Interannual variability of dissolved nutrients in the Canadian Archipelago and Baffin Bay with implications for freshwater flux

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Abstract Dissolved nutrient and oxygen data from August 1997 and 2003 cruises to Baffin Bay and the three main passages of the Canadian Archipelago are presented. As previously reported, higher Si and P concentrations are contributed to upper layers by Pacific waters that have made their way through Bering Strait and Arctic Ocean to our study region. In northern Baffin Bay, higher N tends to originate from the West Greenland Current. Significant along-strait mixing was documented for Nares Strait in 2003: 100% Pacific water comprised the upper 100 m at the northern end, whereas mixing diminished the seawater component to a 50:50 mixture of Atlantic and Pacific water at the southern end. A southward flowing subsurface jet at 100-200 m depth on the western side of Nares Strait is enriched in Si and P derived from Bering Strait in winter. Waters throughout the study region are marked by net denitrification that predominantly reflects their upstream sources. Contrary to previous reports, it seems likely that the composition of organic material being respired in deep Baffin Bay is very similar to that elsewhere in the global oceans. Comparison with previous nutrient measurements suggests that the flux of relatively fresh and nutrient enriched water through all the Archipelago passages was substantially higher in 1997 than in 1977 and 2003. The higher flux occurred during a prolonged high in the Arctic Oscillation Index but work underway should reveal whether and how larger scale atmospheric pressure patterns contribute to Archipelago throughflow variability.

1. Introduction

The channels between within the Canadian Archipelago connect the Arctic Ocean to the North Atlantic through Baffin Bay and the Labrador Sea (Fig. 1). In so doing, they function as key conduits for the global ocean circulation that transports freshwater and nutrients. The freshwater exits Baffin Bay near an important region of North Atlantic deepwater formation in the Labrador Sea and the nutrients fuel the rich ecosystems associated with recurrent polynyas and flaw leads within the Archipelago as and over the shelf and slopes further south [Stirling and Cleator, 1981]. In this paper, we present tracer hydrographic data that was taken in Baffin Bay and passages of the Canadian Archipelago in late summers of 1997 and 2003 and compare it to previously published data [Fig. 2, Based on IBCAO bathymetryJakobsson, et al., 2000]. The 1997 data were acquired as part of the US Canadian Joint Ocean Ice Studies (JOIS) that extended from Hudson Strait to the Beaufort Sea. The 2003 data were obtained in conjunction with a mooring program known as the Canadian Archipelago Throughflow Study (CATS) currently underway in passages west of Greenland. Our focus is on the dissolved inorganic macronutrients for which there are good historical measurements extending back to 1977. We specifically consider silicic acid (H_2SiO_3 or Si for short), phosphate (P) and fixed forms of nitrogen including nitrate (NO_3^-), nitrite (NO_2^-) and ammonium (NH_4^+) (with NO_3^- = N and $NO_3^- + NO_2^- + NH_4^+$ = TIN). We explore geographic and temporal differences in the nutrients that have implications for variability in freshwater throughput from the Arctic Ocean to the North Atlantic as well as local productivity.

2. Background

2.1. Circulation

The semi-enclosed Baffin Bay attains depths approaching 2400 m (Fig. 1). It is bounded on the west by a steeply sloping, narrow shelf and on the east by a much broader shelf. Both shelves are incised by a number of troughs. Baffin Bay has a surface area of about 690,000 km^2 and a volume of 590,000 km^3, values comparable to those of the Black Sea [Ross, et al., 1974]. The net flow of waters from the Arctic Ocean to Baffin Bay occurs through three main passages in the north at Lancaster Sound, Jones Sound and Smith Sound (Fig. 1). Exchange is restricted by shallow sills toward the Arctic Ocean side of the respective sounds at Barrow Strait (≈125 m deep, 55 km wide) and Wellington Channel (≈80 m deep, 30 km wide), Cardigan Strait (180 m deep, 8 km wide) and Hell Gate (125 m deep, 5 km wide), and the southern end of Kane Basin (220 m deep, 100 km wide) [Melling, 2000]. A sill at about 450 m also prevents direct communication of deeper Jones Sound waters with deep Baffin Bay. In the south, Labrador Sea and Baffin Bay waters are exchanged through Davis Strait between Baffin Island and Greenland (300 km wide at narrowest approach). It has a sill depth of about 650 m, with a complex topography.

General surface circulation patterns in the region have long been appreciated from ship and ice drift, hydrography (Fig. 1) [Muench, 1971], and more recently from satellite observations and modeling [Kleim and Greenberg, 2003; Tang, et al., 2004]. At eastern Davis Strait, a small portion of the relatively warm and salty West Greenland Current flows northward along the west Greenland shelf and slope while the dominant fraction veers westward into the Labrador Sea. Along its trajectory into Baffin Bay, the northward extension of the West Greenland Current is cooled and freshened. Modeling studies suggest that an important portion of this current may veer southward by about 72˚N [Dunlap and Tang, 2006; Tang, et al., 2004]. The remainder that continues northward rounds northern Baffin Bay and is joined by the even fresher, colder throughputs from the Canadian Archipelago passages to form the southward moving Baffin Current, also known as the Baffin Island Current or Canadian Current.

Flow within the Canadian Archipelago passages is not simply unidirectional; facing Baffin Bay, waters tend to flow into the channels from Baffin Bay on the left and out to Baffin Bay on the right [Fissel, et al., 1988]. The tidal components of the flow can be considerable (0.3-3 m s^{-1}) throughout much of the Archipelago [Fissel, 1982; Münchow, et al., 2006; Tang, et al., 2004]. This, together with winds, and friction from the bottom topography and ice cover induces significant along channel mixing. Such factors were in fact required for a realistic numerical simulation of summer circulation [Kleim and Greenberg, 2003].

The combined net outflow at Davis Strait has been variously estimated to be 0.5-2.6 Sv (Sv is sverdrup = 10^6 m^3 s^{-1}). The wide range reflects large uncertainties in both model [Kleim and Greenberg, 2003; Rudels, 1986; Steele, et al., 1996] and observation based approaches [Collin, 1962; Cuny, et al., 2005; Muench, 1971; Prinsenberg and Hamilton, 2005] as opposed to knowledge of variability, let alone trends. It is generally asserted that net flows through Lancaster and Smith Sounds are approximately equal with a lesser but not insignificant net flow through Jones Sound. However, such assertions are uncertain since they involve untested assumptions. Only fairly recently have attempts been made to directly and simultaneously observe flows through the individual passages at the resolution required to capture spatial variability at these high latitudes [Münchow, et al., 2006; Prinsenberg and Hamilton, 2005]. Characterization of temporal variability remains sketchy but significant strides can be expected in the coming years based combined observation and modeling programs currently underway.

Circulation at depth in Baffin Bay is less well characterized. Piecing together a number of current meter records at various locations around the perimeter of Baffin Bay from 1978 to

1990, Tang et al. (2004) showed that the deeper currents over the slope, as for the surface, are generally cyclonic. Currents decreased with depth in places such as Lancaster Sound, Davis Strait and southwestern Baffin Bay whereas they increased with depth in southern Smith Sound and on the West Greenland shelf break at about 71˚N. Top monthly mean speeds reached 0.10-0.14 m s^{-1} at 1000 m at the latter two sites and at the surface at Lancaster Sound. A somewhat more detailed picture provided for the North Water Polynya region is consistent with a topographically steered cyclonic mean flow [Melling, et al., 2001].

The canonical descriptions of water masses in Baffin Bay [Muench and Sadler, 1973; Tang, et al., 2004] are illustrated in our profiles from Central Baffin Bay in 2003 (Fig. 3). An upper (100-300 m) cold fresh layer is often called Arctic or Polar Water ($S < 33.7$) but includes both throughflow from the Arctic Ocean and upper West Greenland Current waters. In addition, seasonal heating, sea-ice melt/formation, glacial melt (bergs and runoff), non-glacial runoff, net precipitation (believed to be quite small) and mixing processes variously influence the surface layer. For example, Station B1 has pronounced surface freshening due to largely to Arctic throughflow that has been warmed in transit whereas the nearby station BNS2 in contrast has very little of this influence. Below the Polar water (300-800 m) lays saltier West Greenland Intermediate water ($33.7 \leq S < 34.55$ in Fig. 3) that includes a temperature maximum (approaching 2˚C in Fig. 3) originating in the Davis Strait inflow. Underlying this is Baffin Bay deep ($0.7 \geq T \geq -0.45$˚C, $S \leq 34.5$ in Fig. 3) and bottom waters (≥ 1800m, $T = -0.45$˚C, $S \geq 34.495$ in Fig. 3).

The general trends with depth illustrated in Fig. 3 profiles appear to be fairly homogeneously distributed throughout the basin. The properties ascribed to each of the layers by us differs somewhat from the literature due both to improved accuracy in the measurements and to secular changes in properties discussed below. It has been pointed out that waters of appropriate density to renew deep and bottom waters in Baffin Bay occur just below sill depth in the Lincoln Sea to the north [Muench, 1971] and to the south of Davis Strait [Tan and Strain, 1981]. However it is not clear that such waters could transit from these locations and avoid substantial dilution by entrainment upon sinking to depth [Bourke, et al., 1989]. Hence, local brine injection over shelves by ice formation has been invoked to impart sufficient density to a combination of northern and southern source waters [Bourke, et al., 1989]. The specific mechanisms giving rise to the renewal of the deep and bottom waters remain to be directly observed but transient tracer data indicate renewal times increasing with depth and exceeding several decades and perhaps centuries near the bottom [Top, et al., 1980; Wallace, 1985].

Zweng and Münchow (2006) analyzed historical temperature and salinity data in Baffin Bay covering the period of 1916-2003. They report a statistically significant decadal warming trend (0.2˚C per decade) in the core of West Greenland Intermediate water and extending, although diminishing with depth, to the bottom water. The trend implies warming of Davis Strait source waters over time. They note that heat content in Baffin Bay waters below the Davis Strait sill depth is consistent with supply by downward diffusion from an advected source that is warming. They also report a freshening trend of the Arctic surface layer that is particularly pronounced near Baffin Island (-0.08 per decade). The historical data are not extensive enough to examine annual and seasonal trends.

2.2. Previous discussions of nutrient distributions

The first systematic nutrient measurements of sufficient accuracy and precision for comparative purposes for Baffin Bay and passages were obtained in August and September of 1977 from the CSS Hudson (77-024) [Coote and Jones, 1982; Jones and Coote, 1980]. Except perhaps for Si in restricted areas [Codispoti and Owens, 1975; Franceschetti, et al., 1964], previous data sets exhibit sizeable scatter and offsets when plotted against salinity for subsurface waters and hence are not considered further here. We caution that even the published CSS Hudson 1977 P data were later reported to be too high by about 0.3 mmol m^{-3} due to a calibration error. Phosphate also displayed more scatter than did the other nutrients hence we do not rely on it quantitatively except to discuss relative trends.

Based on the 1977 results, Jones and Coote (1980) noted that surface waters presumably flowing into Baffin Bay through Lancaster and Jones Sounds were more concentrated in Si and P than such waters in Smith Sound. They further speculated in accord with earlier assertions [Codispoti and Owens, 1975], that Pacific waters passing through Bering Strait into the Arctic Ocean most strongly influenced properties in Lancaster Sound, less so in Jones Sound and possibly not at all in Smith Sound. Coote and Jones (1982) found Baffin Bay nutrient concentrations to be distinct in the major water types as delineated by temperature and salinity ranges summarized in the previous section. Depth gradients in the deep and bottom waters were shown to be quite substantial, increasing by about 50% for NO_3^- and P and 4-fold for Si from the intermediate water toward the bottom. The CSS Hudson occupied a few additional stations in central Baffin Bay and Lancaster Sound in 1983 [Wallace, 1985]. Except in very surface waters, nutrients measured only on a subset of the stations were quite similar to nearby stations from 1977.

Alkalinity and total inorganic carbon were also measured in 1977. In the initial discussion of this data, inorganic carbon was corrected for preformed values, changes due to both $CaCO_3$ dissolution using Alkalinity and organic matter decay (including the small contribution to alkalinity by NO_3^- regeneration) using dissolved O_2. Respiration of organic matter was presumed to follow the relationships established by Redfield and colleagues [Redfield, et al., 1963]:

$$[(CH_2O)_{106}(NH_3)_{16}H_3PO_4] + 138[O_2] = 106[CO_2] + 122[H_2O] + 16[HNO_3] + [H_3PO_4] \qquad (1)$$

After correction, the residual inorganic carbon, amounting to about 1% in deep waters, was interpreted to signal the presence of anthropogenic carbon [Jones and Levy, 1981].

Subsequent work showed that the nutrient and oxygen ratios in deep (500-1800 m) Baffin Bay deviated significantly from Redfield like molar ratios; N:P was reported to be 10 rather than 16 and O_2:P was 165 rather than 138 [Jones, et al., 1984]. At the time, it was assumed that the sedimentation rates in Baffin Bay were very low (a few mm per century) and so it was presumed that most organic matter was oxidatively decayed in the water column or right at the sediment-water interface. In explanation of non-Redfield nutrient ratios, Baffin Bay biogenic materials were suggested to differ in stoichiometry from the usual oceanic ones and an implied composition was presented. Since the time of Redfield's work and the Jones et al. (1984) publication, new data has engendered considerable discussion in the literature of stoichioimetric ratios of phytoplankton organic matter and oxygen consumed during remineralization [Sarmiento and Gruber, 2006]. On the world ocean scale, N:P remains close to the original formulation of 16±1:1 but more recent estimates of O_2:P are significantly higher than 138:1, ranging from 141-161:1 [Anderson, 1995] to 170±10:1 [Anderson and Sarmiento, 1994].

Pacific source waters delivered to the Arctic Ocean are depleted in N relative to Atlantic source waters due to denitrification that occurs south of Bering Strait and over the broad Chukchi shelf [Jones, et al., 1998]. Once delivered to the Arctic Ocean interior, N and P in both Atlantic and Pacific source waters vary in roughly constant proportions expected of biological uptake and regeneration governed by Redfield-like behavior. Jones et al. (1998) chose stations based on geographical locations to represent these relationships for Pacific and Atlantic source waters, and calculated the percent Pacific and Atlantic contributions at other locations assuming them to be a mix between the water types. This approach was later extended to mapping Pacific and Atlantic contributions in upper layers of subarctic seas of the North Atlantic using slightly different source water formulations [Jones, et al., 2003].

A subset of the August 1997 JOIS nutrient data (described below) so treated suggested that essentially all of the water flowing through the Lancaster and Jones Sounds and the upper 100 m of Smith Sound at that time was Pacific in origin. Note that this contrasts with earlier assertions based on the 1977 Si data that Nares Strait as represented at Smith Sound experienced little Pacific influence. Unfortunately P in the 1977 data set was not of sufficient quality to derive reliable information from N:P regarding the Pacific influence.

We note that the N:P Pacific source water relationship has recently been revisited [Yamamoto-Kawai, et al., 2006] and it has been shown that due to active nitrogen cycling of the Chukchi shelf that the total inorganic fixed nitrogen species (TIN) is preferable to NO_3 alone. Since our 2003 data set included quality NH_4^+ analyses, we adopt Yamamoto-Kawai's Pacific source water relationship in our TIN:P analyses. Also, strictly speaking, this type of analysis does not account for contributions in addition to Pacific and Atlantic seawater, such as river water and ice melt/formation. To a first approximation, river water can be considered part of the Atlantic component [Jones, et al., 1998]. Since river contributions are restricted to the upper layers in the Arctic Ocean and are generally less than 10% and sea-ice melt/formation exerts a smaller influence than this [Taylor, et al., 2003], we do not concern ourselves with them for the purposes of this publication.

Tremblay et al. (2002) took an analogous approach to Si versus NO_3^- relationships in upper mixed layer waters collected in the spring and early summer (April through July) within North Water Polynya region in 1998 (Fig. 1). The North Water, the largest (up to 80,000 km^2) and best known recurrent polynya in the Canadian Archipelago (Fig. 1), is the locus of an unusually rich ecosystem including whales, marine mammals and polar bear [Stirling and Cleator, 1981]. Their data showed active nutrient cycling to be occurring with a molar 1:1 Si:NO_3^- drawdown in the mixed layer but with higher initial Si concentrations in their northwestern sector. The Si-rich water was assigned a Pacific origin (via Bering Strait) based on a comparison of its properties with those of Pacific layers in the Arctic Ocean; the Si-poor variant was assumed to derive from the south in Baffin Bay [Tremblay, et al., 2002]. With assigned source water relationships, Pacific and Baffin Bay components were quantified. Pacific water analyzed in this way dominated the northwestern study region and penetrated furthest south in May and June when nearby current meter studies indicated largest southerly flows through Smith Sound. Nitrate began to be depleted in the mixed layer began in April and was exhausted in northeastern Baffin Bay by mid-June and in Smith Sound by July.

Diatom dissolution was invoked to explain the marked enrichment of Si relative to N with depth below the mixed layer in northern Baffin Bay. The limiting nutrient appeared to be N but a Si supply from the North was required to avoid Si limitation of the ecosystem. It was suggested, based on previously published spring nutrient data in the region, which include but a handful of surface samples covering two days in May 1991 [Lewis, et al., 1996] and the aforementioned late summer data, that nutrient concentrations and supply might undergo a seasonal cycle, being highest in the spring and low in late summer. As discussed below, our data show that interannual variability in late summer in Smith Sound can rival or exceed this presumed seasonal variability.

3. Methods

3.1. Fieldwork

As part of JOIS Legs 1 and 2, hydrographic tracer sections were conducted from the CCGS Louis S. St. Laurent during 1 August to 2 September 1997 in Hudson Strait, Davis Strait, Barrow Strait, Jones Sounds and Smith Sound (Fig. 2). Continuous conductivity-temperature-depth (CTD) profiling and water sampling were accomplished by deploying a rosette system from the A-frame and winch on the starboard boat deck. The rosette contained an Integrated CTD of Falmouth Scientific Inc. (SN 1329) and 23 10-liter B.O.T. (Brooke Ocean Technology, Dartmouth, Nova Scotia) PVC bottles. In addition to sections in the passages, a detailed tracer profile in deep central Baffin Bay as well as CTD (conductivity, temperature, depth) profiles extending from that deep station toward Lancaster Sound were undertaken. Water samples were collected for a variety of tracers including dissolved oxygen gas and nutrients. Between tracer stations, the hydrographic sections were supplemented by CTD-only profiling. A self-recording Micro CTD of Falmouth Scientific Inc. (SN 1534) was cast from a wire using the A-frame and winch on the foredeck of the vessel.

As part of the CATS program, hydrographic tracer sections were conducted during 26 July to 11 August 2003 from the USCGC Healy in central to western and central to northern Baffin Bay and across Nares Strait at four locations spanning its length (Fig. 2). A rosette system was deployed from the port A-frame on the working deck to carry out continuous CTD profiling with discrete water sampling. The rosette contained an integrated Seabird SBE9plus CTD with dual temperature and salinity sensors as well as an SBE43 dissolved oxygen sensor and 24 12-liter Ocean Test Equipment PVC bottles. Instantaneous currents were measured continuously using a hull mounted 75 kHz phased array (Ocean Surveyor) acoustic Doppler current profiler (ADCP). Additional surveying was carried out in order to gain estimates of the tidal signal of the instantaneous flow over the Baffin Island shelf and slope, near the Greenland coast just south of Smith Sound and in Nares Strait. A detailed description of the approach, which includes quantification of often dominant tidal currents that must be removed from the survey data is given elsewhere [Münchow, et al., 2006].

3.2. Analyses

In 1997, bottle salinities were determined at sea, after equilibrating for at least 12 hours to room temperature, using a model 8400A Guildline Autosal in a temperature controlled room. Results expressed on the practical salinity scale are precise to approximately ± 0.003. Dissolved oxygen was determined at sea by an automated Winkler titration using a Dosimat Titrator (model #665) and a colorimetric endpoint using a Brinkman colorimeter with a 450 nm filter [Carpenter, 1965; Culberson, 1991]. Precision based on replicates is ≤ 0.2%. Nutrients were determined at sea to a precision of ± 1% using a Technicon Autoanalyser II following published procedures with modifications (NO_3^-, NO_2^- and SiO_4) [Armstrong, et al., 1967; Bernhardt and Wilhelms, 1967]. The data from the cruise are available through the archives at the Institute of Ocean Sciences, Department of Fisheries and Oceans, Canada.

In 2003, bottle salinities were determined at sea, after equilibrating for at least 12 hours to room temperature, using a model 8400 B Guildline Autosal in a temperature controlled room. Results expressed on the practical salinity scale are precise to approximately ± 0.001. Dissolved oxygen was determined at sea by an automated Winkler titration using a PC-controlled titrator and amperometric end-point detection [Culberson and Huang, 1987]. The actual apparatus followed the adaptation to PC's by Knapp et al. [Knapp, et al., 1989]. Precision based on replicates is ≤ 0.5%. Nutrients were determined at sea using a hybrid Alpkem RFA 300 and Technicon AA-II (AutoAnalyzer II) — based system and the JGOFS/WOCE suggested nutrient protocols [Gordon, et al., 1994]. The Si, NO_3^-+NO_2^-, and NO_2^- channels were RFA-based, the P and NH_4^+ channels, AA-II. The short-term precision of the nutrient analyses is typically: Si 0.2%; P 0.4%; NO_3^- 0.3%; NO_2^- 0.02 mmol m^{-3}; and NH_4^+ 0.03 mmol m^{-3}. However, the inter-cruise reproducibility achieved during the WOCE Hydrographic Program, Pacific One-Time Survey was for Si, P and NO_3^-, respectively, ca. 1%, 2% and 1% [unpublished data, Ross et al.]. The data from the 2003 cruise are available through the National Snow and Ice Data Center archive, Colorado, USA.

4. Results

4.1. Baffin Bay

We begin with a presentation of properties in Baffin Bay as revealed by the highly detailed tracer hydrographic section taken July 26-31, 2003 (Fig. 4). This section was designed to intersect the shelf and slope bathymetry where it is relatively narrow and smooth and both up and downstream of the archipelago throughputs. Focusing on the upper 500 m of the water column (Fig. 4a), the most prominent feature is a cold fresh wedge that is thickest along the coast of Baffin Island but stretches across most of the section and has a temperature minimum that approaches the freezing point. Overlying this wedge is a relatively thin surface layer influenced by seasonal warming along most of the north-south trending portion of the section and at patches elsewhere. Surface waters are freshest (≤ 32.5) in the east-west trending portion of the section and over the Greenland shelf very close to the coast. Biological activities strip nutrients from the surface stratified layer with the most pronounced depletion occurring in the warmest (and fresh) waters over the Greenland Shelf. Below the surface layer, the cold-fresh wedge is more oxygenated and nutrient replete, except perhaps in TIN, than waters from comparable depths along the Greenland coast. An TIN:P analysis shows that the wedge feature and overlying waters are composed of greater than or equal to 50% Pacific water component derived through Bering Strait. More than 80% Pacific water is found at the surface near the Baffin Coast. Thus the fresh cold wedge and overlying waters result from the archipelago throughflows.

A very pronounced change in current direction, as indicated by the shipboard ADCP over the upper few hundred meters, separated Station BEW4 (at about the 200 km mark in the sections in Fig. 4) from those either side of it. Tracer hydrographic anomalies that are most evident at about 200 m in N and % Pacific and N* (see below) accompanied the current shear at BEW4. Below 500 m, the tracer fields appear displaced to slightly lower depths relative to surrounding stations. These features (and arguments presented below) are suggestive of an eddy that originated in the West Greenland Current. Deeper in the water column in the Baffin Bay section, the subsurface temperature maximum that is associated with the throughput from Davis Strait is most pronounced at about 500 m over the Greenland shelf-slope break (Fig. 4b). Underlying property depth trends are fairly homogenous throughout Baffin Bay.

