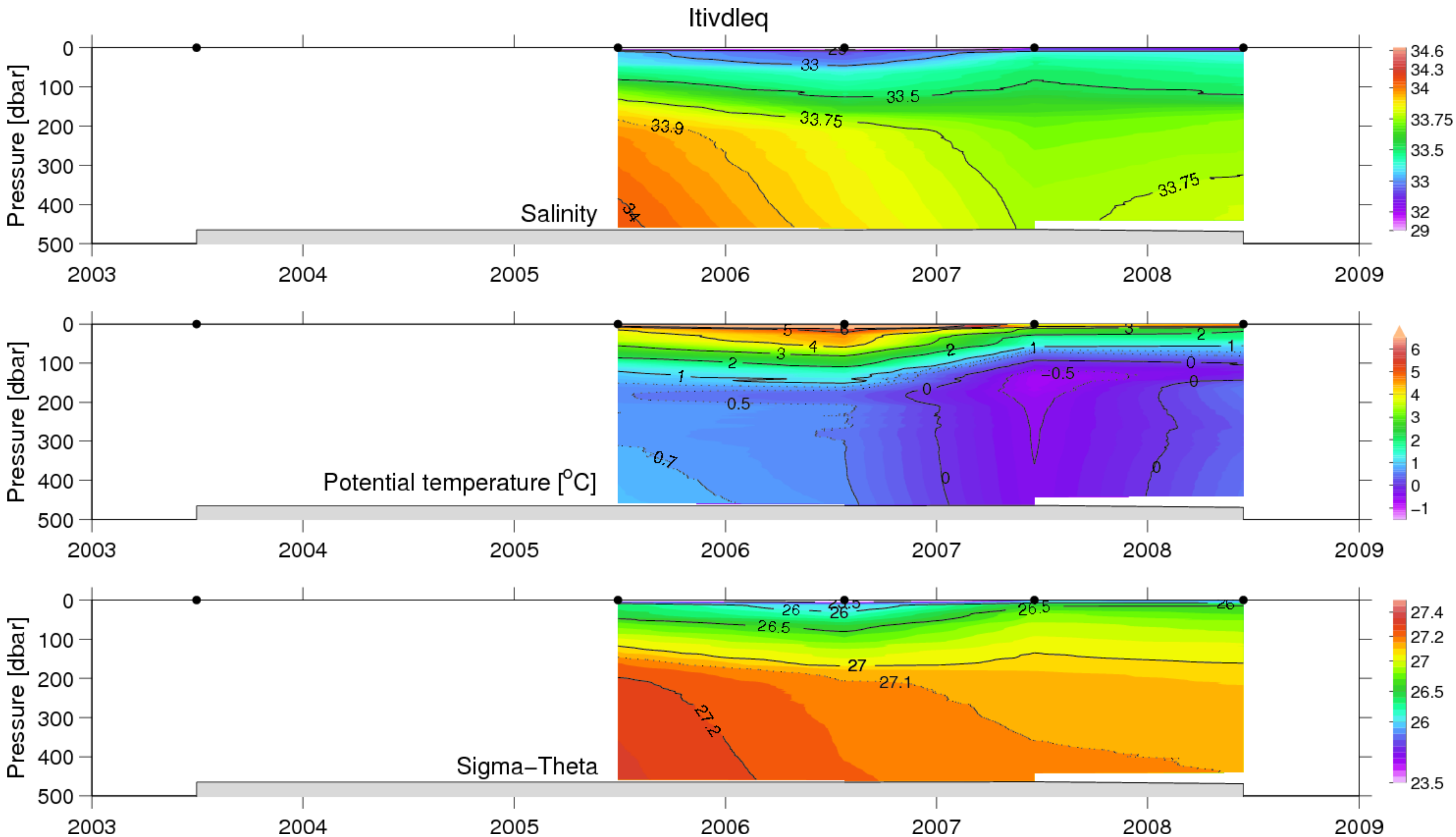

Figure 45. Hovmöller diagram of vertical distribution of temperature, salinity and density at the Itivdleq fjord st.4, late June/July 2005–2008.