Dissolved oxygen (O_2) is depleted from super or near saturation levels in the surface to as low as 120 mmol m^{-3} in Baffin Bay bottom waters while the nutrients increase with depth below the intermediate layer (Fig. 4b). With respect to concentrations at about 200 m, fixed N and P increase 2.5 fold to about 25 and 2 mmol m^{-3} respectively in Baffin Bay bottom waters while Si increases nearly 6-fold to 105 mmol m^{-3}. Below 600 m (Fig. 5), the molar ratio of $P:O_2$ was about -178 ± 6 and inorganic TIN:P ($\approx$ N:P) was 11.2 ± 0.2.

These trends in the nutrients are generally consistent with previous reports [Coote and Jones, 1982; Jones, et al., 1984] but do not necessarily imply regeneration of organic matter of unusual composition. The P:O_2 value is within the range of recent average global ocean estimates [Sarmiento and Gruber, 2006] although the N:P was low. To put the N:P ratios in context, we employ the parameter $N^* = N - 16^*P + 2.9$ mmol m^{-3} that uses phosphate to correct nitrate for organic matter remineralization as it is derived from the global scale [Deutsch, et al., 2001; Gruber and Sarmiento, 1997]. Residual positive values are thought to indicate net N_2-fixation and negative values net denitrification, although these processes may have occurred upstream of where the signals are observed. Our entire Baffin Bay section was characterized by $N^* \leq 0$ (Fig. 4b), reflecting an overprint of denitrification on all resident water masses. The most negative values within Baffin Bay, reaching –11 mmol m^{-3}, occurred in the surface archipelago throughput waters that are strongly influenced by Pacific input to the Arctic. Much less negative values of about –0.5 mmol m^{-3} were associated with mid-depth temperature maximum of the Davis Strait input that originates in the North Atlantic. How these relate to deep and bottom Baffin Bay N* values is pursued in the Discussion section below.

4.2. Nares Strait 2003

It has been appreciated for some time on the basis of temperature and salinity measurements that the Archipelago passages are not simple conduits for Arctic Ocean throughput [Melling, et al., 1984]. Within the straits, waters from the Arctic Ocean and Baffin Bay are blended as they meet and are subject to mixing by wind and tides, with friction exerted by bottom bathymetry and the ice cover over much of the year. Four quasi-synoptic cross-strait sections taken over August 4-11, 2003 provide an unprecedented opportunity to examine along-strait nutrient variability. The sections were located from Smith Sound in the south to Robeson

Channel in the north as shown in Fig. 2. Winds were out of the south for the majority of the sampling program. Instantaneous currents reached up to 0.6 m s^{-1} and were variable in direction. After removal of dominant tidal currents, subtidal flows were generally to the south reaching about 0.3 m s^{-1} below a wind influenced surface layer [Münchow, et al., 2006].

Starting in the north at Robeson channel (Fig. 6a), TS properties are quite similar to previous observations in the Lincoln Sea [Muench, 1971] except in the upper 100 meters where waters were fresher by 2 on the practical salinity scale and slightly warmer at the surface than in June 1967. In 1967, the upper 100 m was proposed to be similar to properties in the upper 100 m of the Eurasian Basin of the Arctic Ocean [Muench, 1971]. It was later suggested that diapycnal mixing over the Canadian polar shelf warmed the cold halocline of Canadian Basin waters so that they fortuitously resembled Eurasian Basin waters [Melling, et al., 1984]. Our 2003 N:P analysis (Fig. 6a) shows nearly 100% Pacific seawater component in the upper 100 m layer all away across the strait and so is consistent with this later interpretation.

On the western side of the strait, high Si (20 mmol m^{-3}) and somewhat elevated P (1.3 mmol m^{-3}) concentrations between 100 and 200 m mark the lower halocline nutrient maximum characteristic of winter Bering seawater (wBSW) that is enriched in nutrients over the Chukchi shelf [Cooper, et al., 1997; Jones and Anderson, 1986]. Detided shipboard ADCP data show that the high nutrients are also coincident with the core of a southward flowing, subtidal, subsurface jet (Fig. 6b) with a core speed of 0.3 m^{-1} that persisted throughout Nares Strait including Smith Sound during our 2003 observations [Münchow, et al., 2006]. As was noted previously, waters below 200 m in Robeson Channel and the Lincoln sea exhibit more of a Canadian Basin character than a Eurasian one [Muench, 1971].

Proceeding south, past Hall Basin into northern Kennedy channel, we show in Fig. 7 that the section displays similar TS properties, although the upper 100 m is slightly warmer than in Robeson Channel. At the same time the Pacific influence in the seawater component has been somewhat diluted in that upper layer, contributing approximately 70% in the upper 50 m across the strait with a diminishing influence spread to slightly deeper depths. The wBSW influence as indicated by Si and P remains very similar in character to that in Robeson Channel and the deeper water clearly originates in the Lincoln Sea.

In southern Kennedy Channel (Fig. 8), the bottom depth decreases by about 100 m. Surface waters do not attain the freshest values observed in the north but deeper water properties remain quite similar to those in northern Kennedy and Robeson Channels. The maximum Pacific influence is now reduced to 60% in the upper 25 m in two lobes toward the center of the channel. The locations of these surface features were not directly correlated to instantaneous surface current speed and direction. The subsurface Si and P maxima that signal wBSW remain on the western side of the channel between 100 and 200 m but are diluted and spread farther across the channel.

Striking contrasts occur south of Kane Basin in Smith Sound (Fig. 9). Recall that the sill in Kane Basin separates waters below about 220 m in the north from those in Smith Sound. Waters below the sill in Smith Sound bear temperatures and salinities characteristic of northern Baffin Bay. The surface mixed layer in Smith Sound is quite warm due to seasonal heating (reaching up to 4˚C) and becomes only as fresh as 31.5 in contrast to 29.5 in the northern sections. Only on the far western side of the channel in the upper 20 m does the Pacific influence reach 60%. Generally, the upper 150 m are a 50:50 mixture of Atlantic and Pacific water. The cold core of the southward moving subsurface jet remains on the western side of the channel Along Ellesmere Island at about 100 m (not shown). The wBSW nutrient signal is less distinct than in northern sections since Baffin Bay waters are relatively enriched in Si and to a lesser extent in P with depth below the sill depth. In their assessment of the diatom dominated biogeochemical cycling in the North Water Polynya region, Tremblay et al. (2002) invoked a northern source of Si in order to sustain productivity. If this subsurface jet persists in time and if its vertical current shear facilitates upward mixing, then it could serve as an important source of P and Si to euphotic zone of the more southern North Water Polynya.

5. Discussion

5.1. Nitrogen cycling in Baffin Bay

What is to be made of the unusual N:P of deep and bottom waters of Baffin Bay? Further insight is gained by examining salinity versus N* for Baffin Bay and surrounding passages (Fig. 10). Focusing on the Baffin Bay section, we discern that there is a distinct mixing line that connects the low N* of archipelago throughput with the maximal N* of Davis Strait input waters. At depths below the N*-salinity maximum, N* declines with depth while salinity changes little. On the Greenland side of Davis Strait at depths of between 200 and 500 m, comparably positive N* values (up to 1.2 mmol m^{-3}) and moderately high nutrient concentrations are associated with higher salinities than found anywhere else within Baffin Bay. This is not surprising since the adjacent North Atlantic Ocean to the south, that serves as the upstream source to Davis Strait, has been shown to be overprinted by net nitrogen fixation and so have positive N* values of up to 3.4 mmol m^{-3} [Sarmiento and Gruber, 2006]. The western Davis Strait samples constitute an extension of the distinct mixing line in Baffin Bay.

Quite a few points scatter to the left of the mixing line; most likely, these can be attributed to dilution by ice melt with negligible or perhaps slightly N-enriched nutrient contents. This appears to be the case for the two shallow stations closest to the Greenland coast (BNS13 and BNS 14) that are most extreme points on the upper left quadrant of Fig. 10. They represent a Greenland coastal current system, which derives its nutrients from the North Atlantic at Davis Strait but is diluted along transit with run-off from Greenland and sea ice melt. Another unique cluster of points with positive N* and moderately high nutrient contents occurred between salinity 33 and 34 (Fig. 10). These are from near 200 m depth in the eddy-like feature at BEW4 in the interior of Baffin Bay. It would appear that, during its transit in Baffin Bay to BEW4, the eddy experienced dilution of its salinity by ice-melt or runoff but little change in its nutrient relationships acquired at Davis Strait.

Interestingly, a group of samples from southern Kennedy Channel deeper than the sill in Kane Basin (≥ 220 m) showed salty, nutrient replete and positive N* values of up to 1.6 mmol m^{-3} similar to the Davis Strait waters. Waters from south of Kennedy Channel in Smith Sound and Baffin Bay do not attain salinities comparable to the ≥ 200 m waters in southern Kennedy Channel. Presumably the deeper southern Kennedy Channel properties near salinities 34.6 originate from North Atlantic waters that have circulated through passages east of Greenland through the Arctic Ocean and to the Lincoln Sea. The situation is not completely straightforward since samples of comparable and greater salinities and depths at more northern locations (northern Kennedy Channel, Hall Basin and Robeson Channel) did not exhibit quite so positive N* values (Fig. 10). Since it is unlikely the nitrogen fixation is occurring in situ at this location, it is more likely that the northern connection with the “Atlantic” influence is intermittent. Such intermittency is concordant with previous inferences based on comparing temperature and salinity fields for the only other surveys to cover the entire length of Nares Strait in 1971 and 1986 [Bourke, et al., 1989].

Data from within Barrow Strait in 1997 showed even more negative N* (down to –12.3 mmol m^{-3}) than found within Baffin Bay which suggests that this passage may be providing the low endmember of the N*-salinity mixing trend within Baffin Bay. A geographical gradation in "Pacific" character, extending from the most prominent at Lancaster, to less so at Jones and the least although not negligible at Smith Sound, is manifest in N* distributions. This gradation appears to persist through considerable variation in throughput as discussed in more detail below.

The 1997 Jones Sound section displays a truncated version of the Baffin Bay main N*-salinity mixing line between the archipelago throughput and Davis Strait input. Below its maximum (–2.0 mmol m^{-3}), N* decreases with depth while salinity changes little, much like in deep Baffin Bay but displaced to a lower salinity. Similarly O_2 (not shown) decreases with depth and is less in deep Jones Sound than in Baffin Bay; i.e. @ ca. 675 m 220 mmol O_2 m^3 in Jones Sound and 230 mmol O_2 m^3 in Baffin Bay. Near bottom N* in Jones Sound was significantly lower (–6.0 mmol m^{-3}) than in Baffin Bay (–4.7 mmol m^{-3}). The sill at about 450 m that separates deep Jones Sound from Baffin Bay restricts mixing and so contributes to maintaining these property differences. Without knowing by what mechanism and how fast the deep waters are renewed in either location, it is difficult to be certain about what generates these chemical differences. In the paragraphs that follow, we explore possibilities.

Both Jones Sound and Baffin Bay bottom waters have N*-salinity properties that fall below simple mixing lines in the 1997 and 2003 data for overlying waters (Fig. 10). Intermediate and deep waters in Robeson and northern Kennedy Channels and Hall Basin deviate to the right of the main mixing line in Baffin Bay. They are saltier for a given N* than in Baffin Bay and so their trends at about 200 m depth or near the sill depth of Kane Basin intersect the N*-salinity lines for deep Jones Sound and Baffin Bay. Their properties do not match deeper Baffin Bay and Jones Sound .

Waters that we sampled having the required N* would need to acquire salt in order to sink to depth. These waters occurred at such depth (≥200 m) that they are unlikely to directly accumulate sufficient brine [Bourke, et al., 1989; Muench, 1971]. Brine enrichment of low N* upper waters in the high ice production area of the North Water Polynya might be invoked as a way to acquire the necessary density. Then such waters would have to entrain higher N* waters upon sinking to depth to produce the temperature, salinity, and N* observed in Jones Sound and Baffin Bay bottom waters. However, there is no empirical evidence to support such brine accumulation in the high ice production area; the opening of the polynya by strong winds is very energetic so it is unlikely that surface waters reside long enough to accumulate sufficient salt [Melling, et al., 2001]. Note that dissolved O_2 contents are well below what would be expected from sinking of surface waters. Thus organic matter is being regenerated while O_2 is being consumed in situ. The O_2 depletion is yet another manifestation of a low rate of deep and bottom water renewal.

The situation is further complicated by the possibility of denitrification occurring in the sediments in Jones Sound and Baffin Bay. Exchange with pore waters of deep and bottom waters could contribute to the low N* values. Dissolved O_2 concentrations at depth in this region exceed the upper limit 150 mmol O_2 m^{-3} threshold for denitrification to be occurring in the water column except perhaps in microenvironments [Sarmiento and Gruber, 2006]. We are unaware of any direct attempts to determine whether denitrification is occurring within Baffin

Bay sediments, however, measured sedimentation rates in Baffin Bay are at least an order of magnitude higher than was assumed by Jones et al. (1984) [Andrews, et al., 1998]. If denitrification is occurring in Baffin Bay sediments, the impact on the water column may be analogous to that of sedimentary denitrification in the world ocean that reduces the apparent N:P utilization ratio to 12 ± 2 in waters between 1000 and 3000 m [Anderson and Sarmiento, 1994]. Relatively long deep and bottom water residence times would help to promote measurable impact from sedimentary processes. The lower N* in Jones Sound relative to Baffin Bay could be fostered by a larger sedimentary surface to water volume ratio.

A definitive resolution of the cause of low N* in deep and bottom Jones Sounds and Baffin Bay requires direct measurement of denitrification rates in sediments, better constrained water residence times and observations of tracer hydrographic properties throughout the year. We can make a crude upper limit estimate for the rate of denitrification in Baffin Bay sediments by assuming that only the West Greenland Current provides preformed N* (-0.5 mmol m^{-3}), that the volume of deep and bottom waters in Baffin Bay is about 94,700 km^3 [Bourke, et al., 1989] with an average N* of –4.0 mmol m^{-3} and that the residence time is minimally 100 years:

$$\frac{94,700\ \text{km}^3}{100\ \text{yrs}}\cdot[-0.5\text{mmol m}^{-3}-(-4.0\text{mmol m}^{-3})]\cdot\frac{14\text{gm N}}{\text{mol N}}\ ;\quad 0.05\ \text{Tg N yr}^{-1} \qquad (2)$$

This amounts to a negligible contribution to estimated global benthic denitrification of a few 100 Tg N yr^{-1} [Codispoti, et al., 2001; Gruber, 2004].

5.2. Interannual variability in nutrient distributions

Nutrients in Archipelago Passages 1977, 1997, 2003

Along-strait mixing, in-situ heating as well as ice melt and formation can all obscure attempts to quantify net throughput fluxes. This data set demonstrated that the seawater component of the upper 100 m layer was entirely Pacific in Robeson channel but appears to be diluted to ≤ 50% with Atlantic water in Smith Sound 400 km to the south. Very little time-series information for nutrients exists for this region, a situation probably best be remedied by deploying moored sensors and/or time-water sampling devices. In the meanwhile, we compare available data of sufficient quality to gain insights about interannual variability in August nutrient distributions in the three Archipelago passages.

In order to determine whether historical data sets differ from our more recent ones due to changes in the environment or due to analytical imprecision, we examined distributions for deep waters in Baffin Bay that are less likely to have changed much in time. We limit this exercise to the trustworthy historical datasets from 1977 & 1983 Hudson expeditions. Unfortunately nutrient data were very limited in geographical scope for the latter and will not be discussed further. Figure 11a illustrates that comparable deep and bottom water Si concentrations occurred in Central Baffin Bay during the 1977, 1997 and 2003 sampling programs. Intermediate waters differ in Si contents for a given salinity range by a few mmol m^{-3} within a given sampling year and between years, which may reflect geographic gradients and or temporal variability. Surface waters (salinity ≤ 33) are subject to seasonal productivity, variable ice melt/formation processes and source waters. Hence we do not necessarily expect comparable nutrient inventories from year to year.

The one passage for which quality nutrient data exist is Smith Sound where samples were taken in August of 1977, 1997 and 2003 (Fig. 11b). When plotting nutrients against salinity for sections across the archipelago passages, the data form an envelope that coalesces to low surface concentrations at low salinities and higher deep concentrations characteristic of Baffin Bay at the highest salinities. In Smith Sound the upper portion of the envelope in the intermediate salinity range is defined by the inflowing wBSW at the western side of the Sound. The eastern side of the sound defines the lower portion of the envelope. Note that the western side of Smith Sound was not fully sampled in 1977 due to the presence of ice. Taking that into account, we find that the data envelopes for 1977 and 2003 are quite similar (Fig. 11b). The entire data envelope is shifted up and to the left (higher nutrients in somewhat fresher waters) in 1997. For comparison, the Robeson Channel section data are also plotted in Fig. 11b. Although the deeper data coalesce to the higher salinities and lower Si characteristic of the Lincoln Sea, the Si in the mid-salinity range reaches values comparable to those observed in 1997 in Smith Sound.

In Jones Sound, waters that exit on the south define the upper portion of the Si-salinity data envelope while waters that enter on the north define the lower portion of the data envelope (Fig. 11c). Values of Si below 450 m increase steeply with the profiles coalescing to high concentrations at a salinity that is slightly less than on the Baffin Bay side of the sill. A similar contrast to that in Smith Sound is found between 1977 and 1997 results with the 1997 data envelope shifted up and to the left (Fig. 11c). While the shift may not appear to be as dramatic as for Smith Sound, note that the 1997 section was taken further to the east and so farther from the Pacific source waters in Jones Sound than in 1977 (Fig. 2). The upper part of the data envelope in 1997 is quite similar to that of 1977 station 45 at the western most end of Jones Sound. Station 45 is immediately downstream of the possible Pacific input at Cardigan Strait and Hell Gate. Lower concentrations in the upper most waters in 1997 may be attributable to in situ biological drawdown that occurs within Jones Sound. The attenuation of the nutrient contents due to mixing across Jones Sound can be gauged by comparing station 45 to the other stations in 1977.

As in Jones Sound, waters exiting on the south of Lancaster Sound define the upper portion of the Si-salinity data envelope and waters entering on the north define the lower portion of the data envelope (Fig. 11d). In 1997, sampling was conducted only in the environs of Barrow Strait and Wellington Channel (Fig.'s 1 & 2). A section somewhat farther to the west and very close to the sill was occupied in 1977 with additional sampling to the east of the 1997 stations and into Baffin Bay (Fig. 2) [Coote and Jones, 1982]. Despite the closer proximity to the Pacific source waters in 1977, the data envelope for 1997 is again shifted up and to the left by comparison. The more eastern stations occupied in 1977 coalesce to the high salinities and nutrients characteristic of deep Baffin Bay.

Comparing the three passages for any given time frame, we find that nutrient contents are highest, that is most Pacific-like, in Lancaster Sound, followed by Jones Sound and finally Smith Sound. The nutrient contents in all three passages are higher in 1997 than in 1977 and in Smith Sound, 1977 and 2003 contents were roughly similar. In both Jones and Smith Sounds, 1997 levels were similar to what has been observed farther upstream closer to high nutrient fresher Pacific source waters in 1977 and 2003, respectively. In Lancaster Sound, nutrient levels in 1997 were even higher than on a section located upstream in 1977. Mixing processes in Nares Strait resulted in lesser attenuation of nutrient signals in 1997 as compared to 1977 and 2003. The most straightforward interpretation of these results is that the fluxes of Pacific-influenced waters were significantly larger in August 1997 compared to August in 1977 and 2003.

Tremblay et al. (2002) correlated relatively high nutrient contents and high Si:N in western Nares Strait and in the North Water polynya region in May and June as opposed to July in 1998 with stronger southward current as measured by ADCP at the same time frame [Melling, et al., 2001]. Based on their results and limited nutrient measurements in May 1991 [Lewis, et al., 1996] and the August 1977 data, they proposed that high nutrients and higher fluxes in the spring might be part of a recurrent seasonal pattern. The variability we observed in the August time frame in Smith Sound and other passages rivals their proposed seasonal variability. Since nutrients must be supplied from the north to sustain high productivity in the North Water Polynya, it is important to understand the nature of variability in nutrient fluxes through Nares Strait. Moreover, as they are associated with lower salinities, the higher nutrient fluxes imply larger freshwater fluxes.

What gives rise to interannual variability in fluxes through the passages? Three years of August data for Smith Sound and two years of August data for Lancaster and Jones Sounds do not make for a definitive answer to this question. We speculate, however, that variability in fluxes through archipelago are related to variations in Arctic Ocean circulation that appear to be driven, at least in part, by changes in large scale atmospheric patterns [Morison, et al., 2006; Rigor, et al., 2002]. The Arctic Oscillation index (AO) provides a measure of the atmospheric variability (Fig. 12). In 1977 and 2003, the AO was circum-neutral whereas in 1997, it is positive after a prolonged positive period. Under a positive AO, the Beaufort Gyre is compressed along the northern reaches of the archipelago and Arctic transpolar drift shifts from alignment over the Lomonosov Ridge to over the Alpha-Mendeleev Ridge [Rigor, et al., 2002]. Perhaps this enhances the sea-surface height difference between the Archipelago and Baffin Bay and drives larger fluxes both of freshwater in the form of freshened seawater and nutrients.

6. Summary and Conclusions

Data from August 1997 and 2003 expand our understanding of the spatial and temporal variability of nutrient distributions in Baffin Bay and the passages of the Canadian Archipelago. Consistent with previous reports, the highest concentrations of Si and P in the upper waters of the passages are associated with Pacific input to the Arctic Ocean through Bering Strait, whereas N can sometimes be more concentrated in surface waters of the West Greenland Current. Within

Baffin Bay, nutrients are depleted from the upper mixed layer by biological activity. Also in accord with previous findings, the Pacific influence where the Archipelago passages meet Baffin Bay follows a gradation such that it is most pronounced in Lancaster Sound, followed by Jones Sound and finally Smith Sound. This relative relationship appears to hold despite changes in fluxes from year to year. We document for the first time nutrient enrichment (derived largely from wBSW) of a subsurface southward flowing jet on the western side of Nares Strait within about 5-10km of the Ellesmere Island coast.

Waters of Baffin Bay and the three main passages of the Canadian Archipelago are all overprinted by net denitrification. For upper waters, the denitrification has clearly occurred upstream in Pacific waters passing through Bering Strait that are impacted by processes in the Bering Sea and over the shelves of the Chukchi and East Siberian Seas. Below sill depths in Jones Sound and in Baffin Bay, relatively long residence times allow significant O_2 depletion and nutrient regeneration due to organic matter respiration and dissolution primarily of Si-bearing diatom shells. The extent of O_2 depletion and nutrient enrichment is measurably higher in deep Jones Sound than at comparable depths in Baffin Bay.

It seem likely that the composition of organic matter being regenerated in the region is comparable to that elsewhere in the world's oceans. The O_2:P in deep and bottom waters of Baffin Bay are in line with more recent estimates for organic matter regeneration in the global oceans. These are accompanied by unusually low N:P that arises largely from preformed values affected by upstream net denitrification. Dentrification occurring in the sediments may further overprint the water column N:P and N*. If the latter is occurring, it is of minor significance in the global N budget.

Interannual variability in nutrient contents in the archipelago passages rivals what little is known of seasonal variability. The most straightforward interpretation of the data implies that higher nutrient contents are associated with larger fluxes of the fresher nutrient replete water through the passages. Interestingly larger fluxes are indicated in 1997 at the gateways of all three passages (Lancaster, Jones and Smith Sounds) relative to 1977. This suggests a fairly large scale driving force may be involved. Though the 1997 mission occurred during a sustained positive phase of the Arctic Oscillation Index, whether and how atmospheric pressure patterns are related to Archipelago throughput fluxes remains unclear. Ongoing efforts to obtain moored times series of currents and pressure gradients in Nares Strait can be expected to shed further light on this issue.

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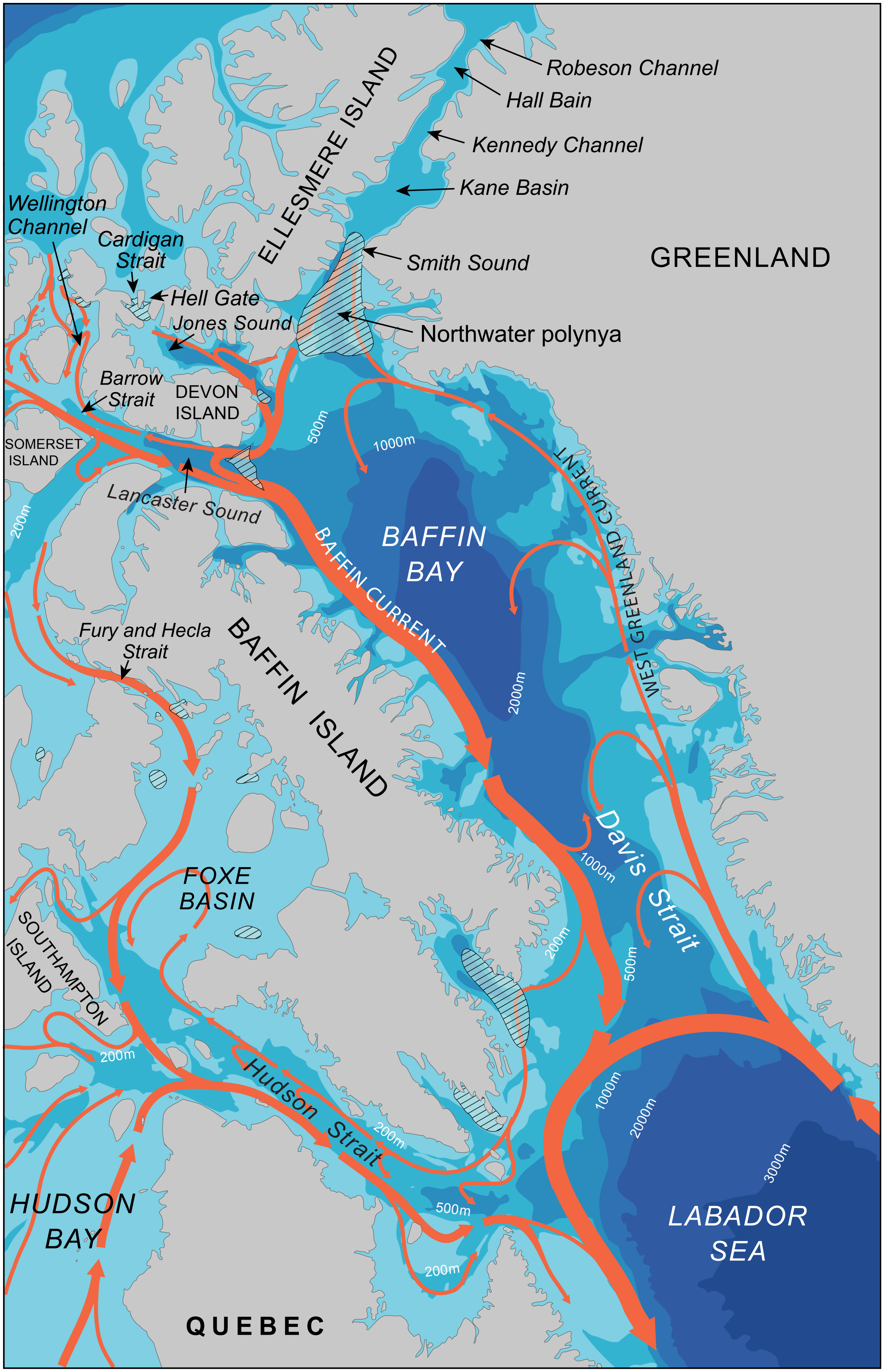
Robeson Channel
Hall Bain
Kennedy Channel
Kane Basin
ELLESMERE ISLAND
Wellington Channel
Cardigan Strait
Smith Sound
GREENLAND
Hell Gate
Jones Sound
Northwater polynya
Barrow Strait
DEVON ISLAND
SOMERSET ISLAND
500m
1000m
Lancaster Sound
WEST GREENLAND CURRENT
200m
BAFFIN BAY
BAFFIN CURRENT
Fury and Hecla Strait
BAFFIN ISLAND
2000m
Davis Strait
1000m
FOXE BASIN
200m
500m
SOUTHAMPTON ISLAND
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Hudson Strait
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LABADOR SEA
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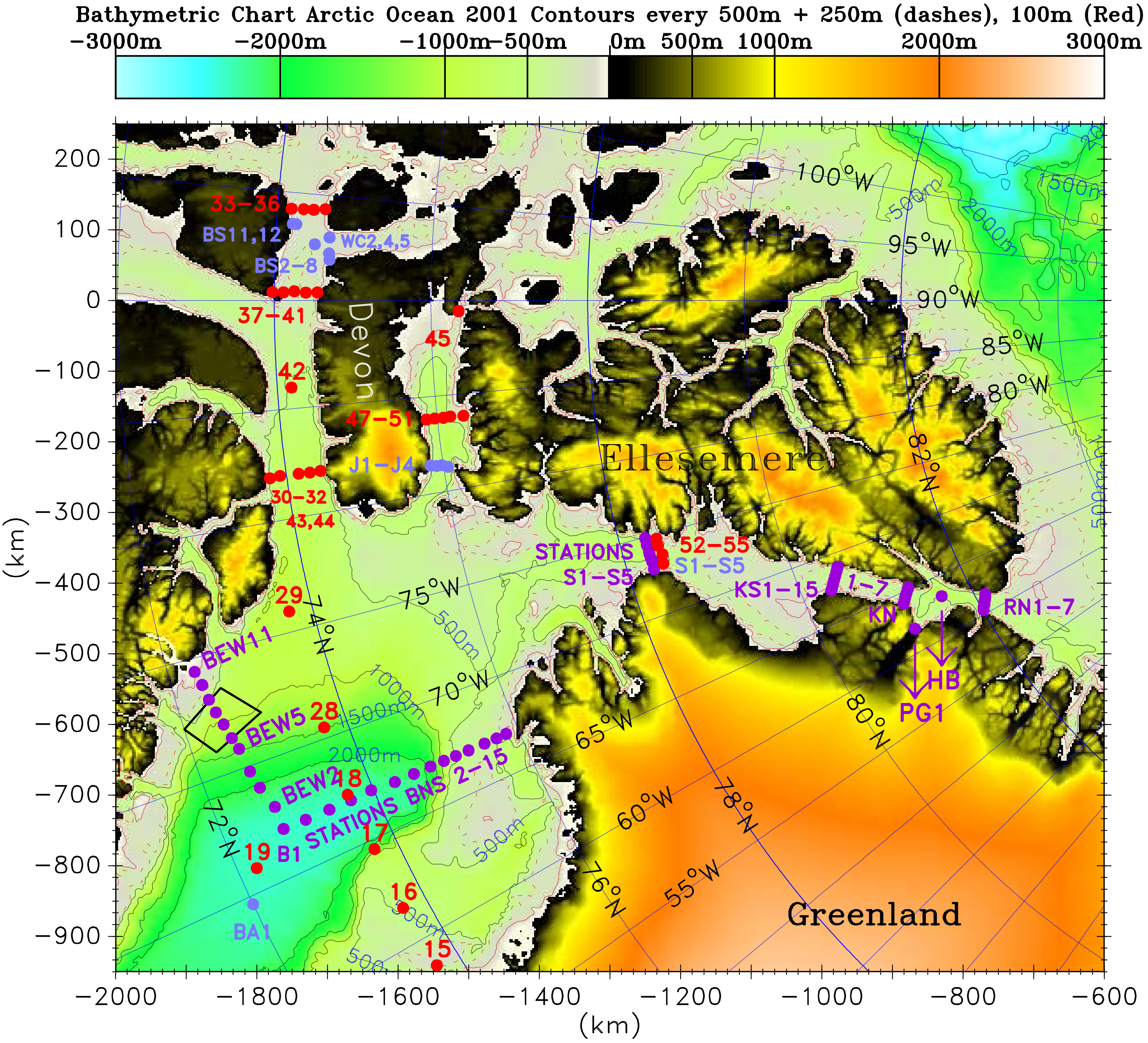
QUEBEC


Bathymetric Chart Arctic Ocean 2001 Contours every 500m + 250m (dashes), 100m (Red)
−3000m
−2000m
−1000m
−500m
0m
500m
1000m
2000m
3000m
33−36
BS11,12
WC2,4,5
BS2−8
37−41
Devon
45
42
47−51
J1−J4
30−32
43,44
29
74°N
75°W
BEW11
BEW5
28
70°W
BEW2
18
STATIONS BNS 2−15
B1
19
17
72°N
16
15
BA1
Ellesemere
100°W
95°W
90°W
85°W
80°W
82°N
STATIONS
S1−S5
52−55
S1−S5
KS1−15
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KN
RN1−7
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PG1
80°N
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78°N
55°W
76°N
Greenland
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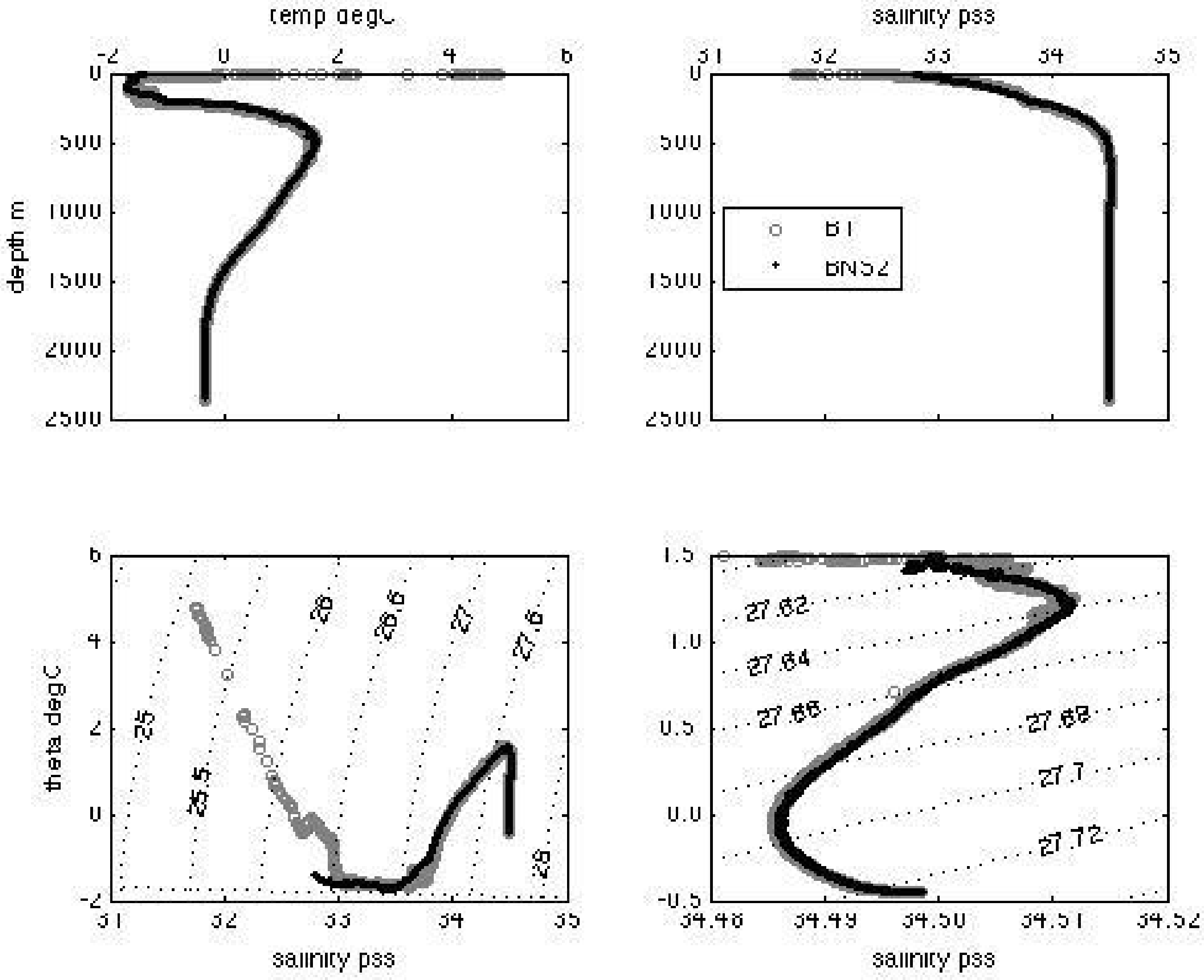
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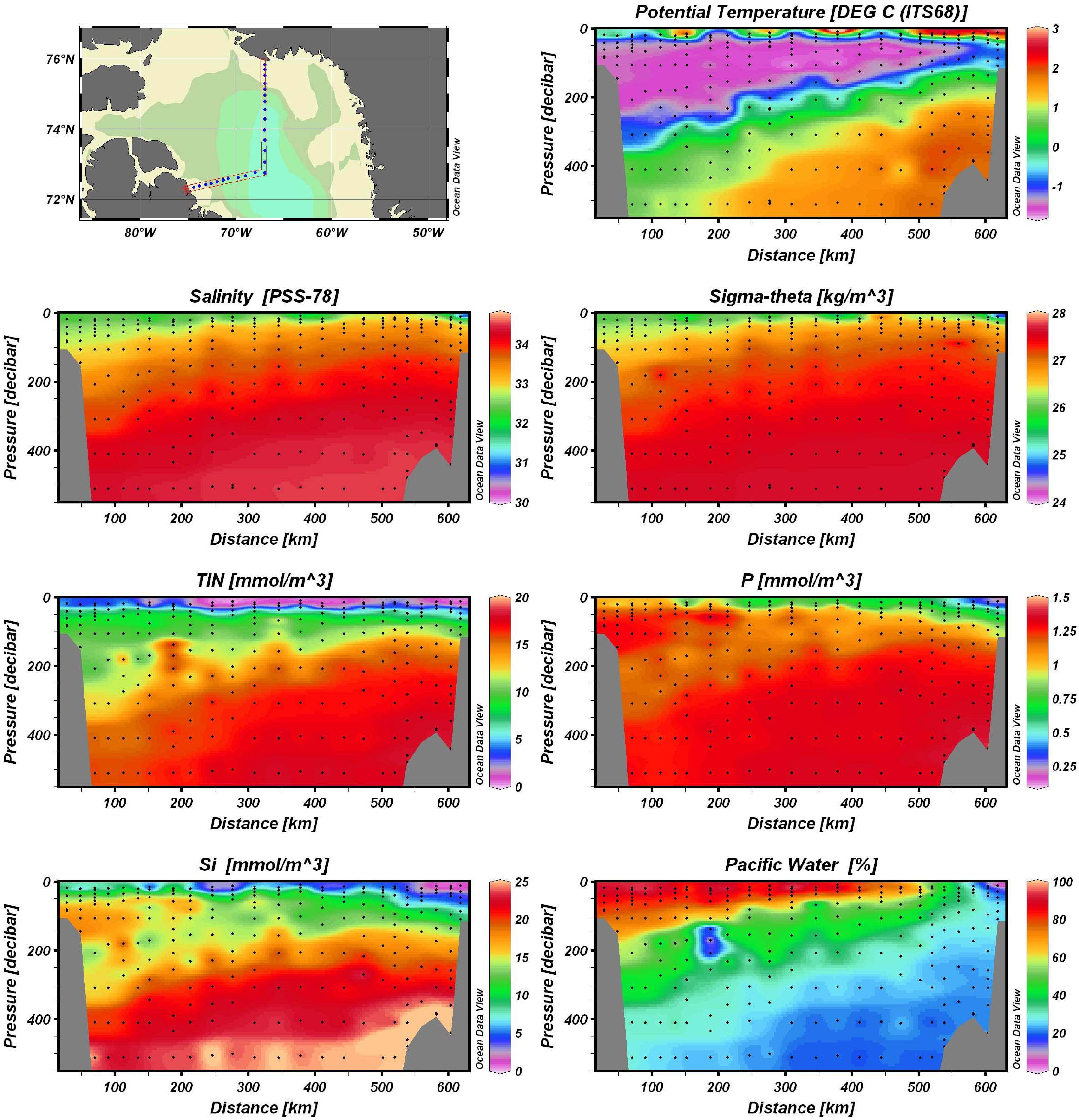
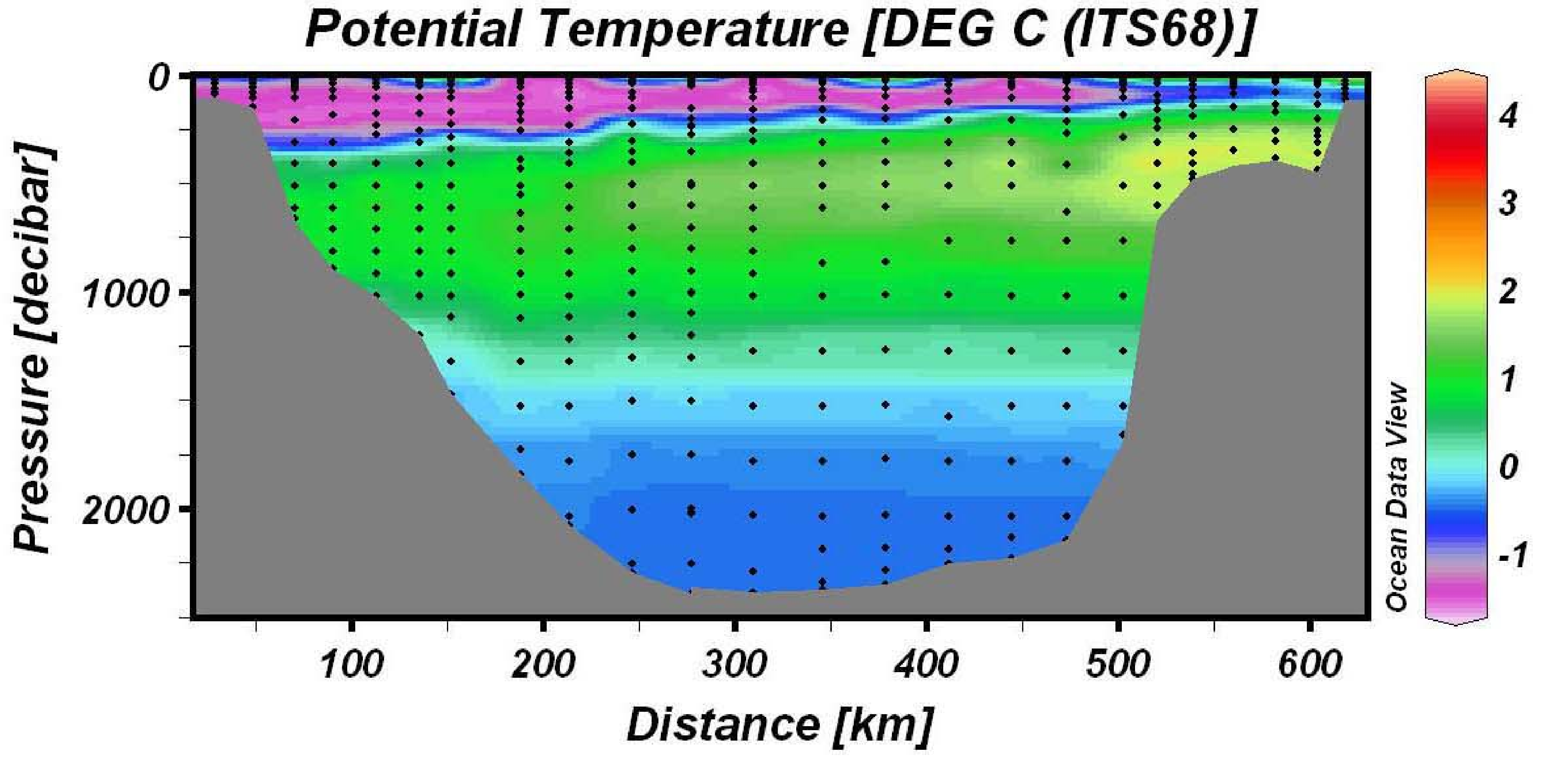
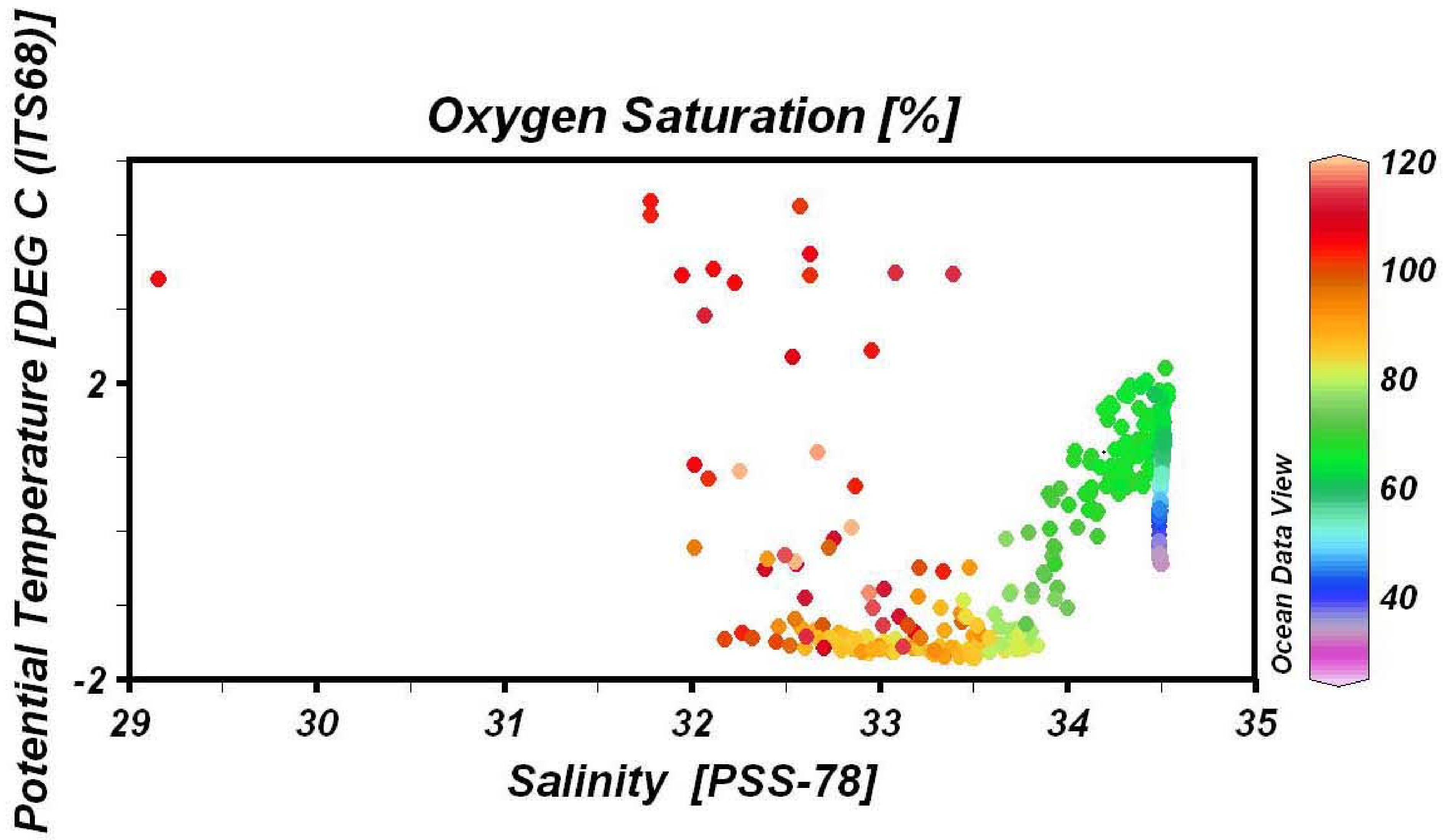
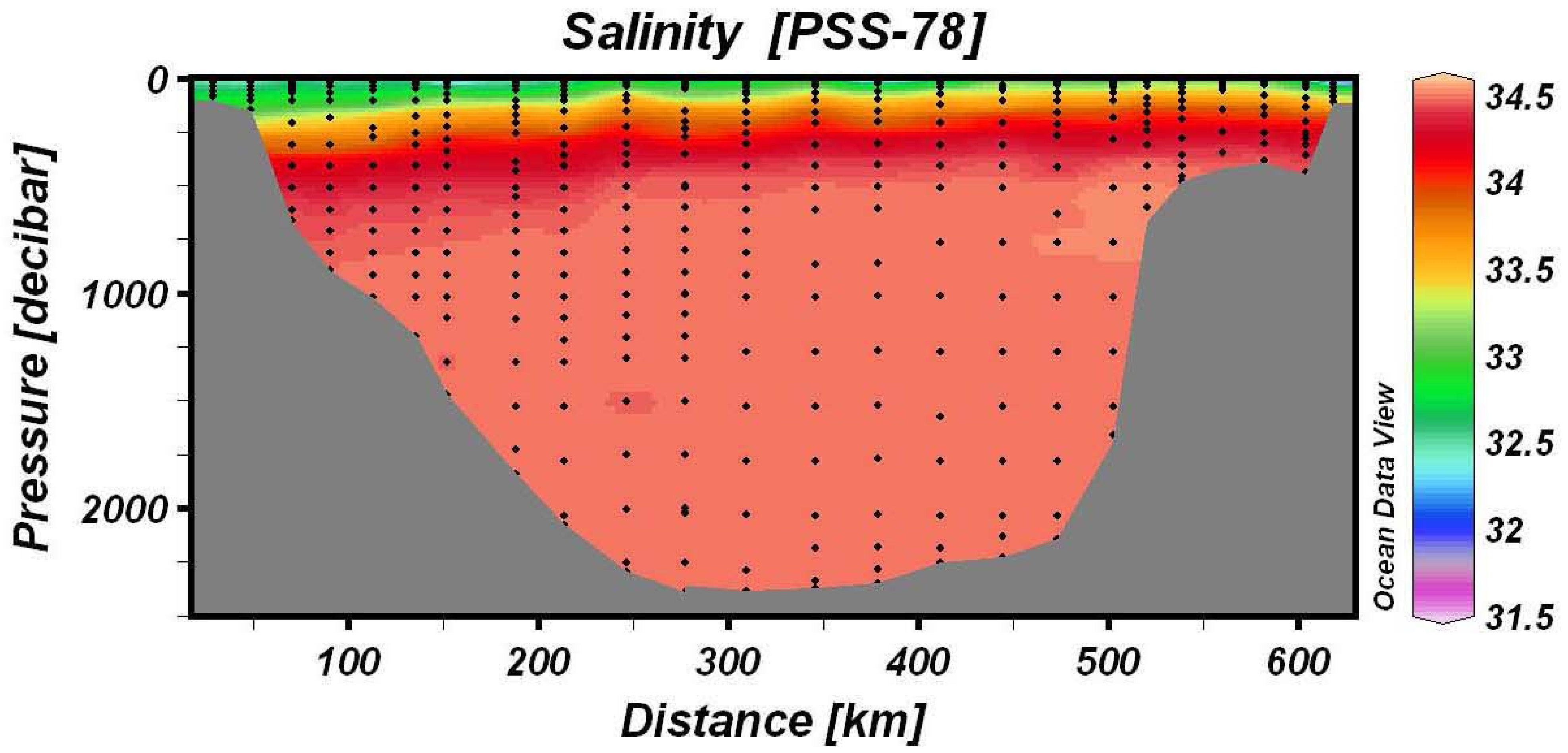
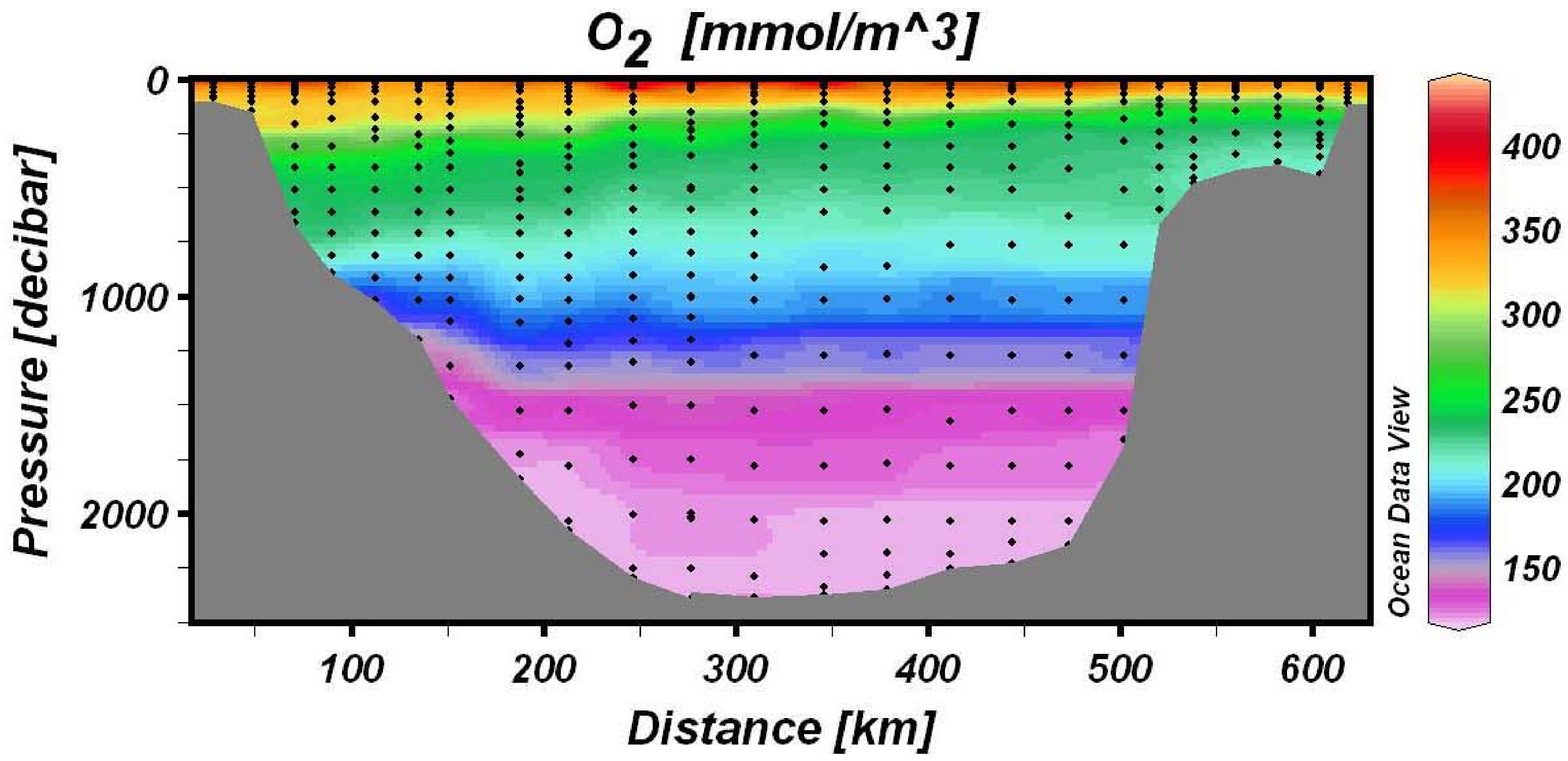
0
500
1000
1500
2000
2500
salinity pss
31
32
33
34
35
0
500
1000
1500
2000
2500
BT
BN52
theta degC
6
4
2
0
-2
31
32
33
34
35
salinity pss
25
25.5
26
26.5
27
27.5
28
1.5
1.0
0.5
0.0
-0.5
27.62
27.64
27.66
27.68
27.7
27.72
34.48
34.49
34.50
34.51
34.52
salinity pss

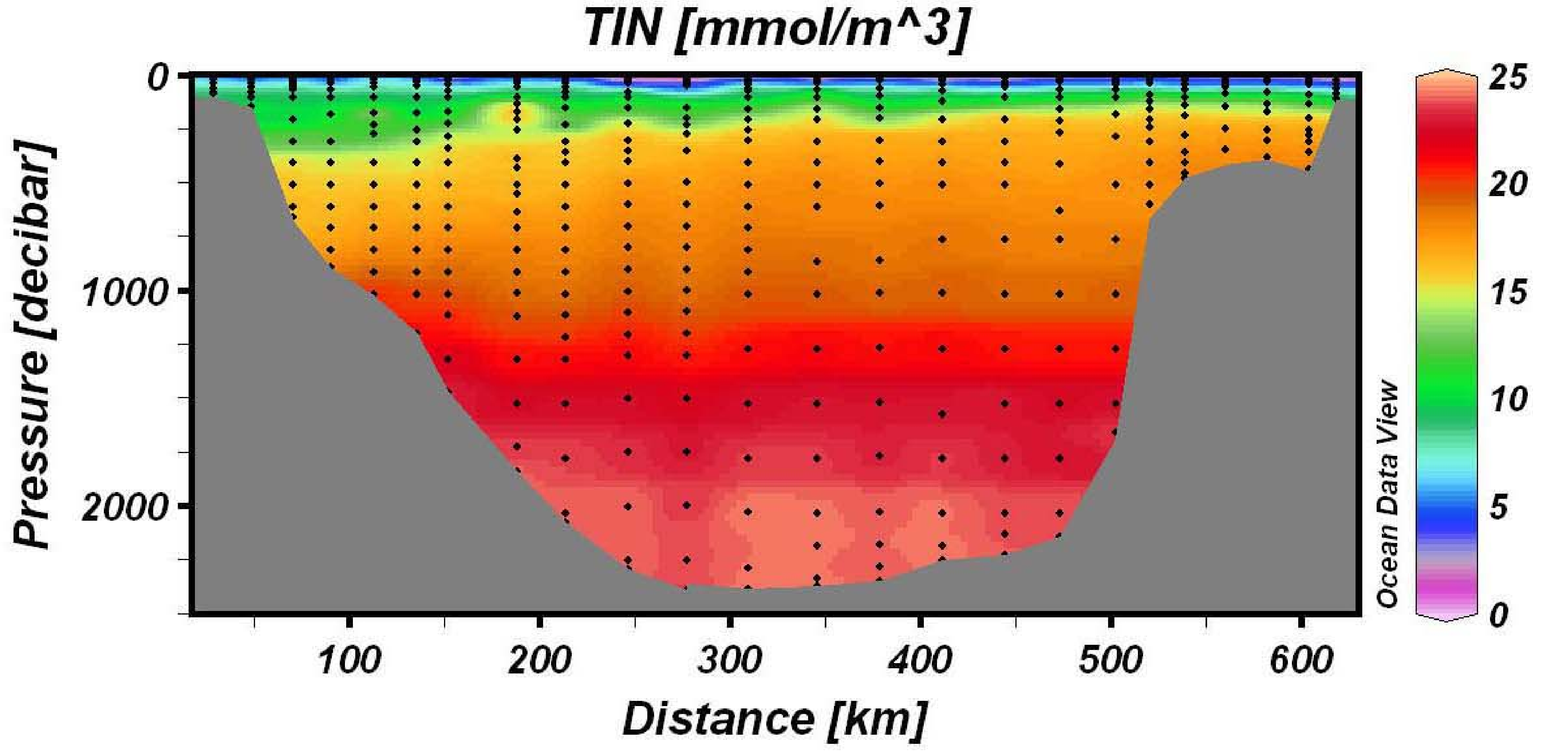

76°N
74°N
72°N
80°W
70°W
60°W
50°W
Ocean Data View
Potential Temperature [DEG C (ITS68)]
Salinity [PSS-78]
Sigma-theta [kg/m^3]
TIN [mmol/m^3]
P [mmol/m^3]
Si [mmol/m^3]
Pacific Water [%]
Pressure [decibar]
Distance [km]
0
200
400
100
200
300
400
500
600
3
2
1
0
-1
34
33
32
31
30
28
27
26
25
24
20
15
10
5
0
1.5
1.25
1
0.75
0.5
0.25
25
20
15
10
5
0
100
80
60
40
20
0

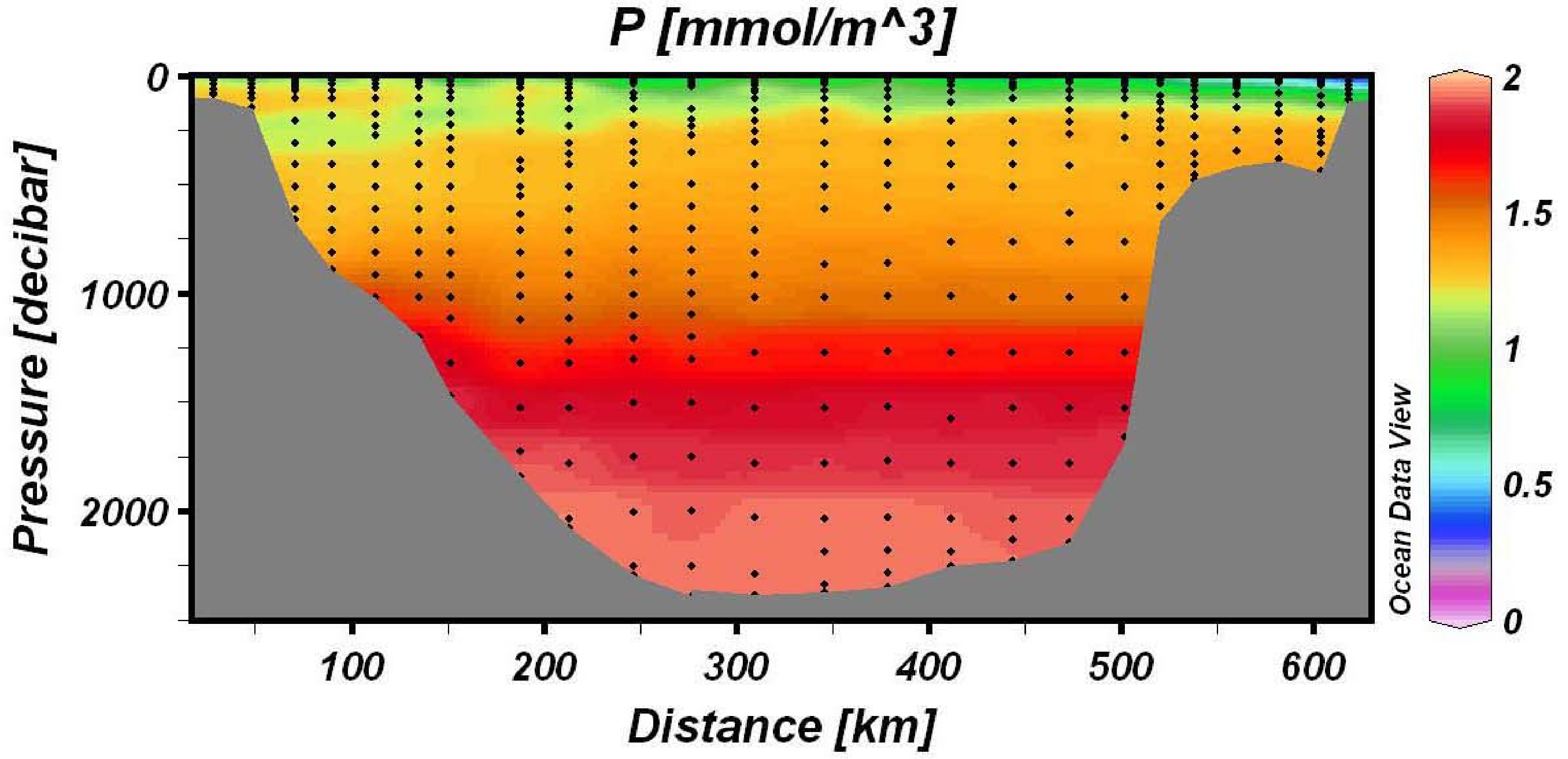

Potential Temperature [DEG C (ITS68)]
Pressure [decibar]
0
1000
2000
Distance [km]
100
200
300
400
500
600
4
3
2
1
0
-1
Ocean Data View

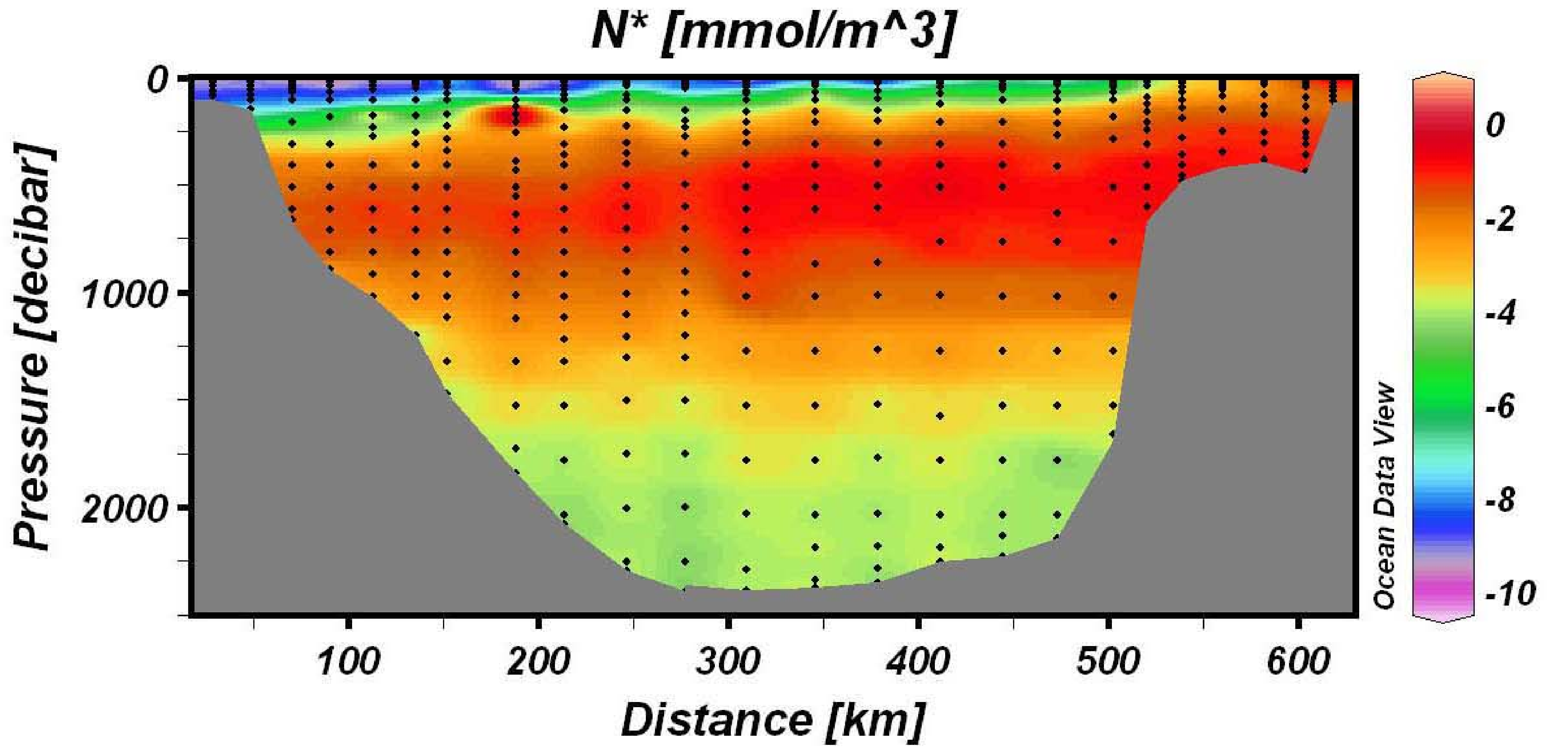

Oxygen Saturation [%]
Potential Temperature [DEG C (ITS68)]
2
-2
Salinity [PSS-78]
29
30
31
32
33
34
35
120
100
80
60
40
Ocean Data View

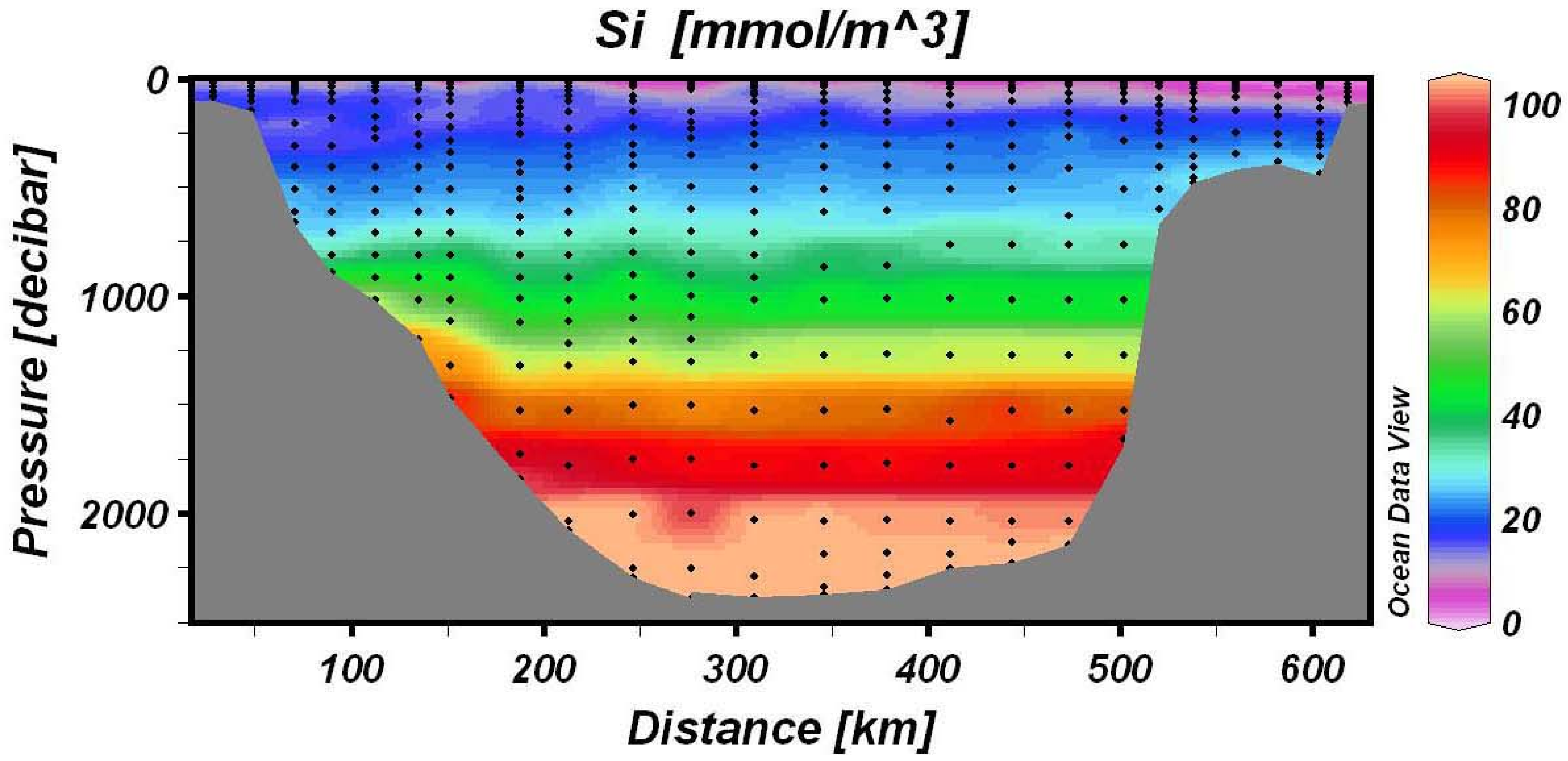

Salinity [PSS-78]
Pressure [decibar]
0
1000
2000
Distance [km]
100
200
300
400
500
600
34.5
34
33.5
33
32.5
32
31.5
Ocean Data View

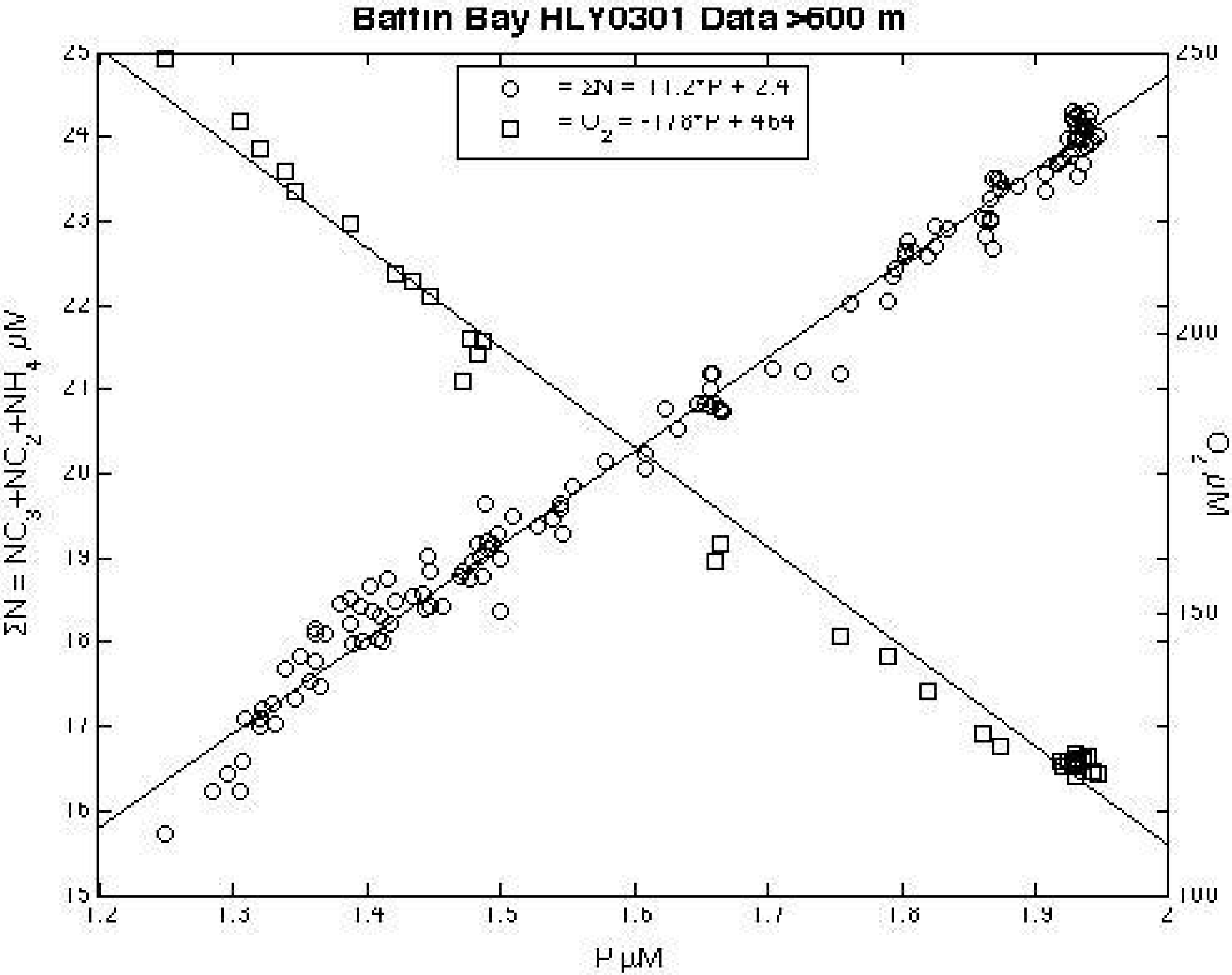

O2 [mmol/m^3]
Pressure [decibar]
0
1000
2000
Distance [km]
100
200
300
400
500
600
400
350
300
250
200
150
Ocean Data View

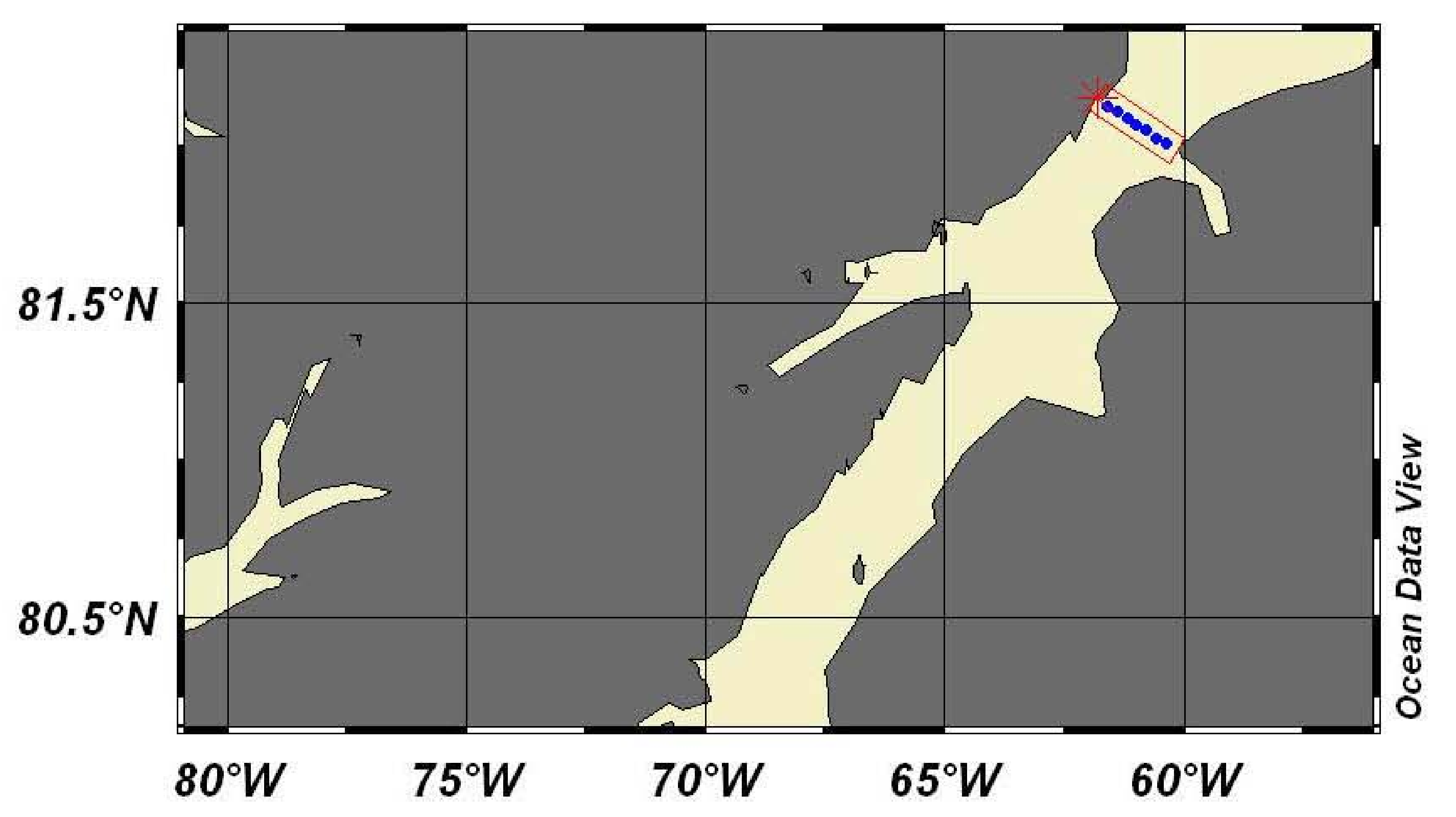

TIN [mmol/m^3]
Pressure [decibar]
0
1000
2000
Distance [km]
100
200
300
400
500
600
25
20
15
10
5
0
Ocean Data View

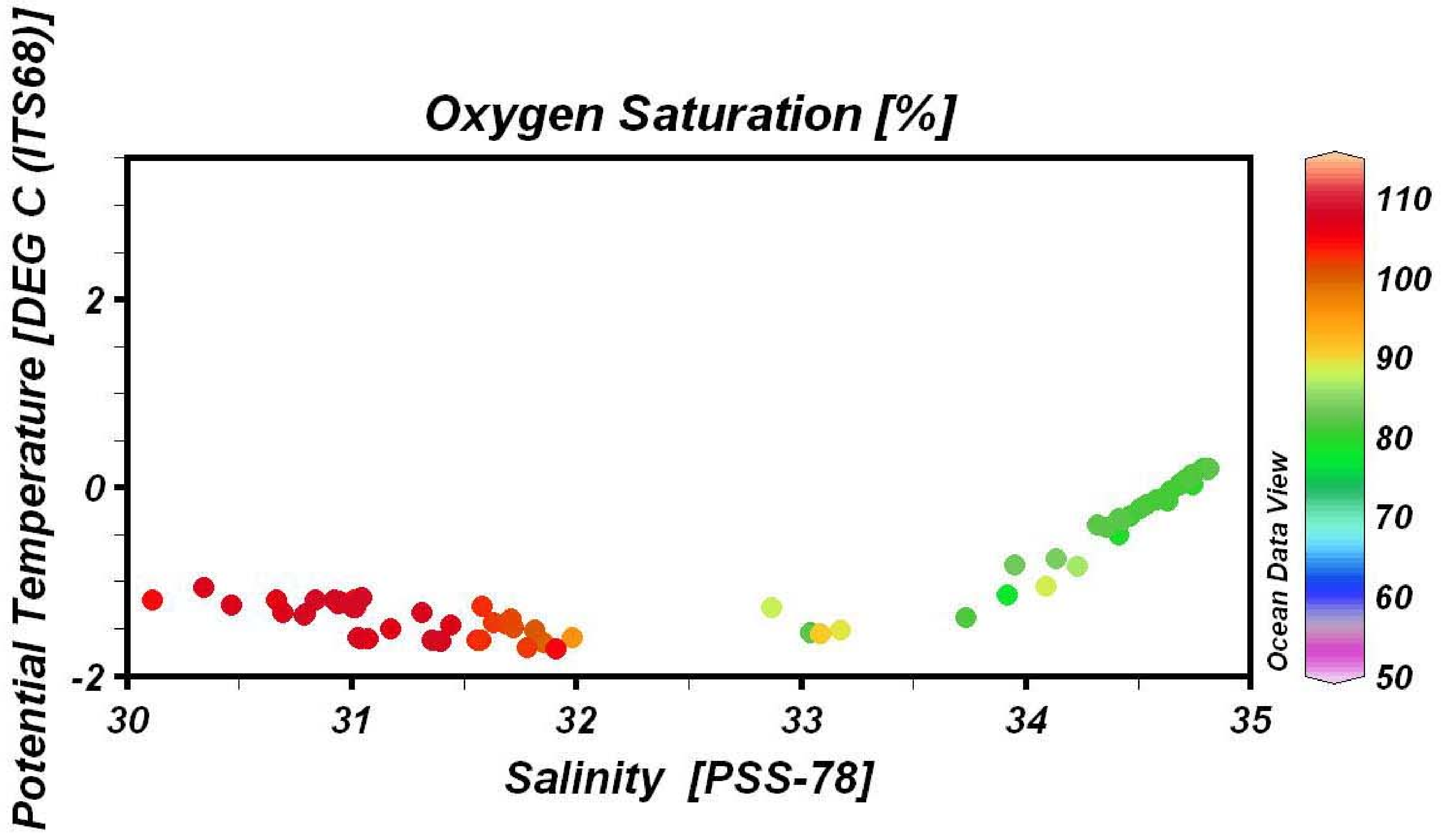

P [mmol/m^3]
Pressure [decibar]
0
1000
2000
Distance [km]
100
200
300
400
500
600
2
1.5
1
0.5
0
Ocean Data View

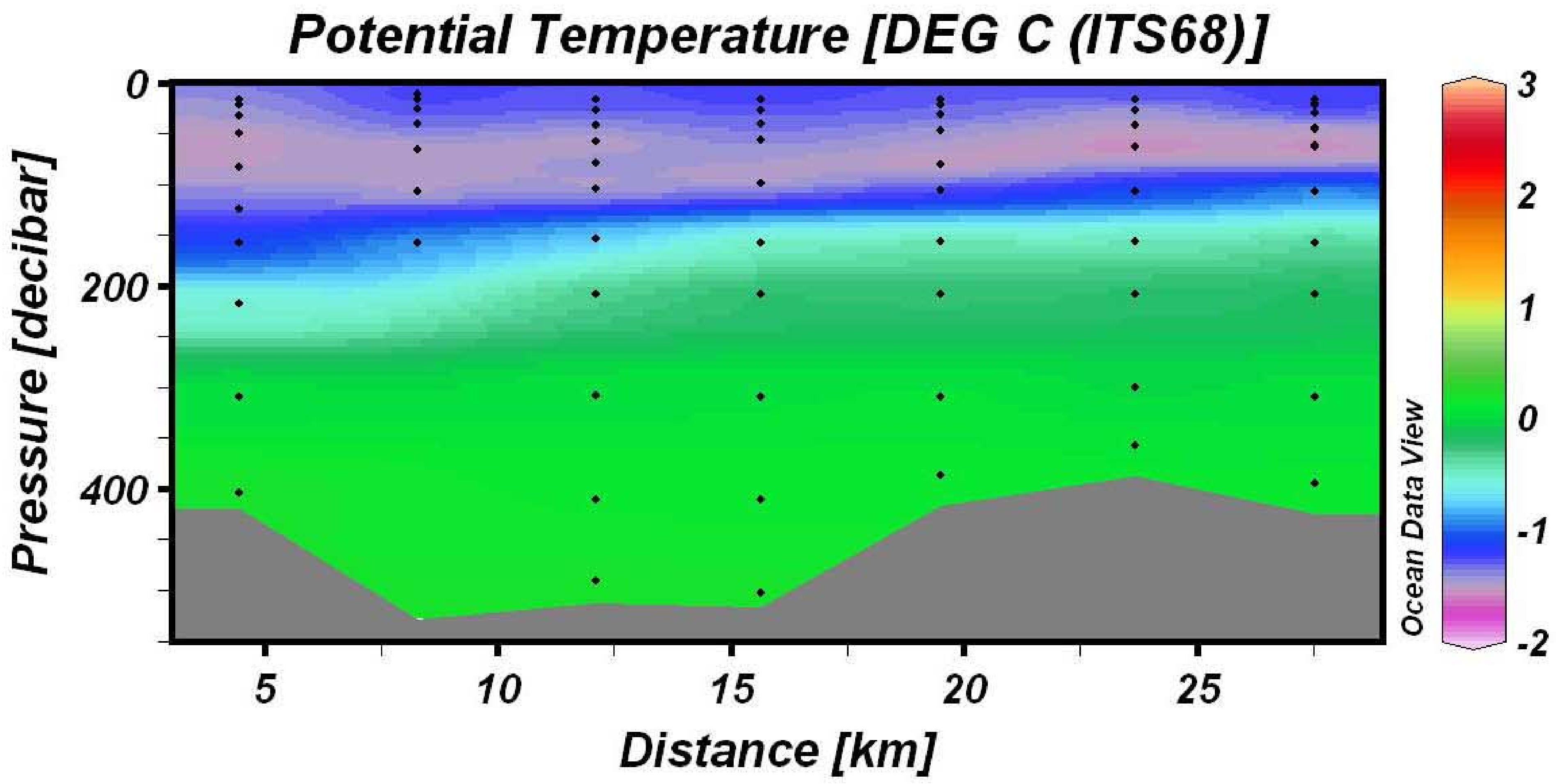

N* [mmol/m^3]
Pressure [decibar]
0
1000
2000
Distance [km]
100
200
300
400
500
600
0
-2
-4
-6
-8
-10
Ocean Data View

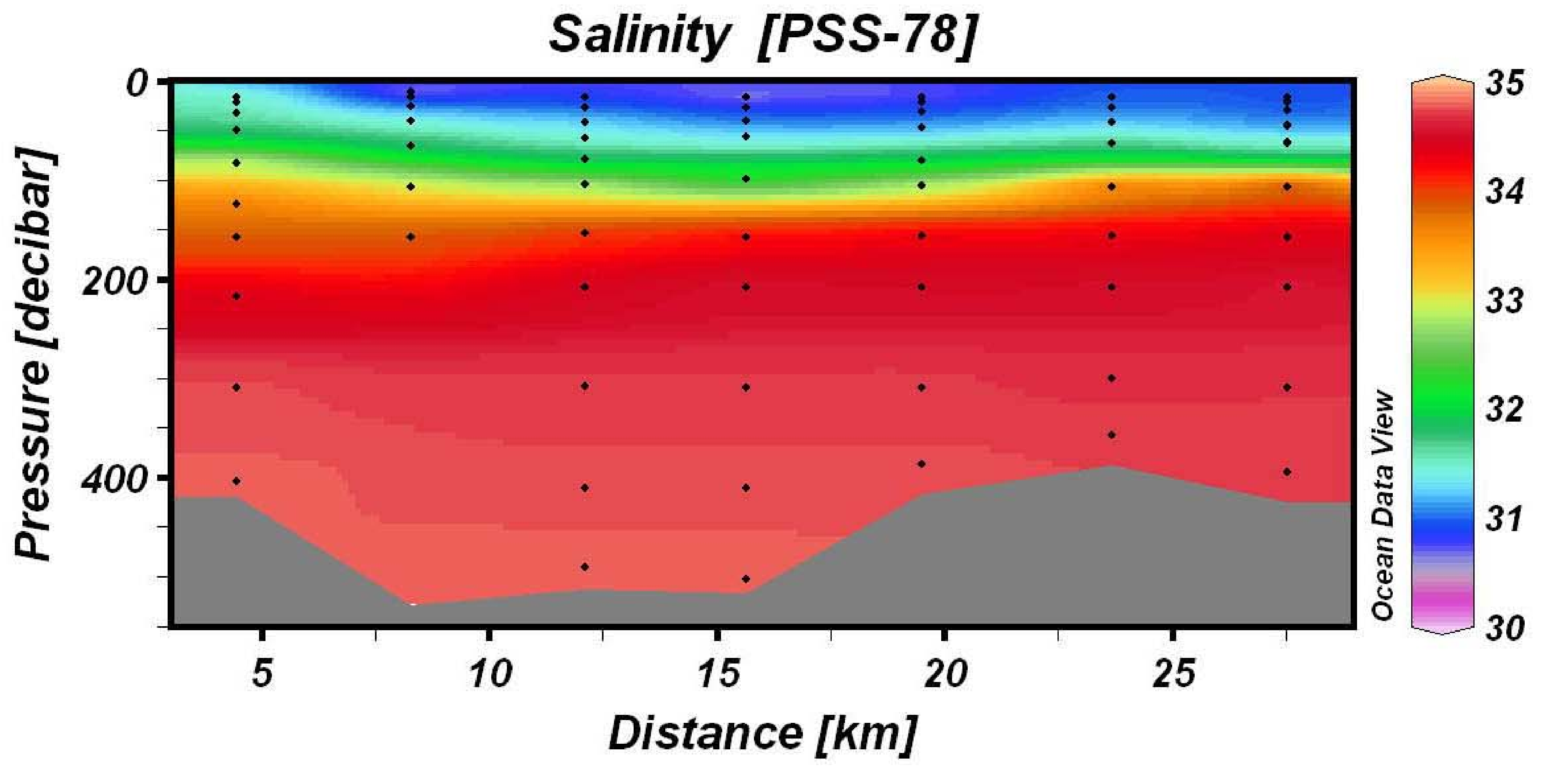

Si [mmol/m^3]
Pressure [decibar]
0
1000
2000
Distance [km]
100
200
300
400
500
600
100
80
60
40
20
0
Ocean Data View

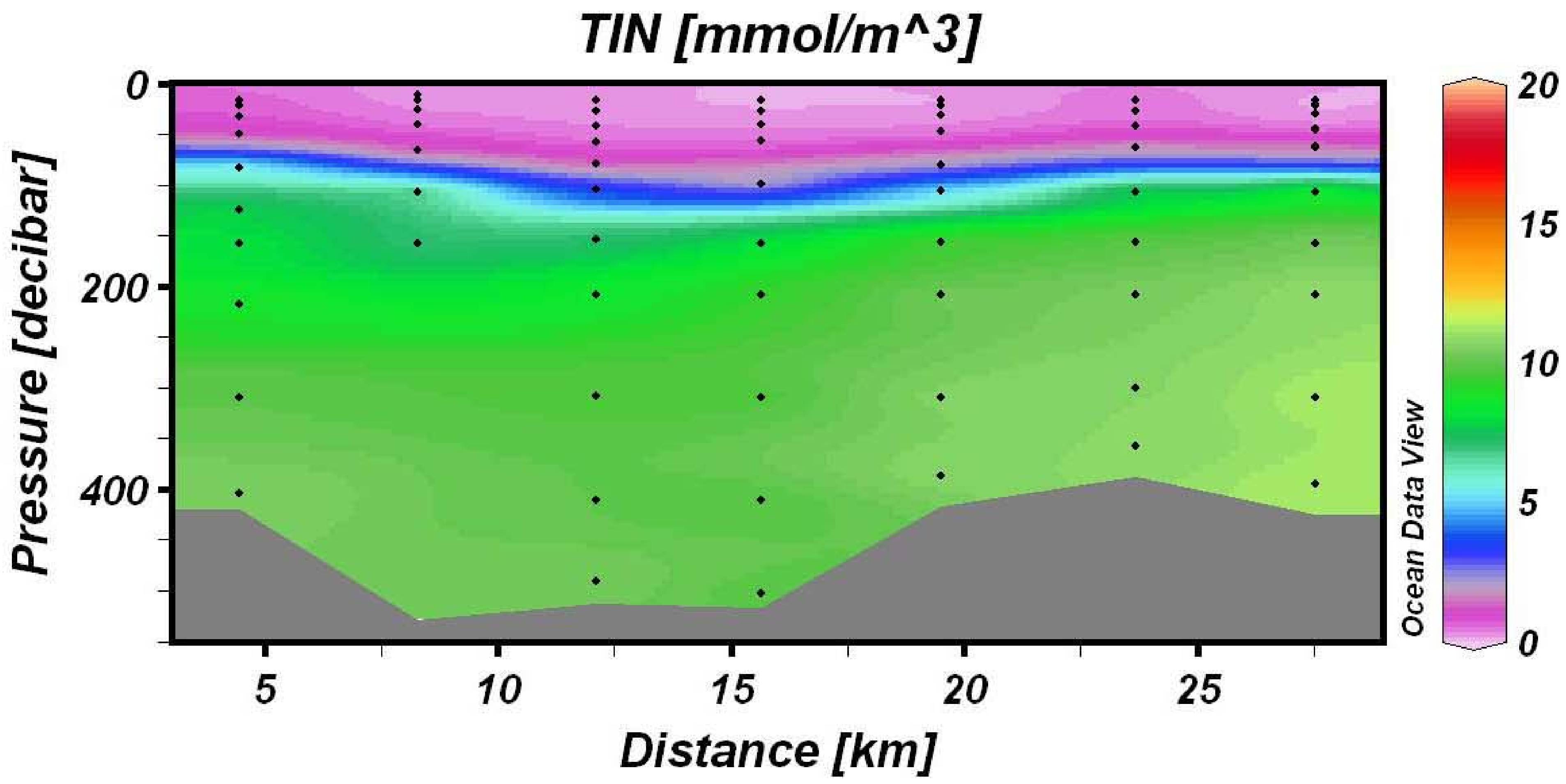

Baffin Bay HLY0301 Data >600 m
○ = ΣN = 11.2*P + 2.4
□ = O_2 = -178*P + 464
$\Sigma N = NO_3+NO_2+NH_4$ µM
O_2 µM
P µM
15
16
17
18
19
20
21
22
23
24
25
100
150
200
250
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9
2

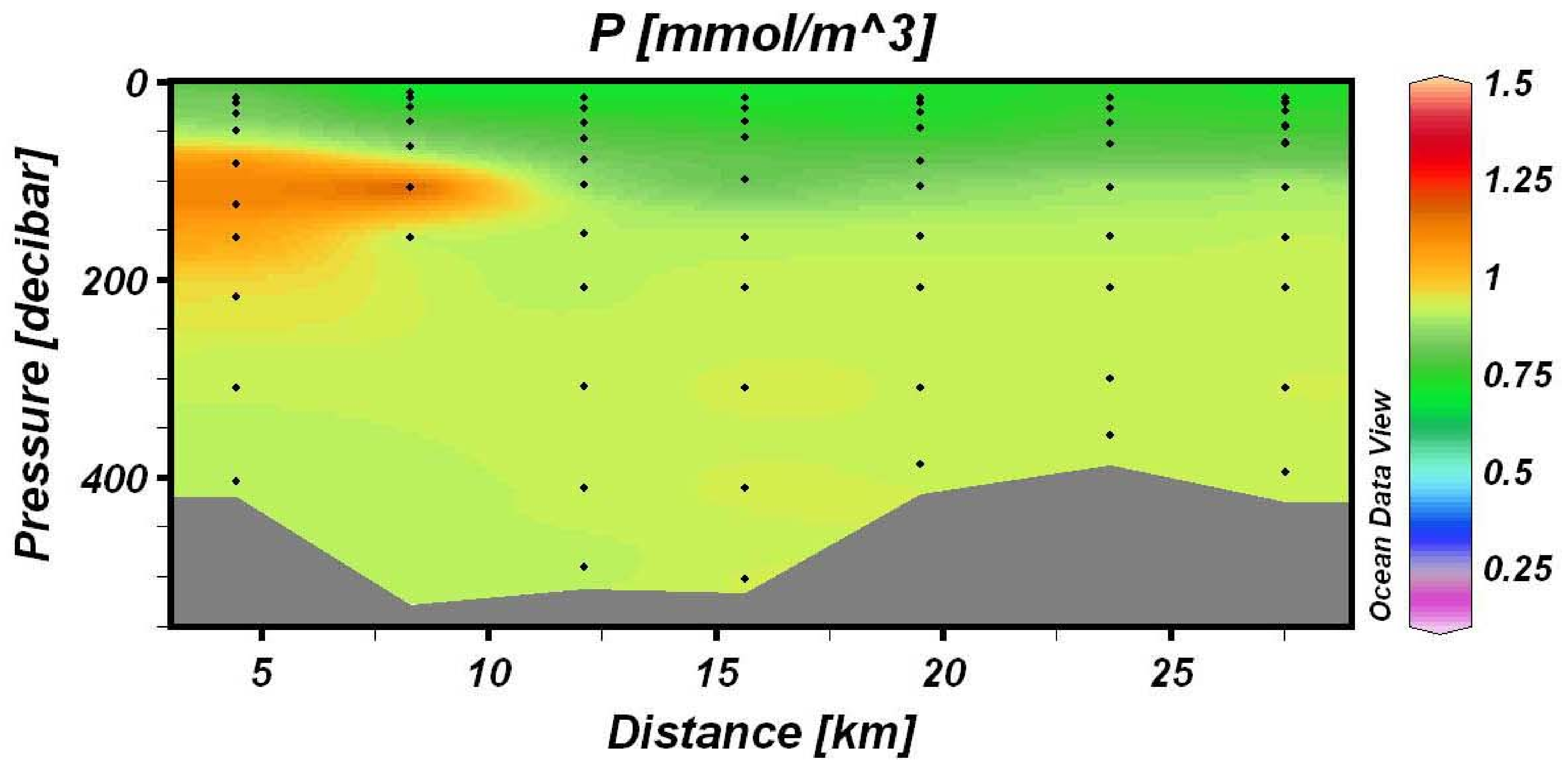


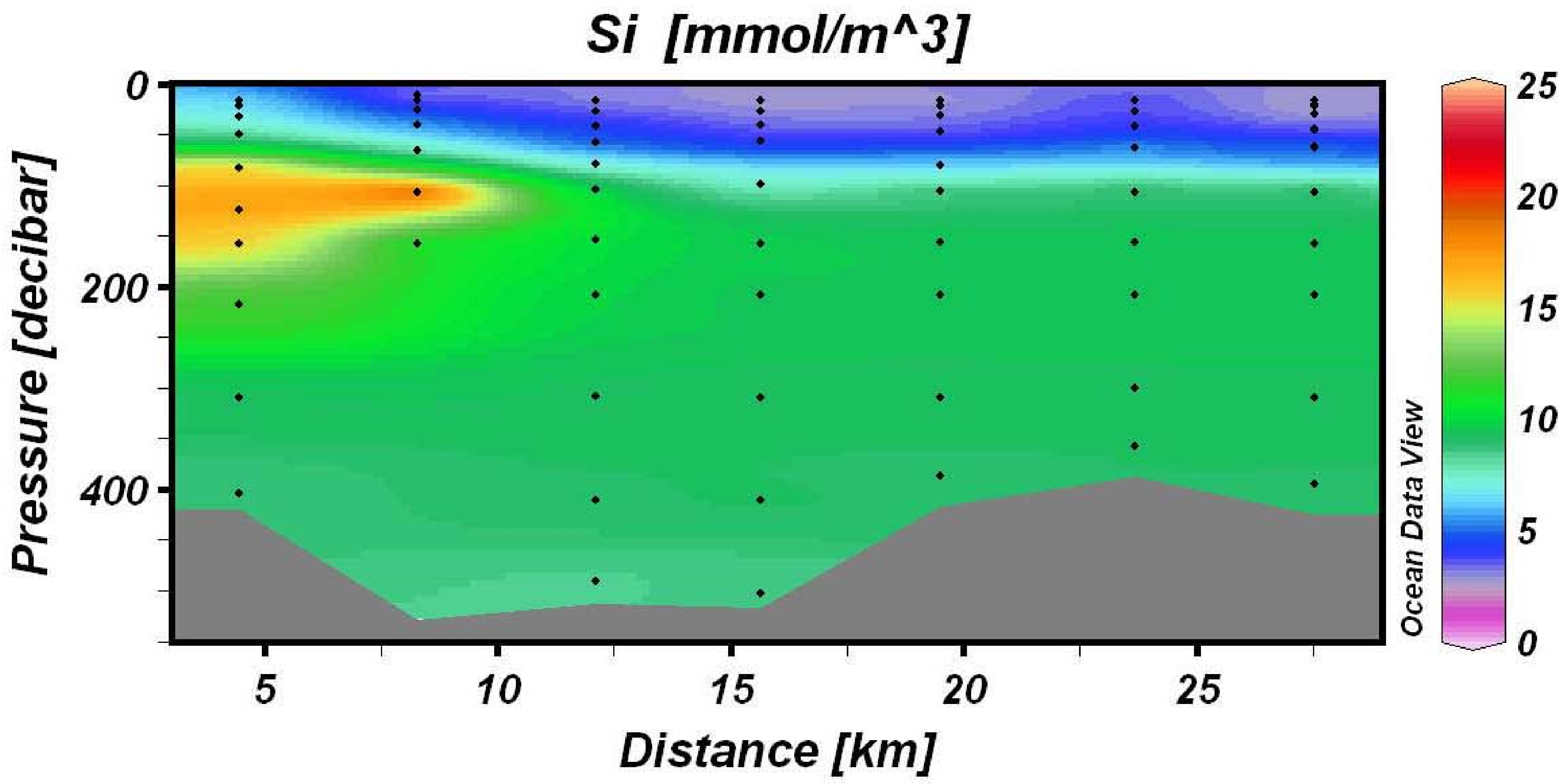

Oxygen Saturation [%]

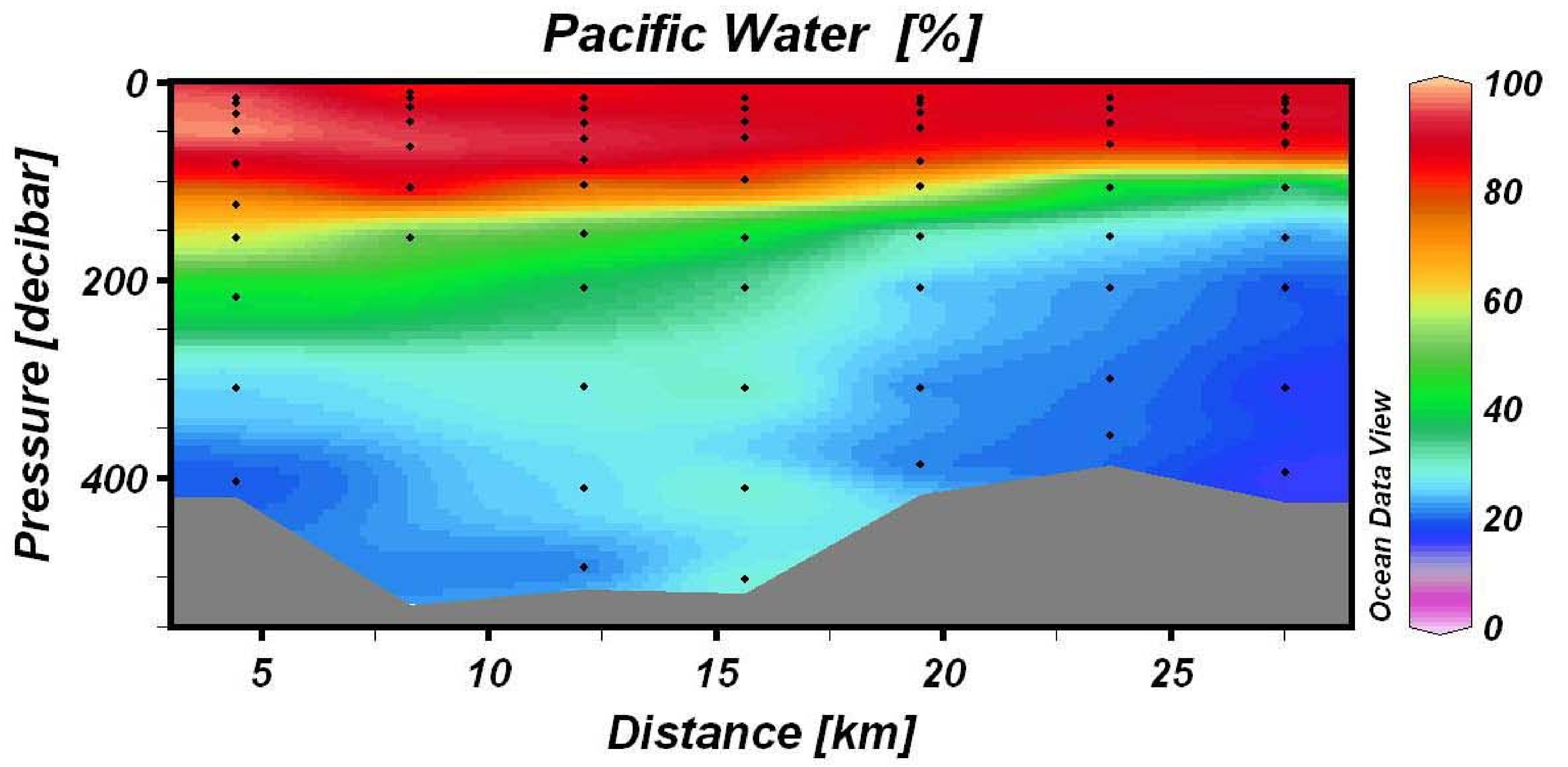

Potential Temperature [DEG C (ITS68)]

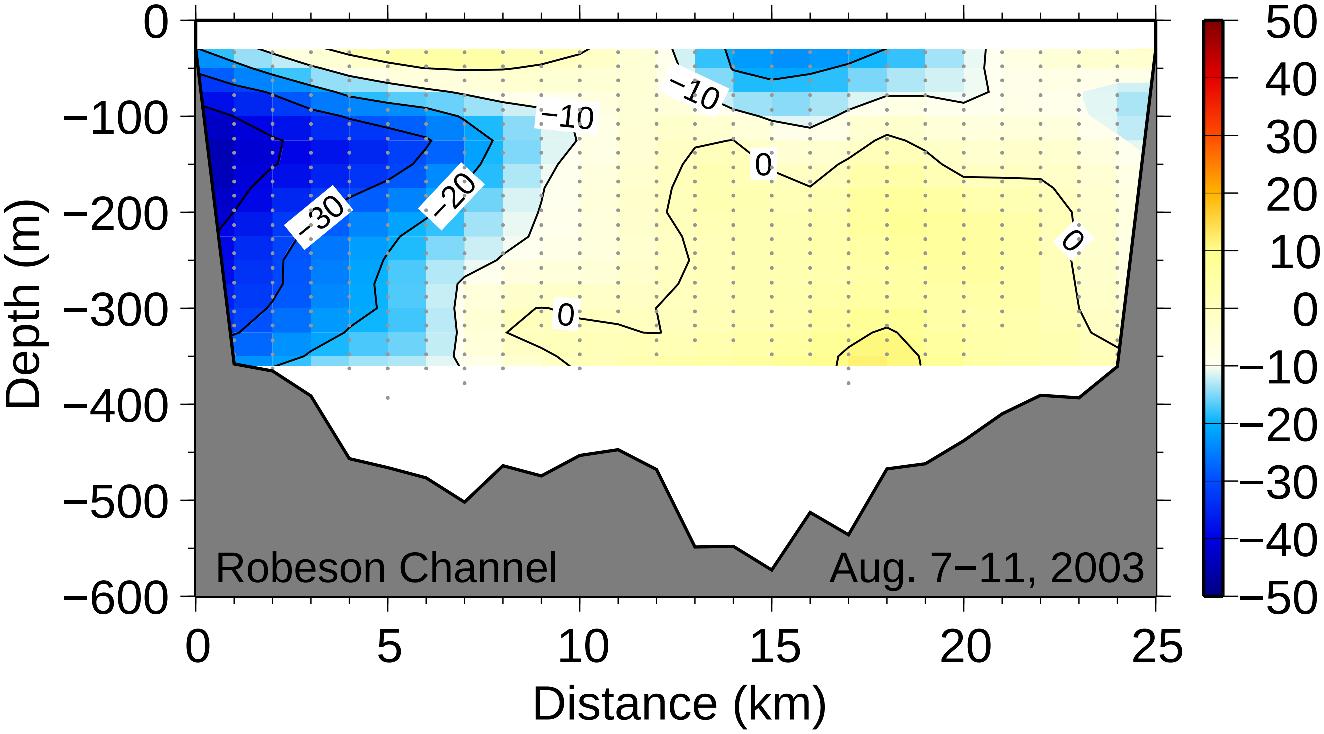

Salinity [PSS-78]

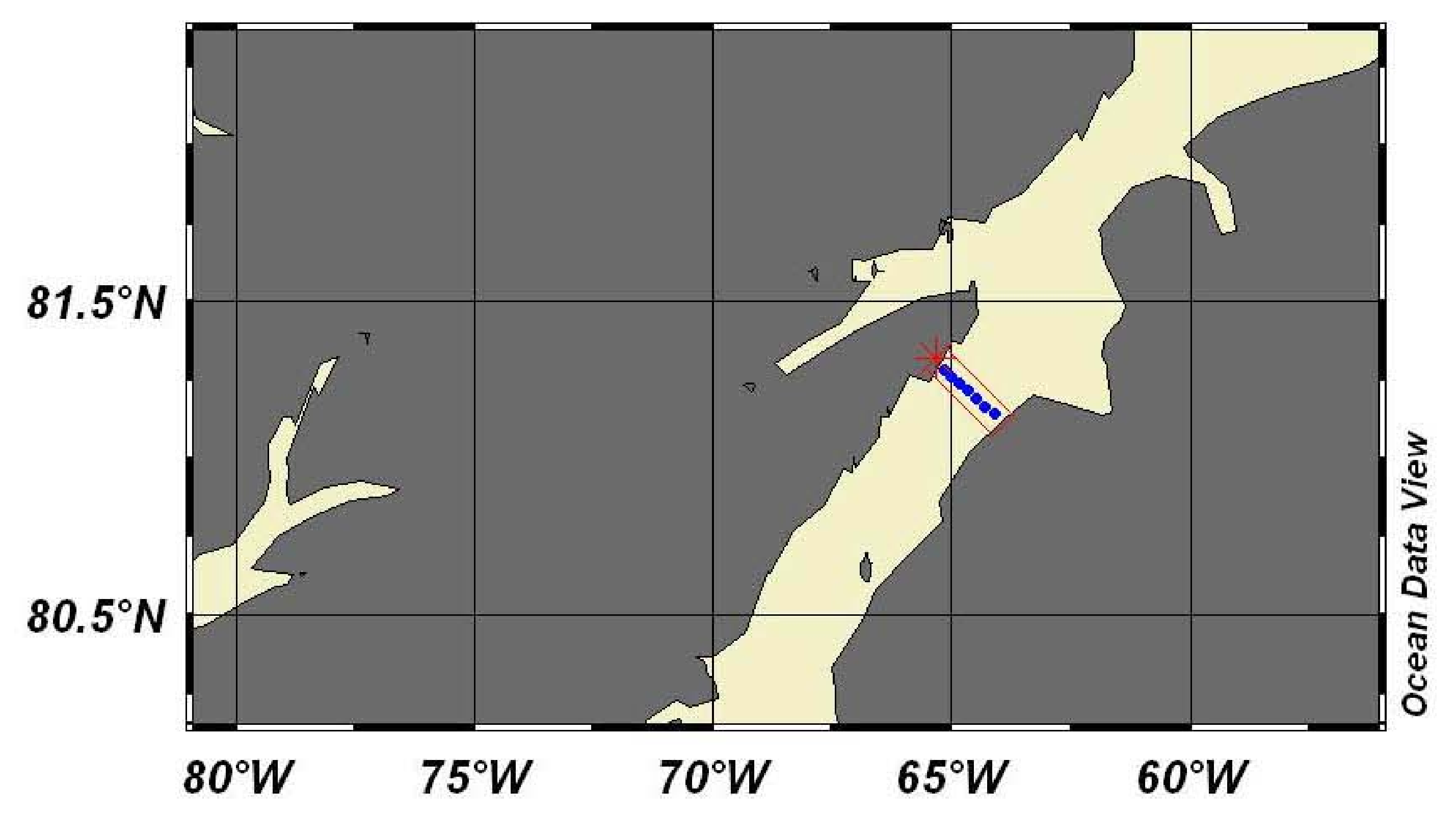

TIN [mmol/m^3]

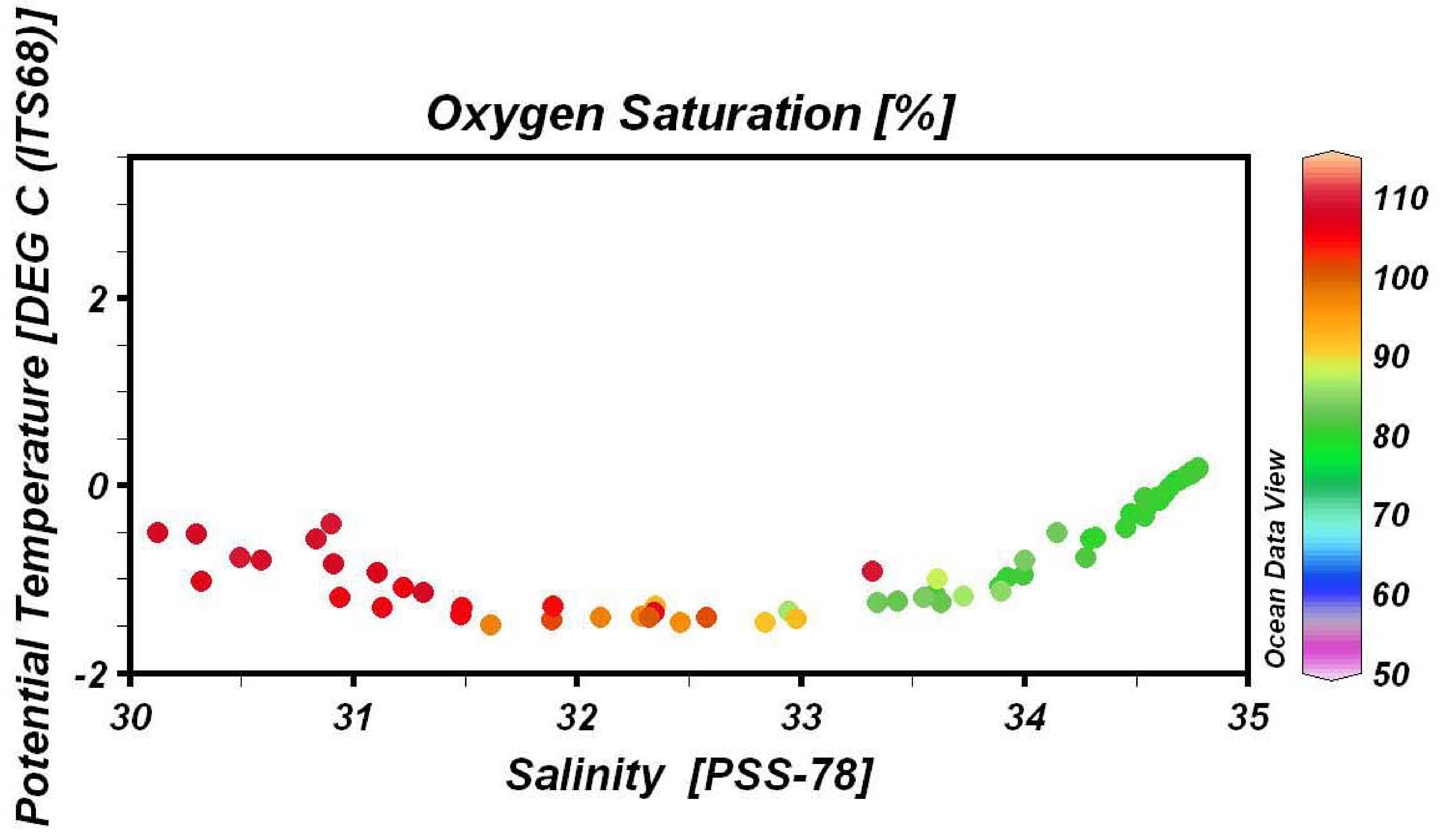

P [mmol/m^3]

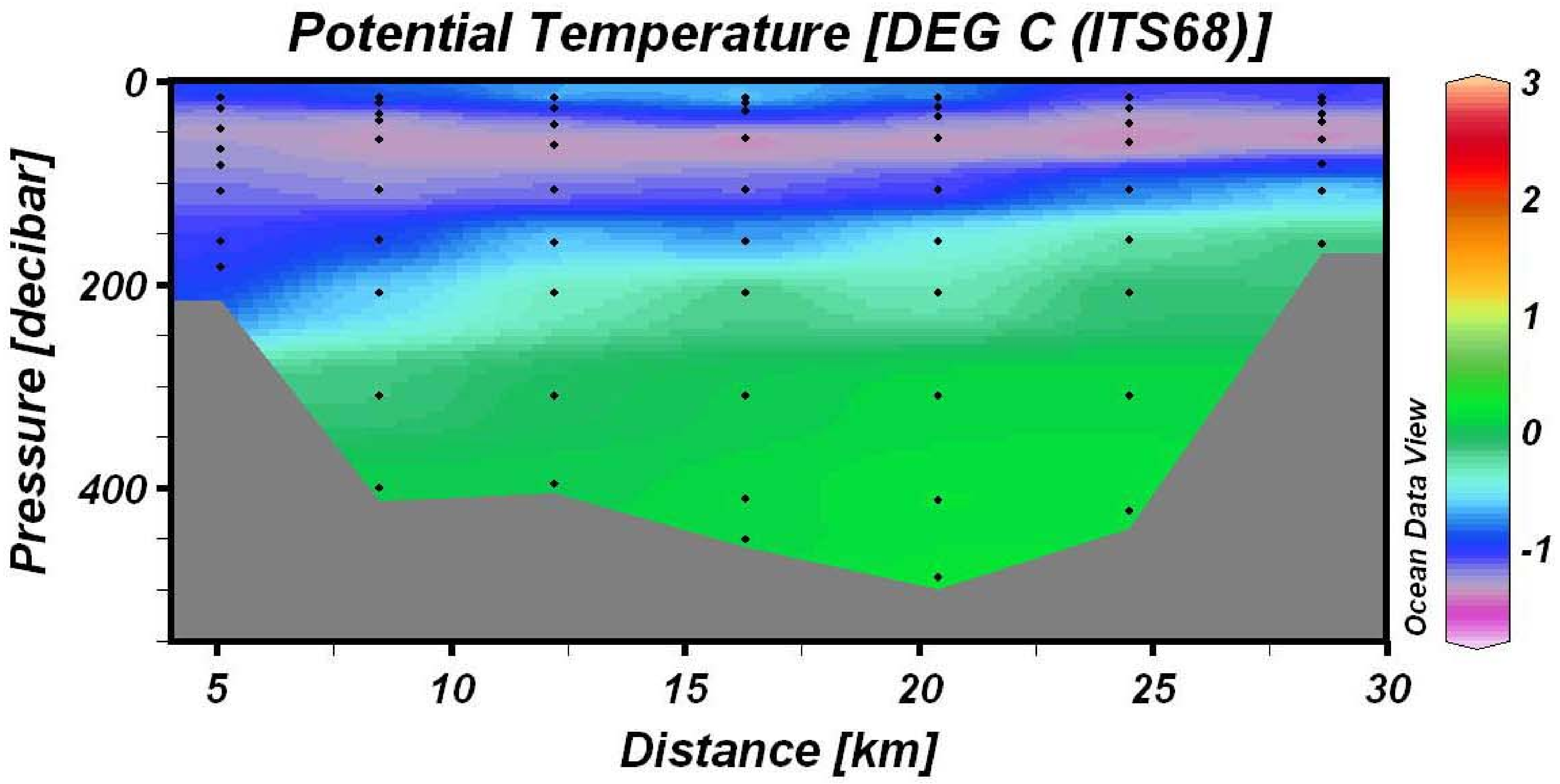

Si [mmol/m^3]

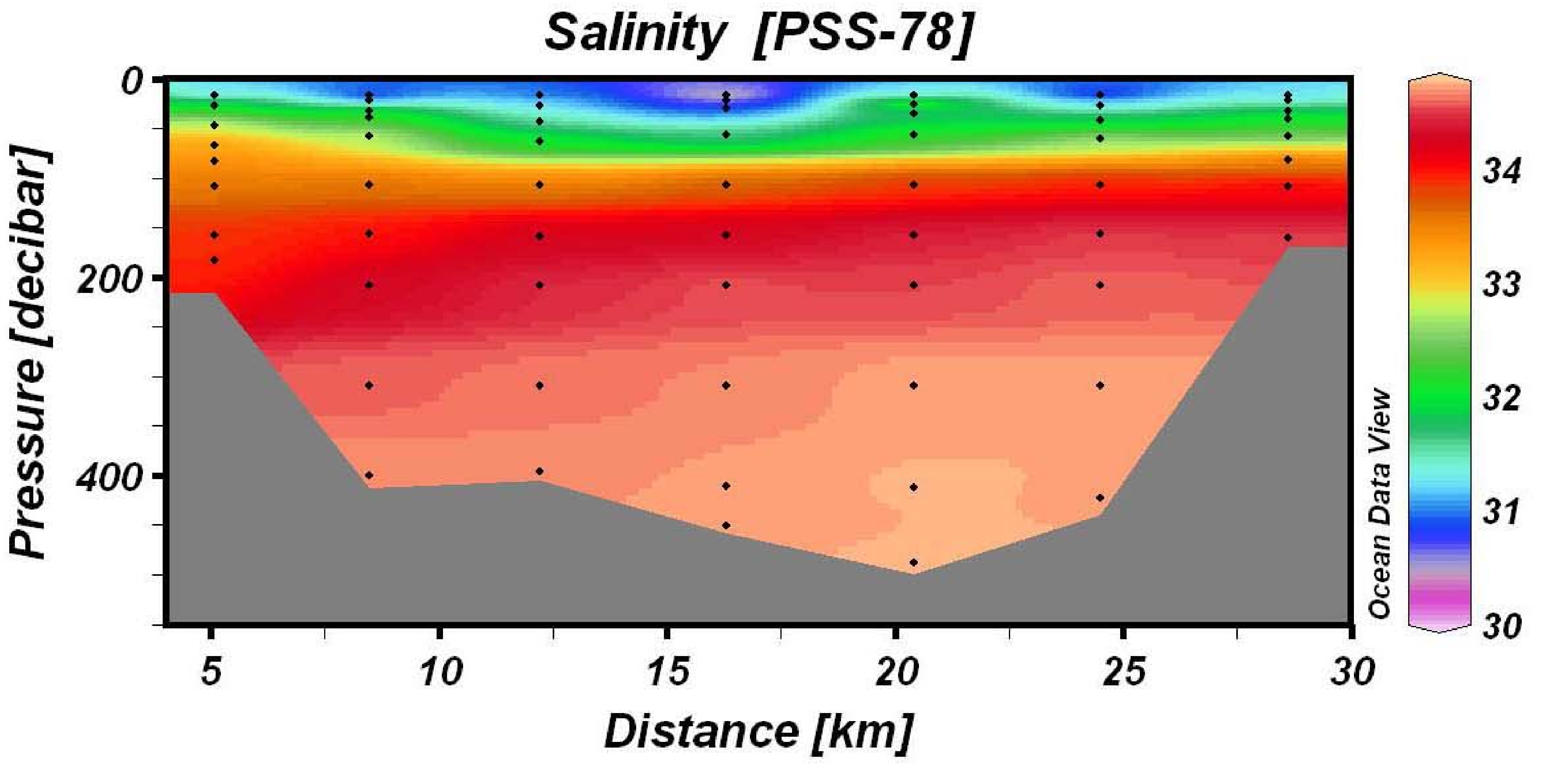

Pacific Water [%]

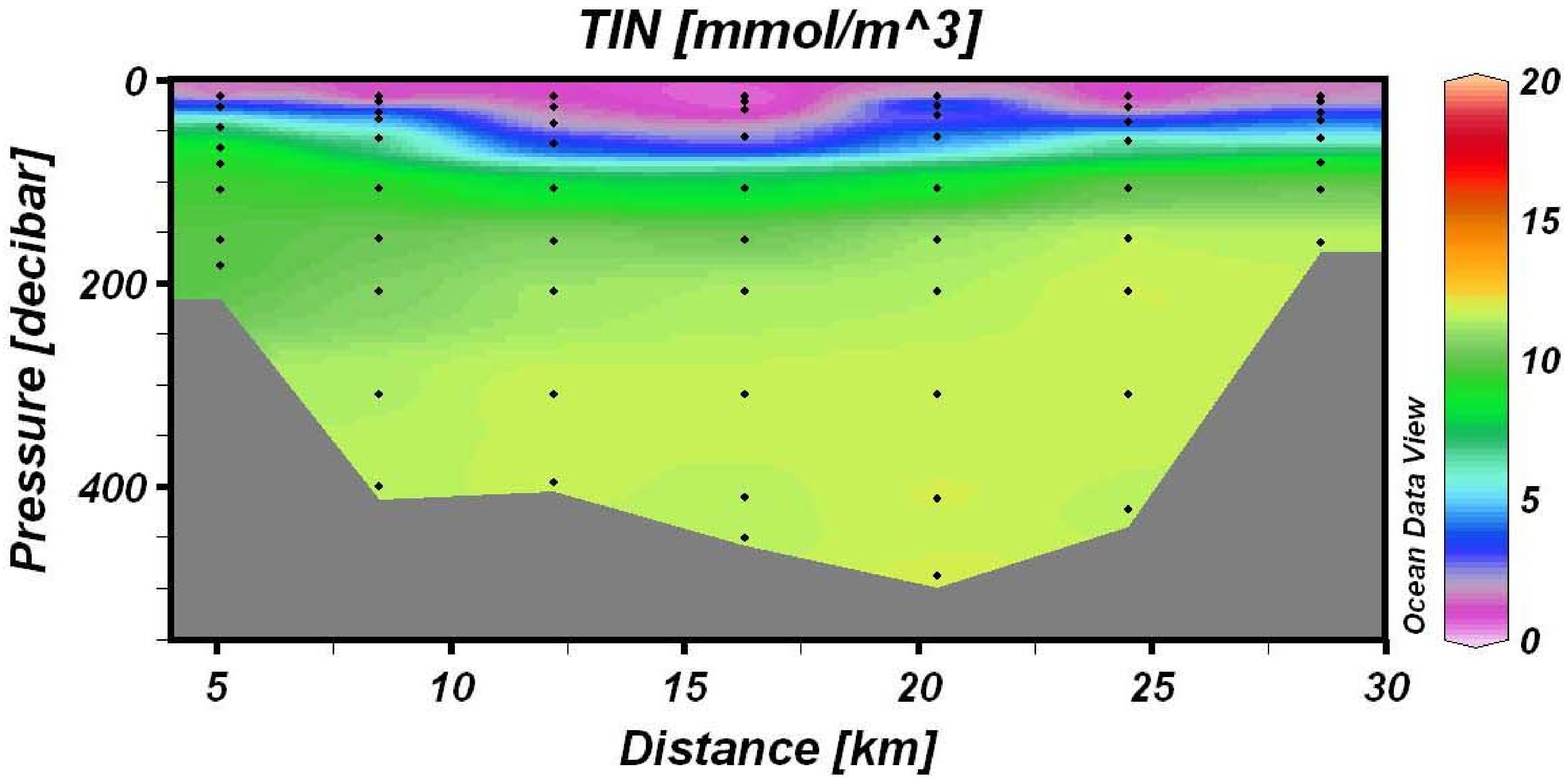

Robeson Channel
Aug. 7−11, 2003
Depth (m)
Distance (km)
0
−100
−200
−300
−400
−500
−600
0
5
10
15
20
25
−30
−20
−10
−10
0
0
0
50
40
30
20
10
0
−10
−20
−30
−40
−50

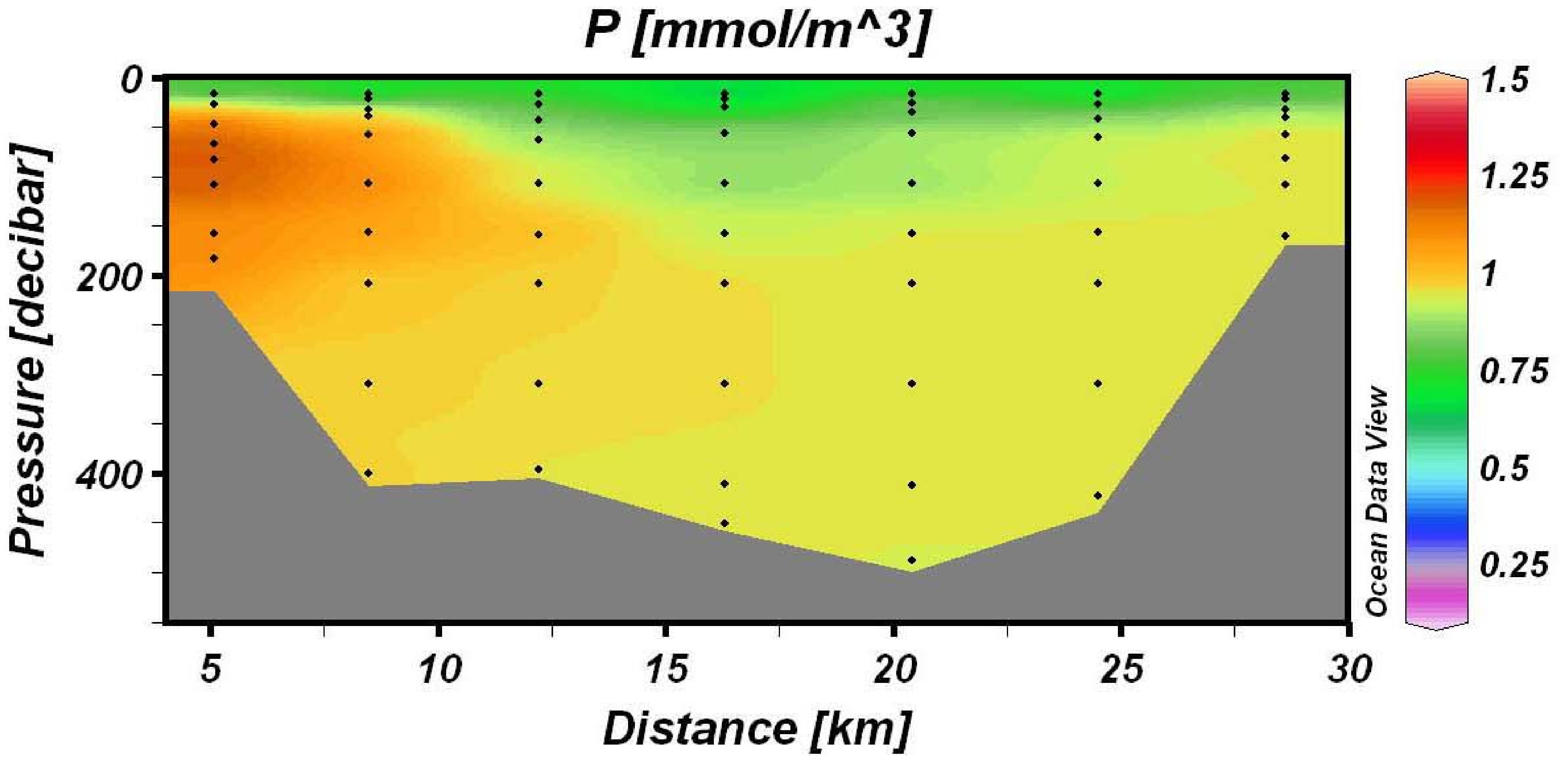


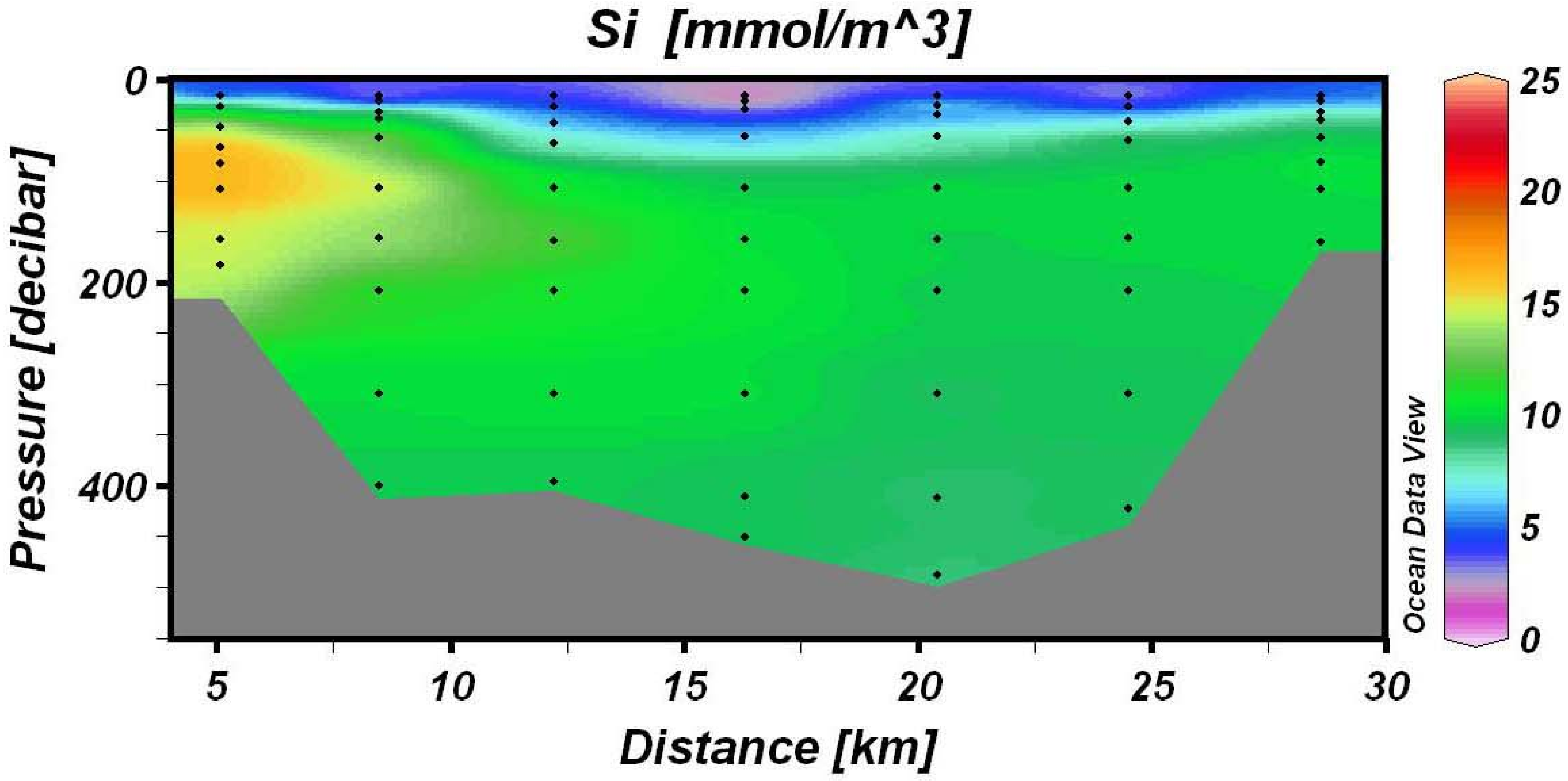

Oxygen Saturation [%]

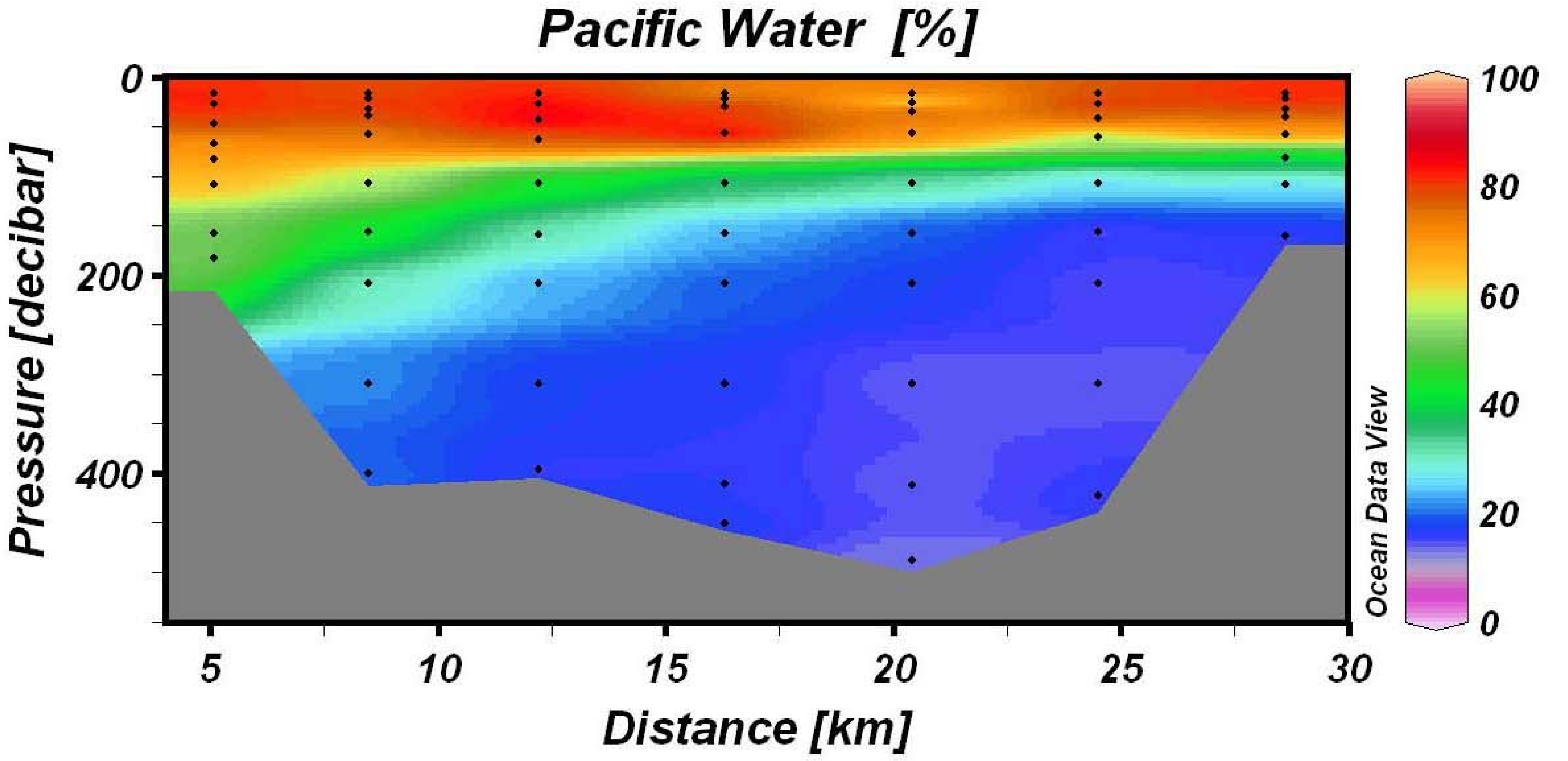

Potential Temperature [DEG C (ITS68)]

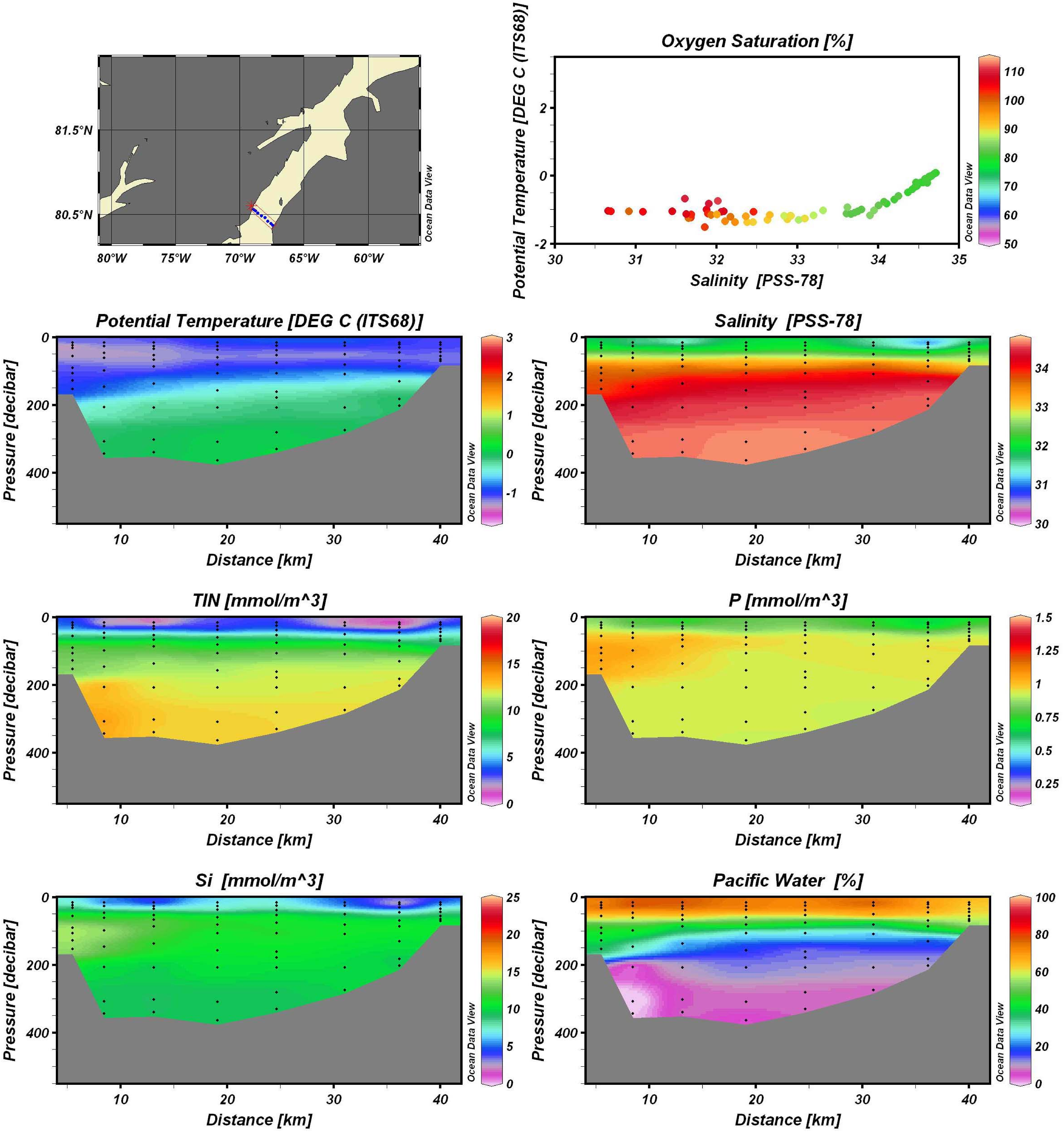

Salinity [PSS-78]

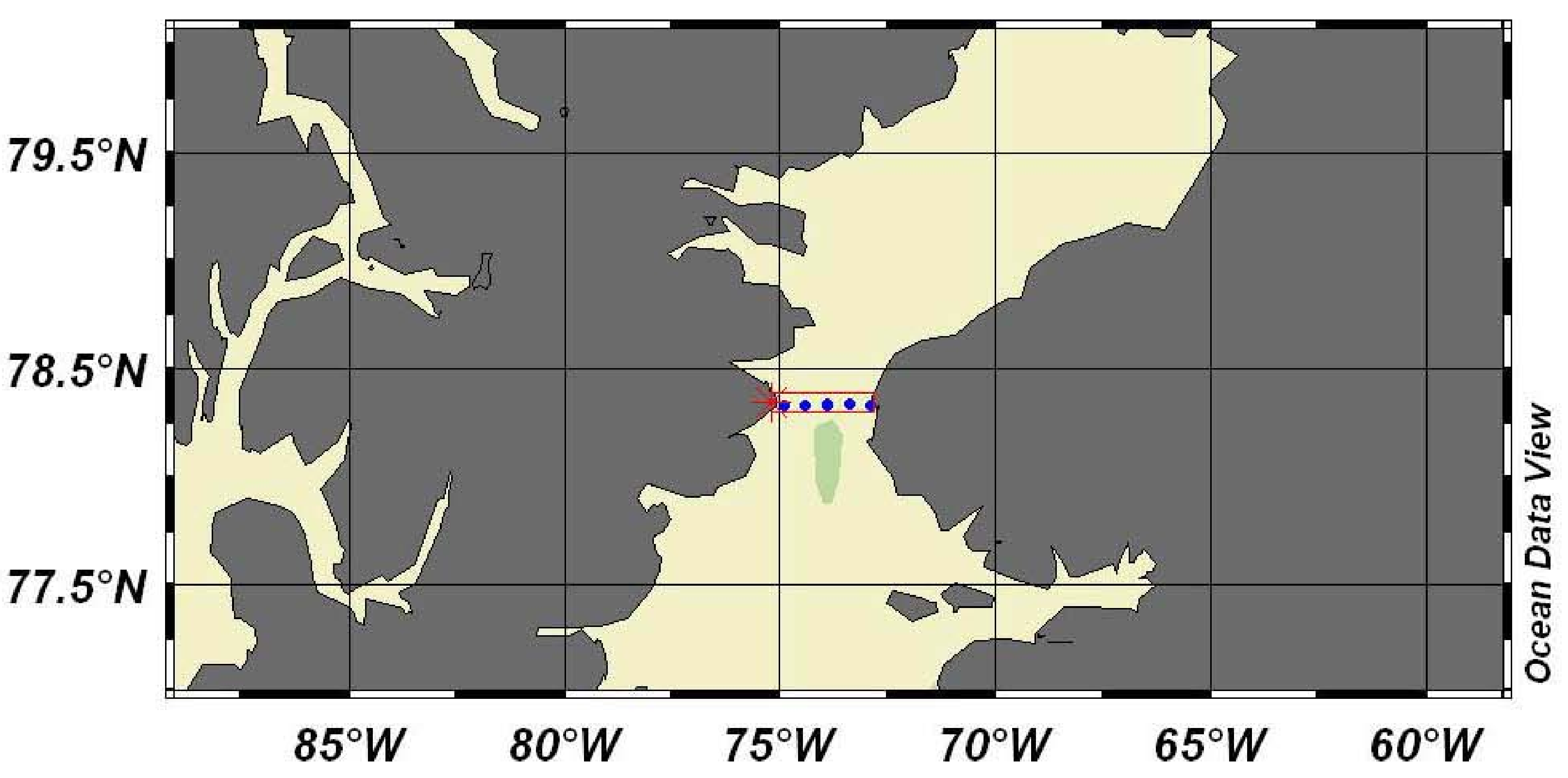

TIN [mmol/m^3]

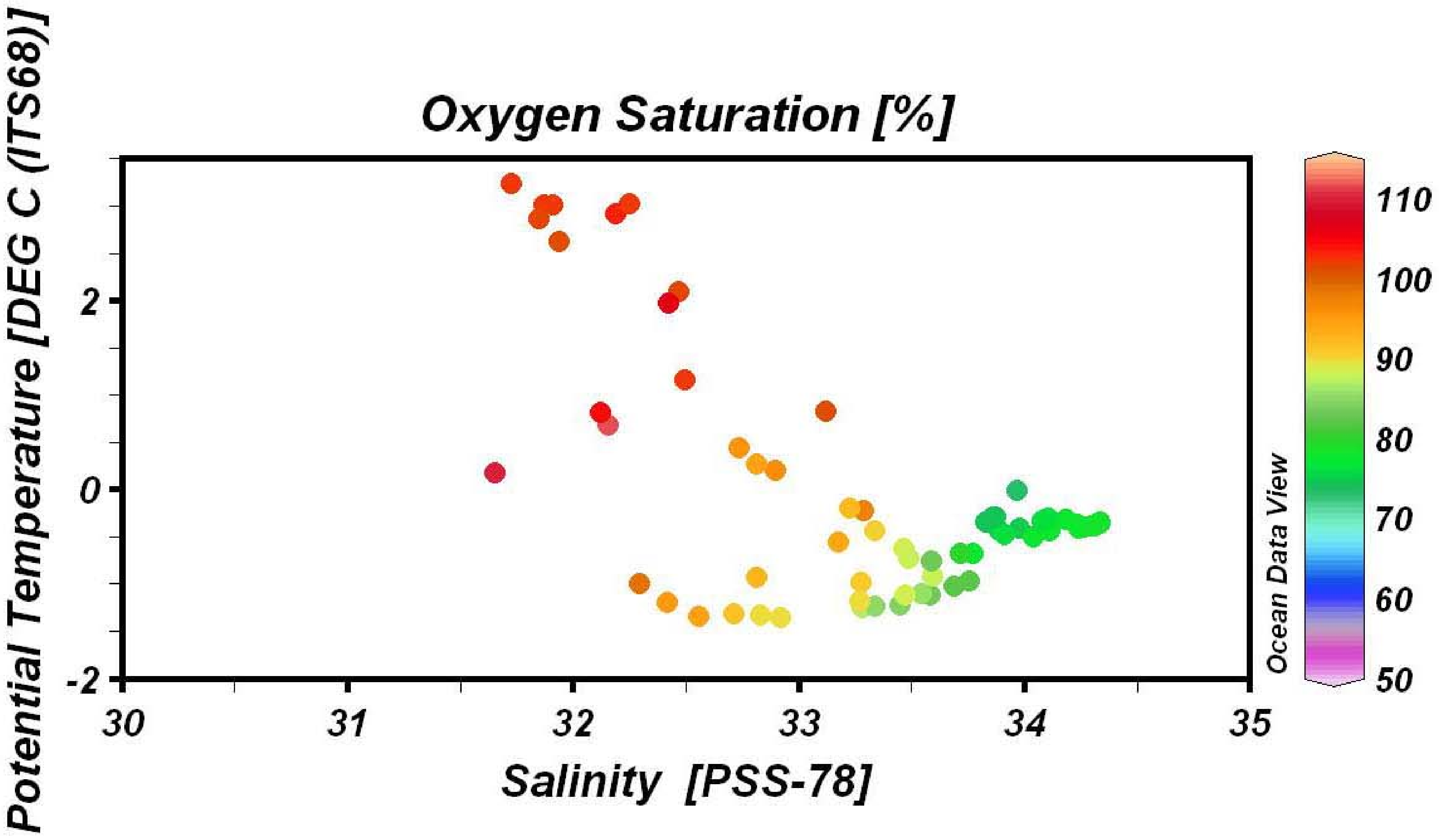

P [mmol/m^3]

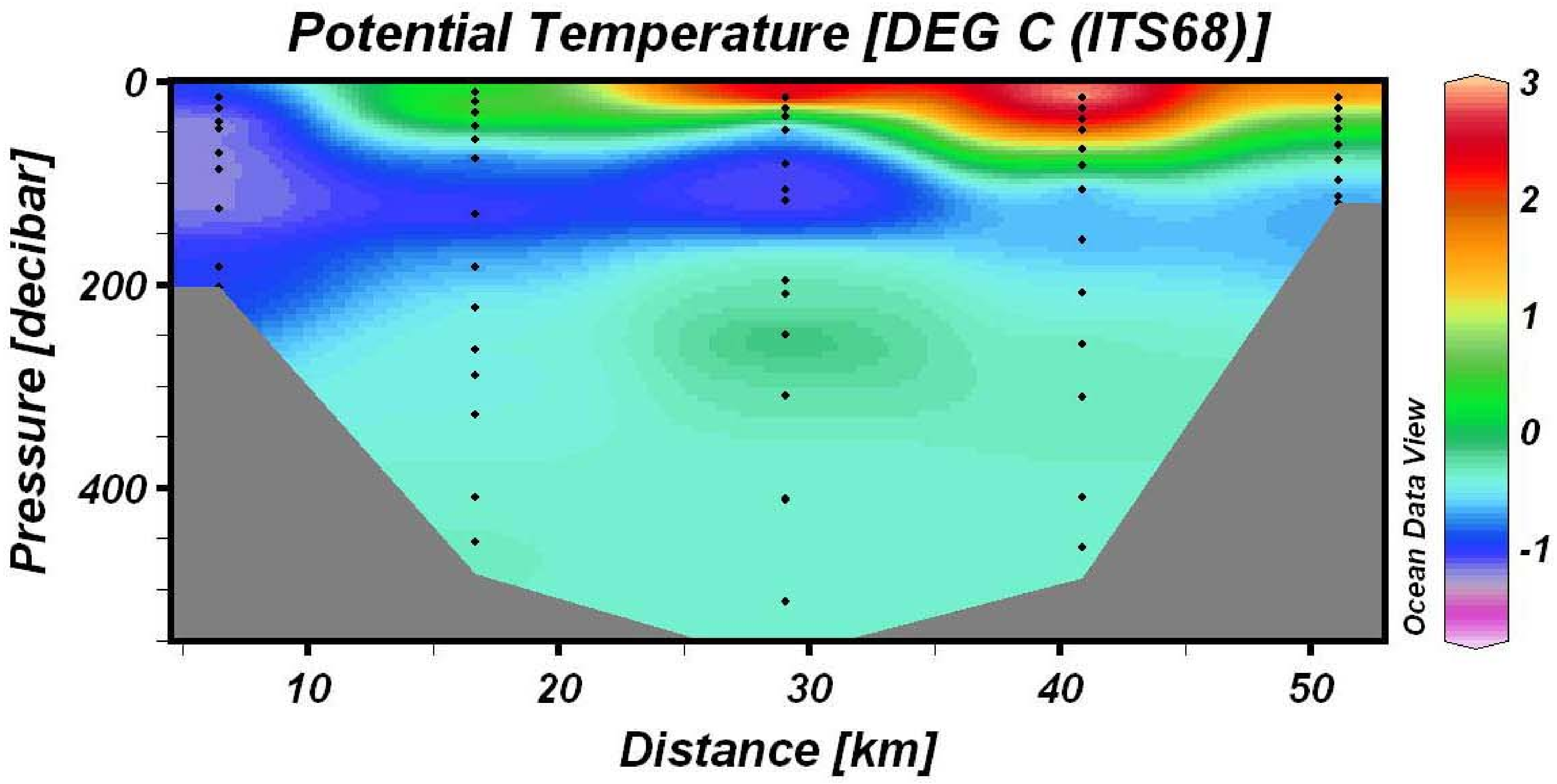

Si [mmol/m^3]

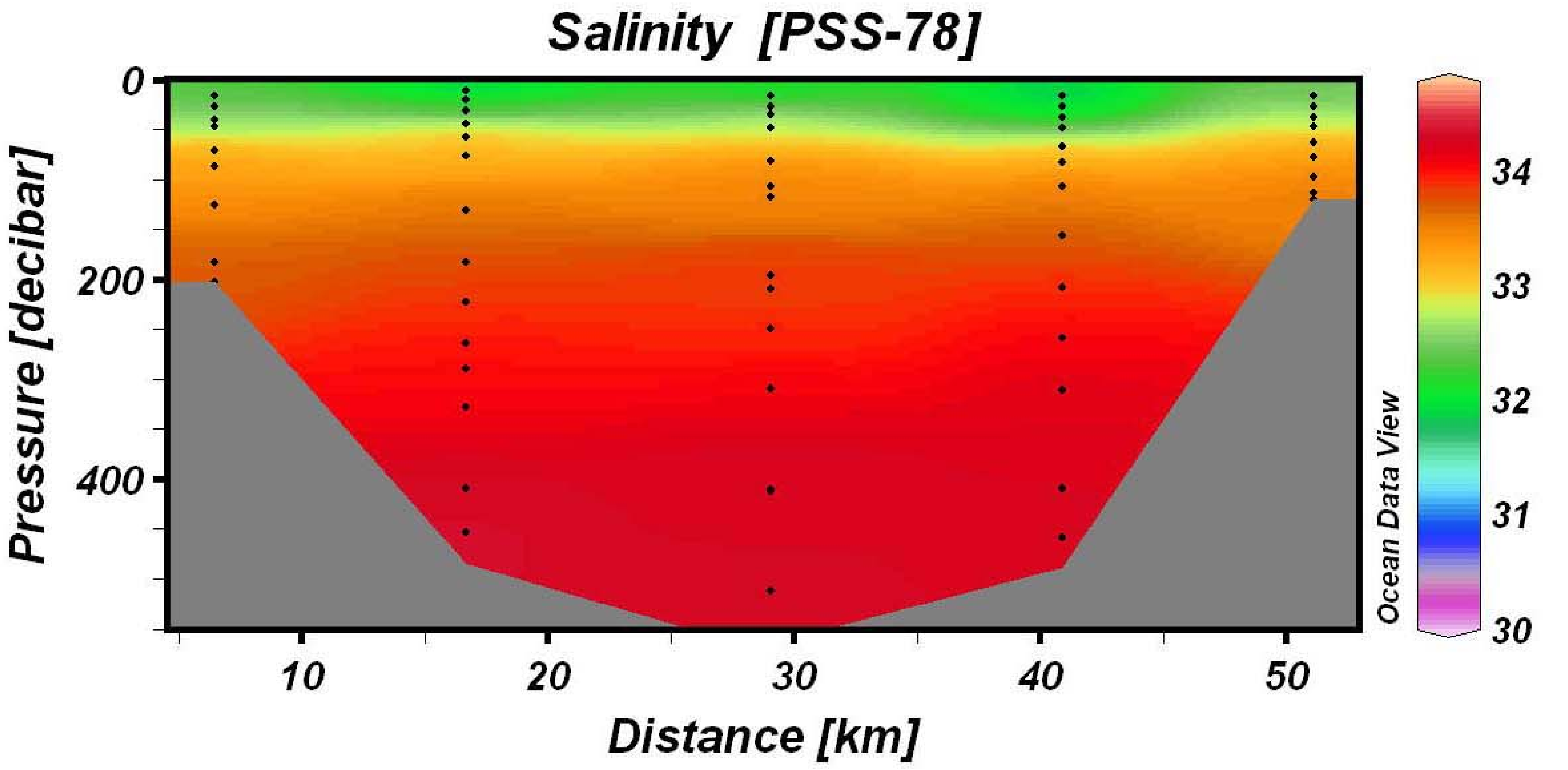

Pacific Water [%]

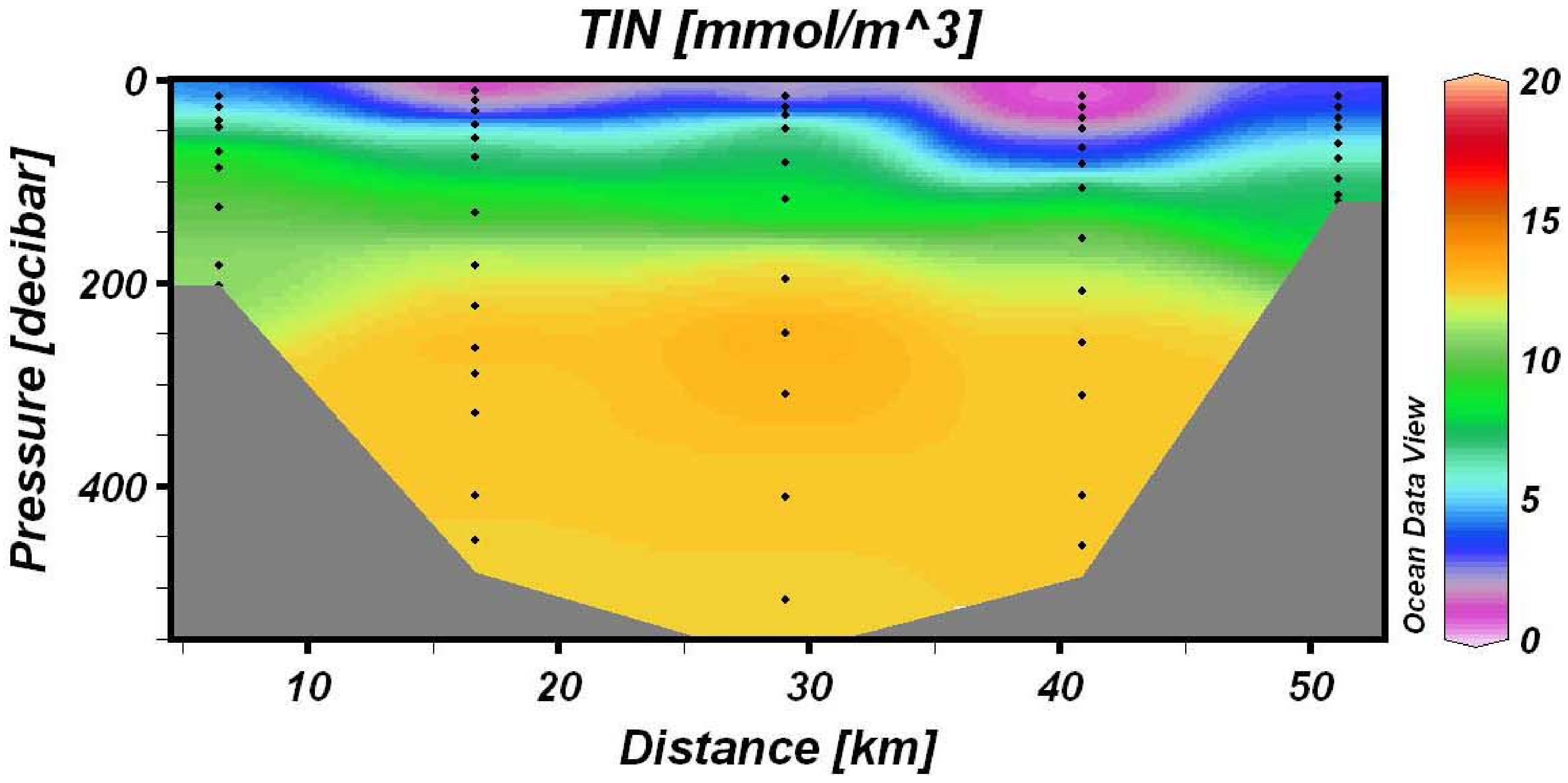

81.5°N
80.5°N
80°W
75°W
70°W
65°W
60°W
Ocean Data View
Oxygen Saturation [%]
Potential Temperature [DEG C (ITS68)]
Salinity [PSS-78]
2
0
-2
30
31
32
33
34
35
110
100
90
80
70
60
50
Potential Temperature [DEG C (ITS68)]
Salinity [PSS-78]
TIN [mmol/m^3]
P [mmol/m^3]
Si [mmol/m^3]
Pacific Water [%]
Pressure [decibar]
Distance [km]
0
200
400
10
20
30
40
3
2
1
0
-1
34
33
32
31
30
20
15
10
5
0
1.5
1.25
1
0.75
0.5
0.25
25
20
15
10
5
0
100
80
60
40
20
0

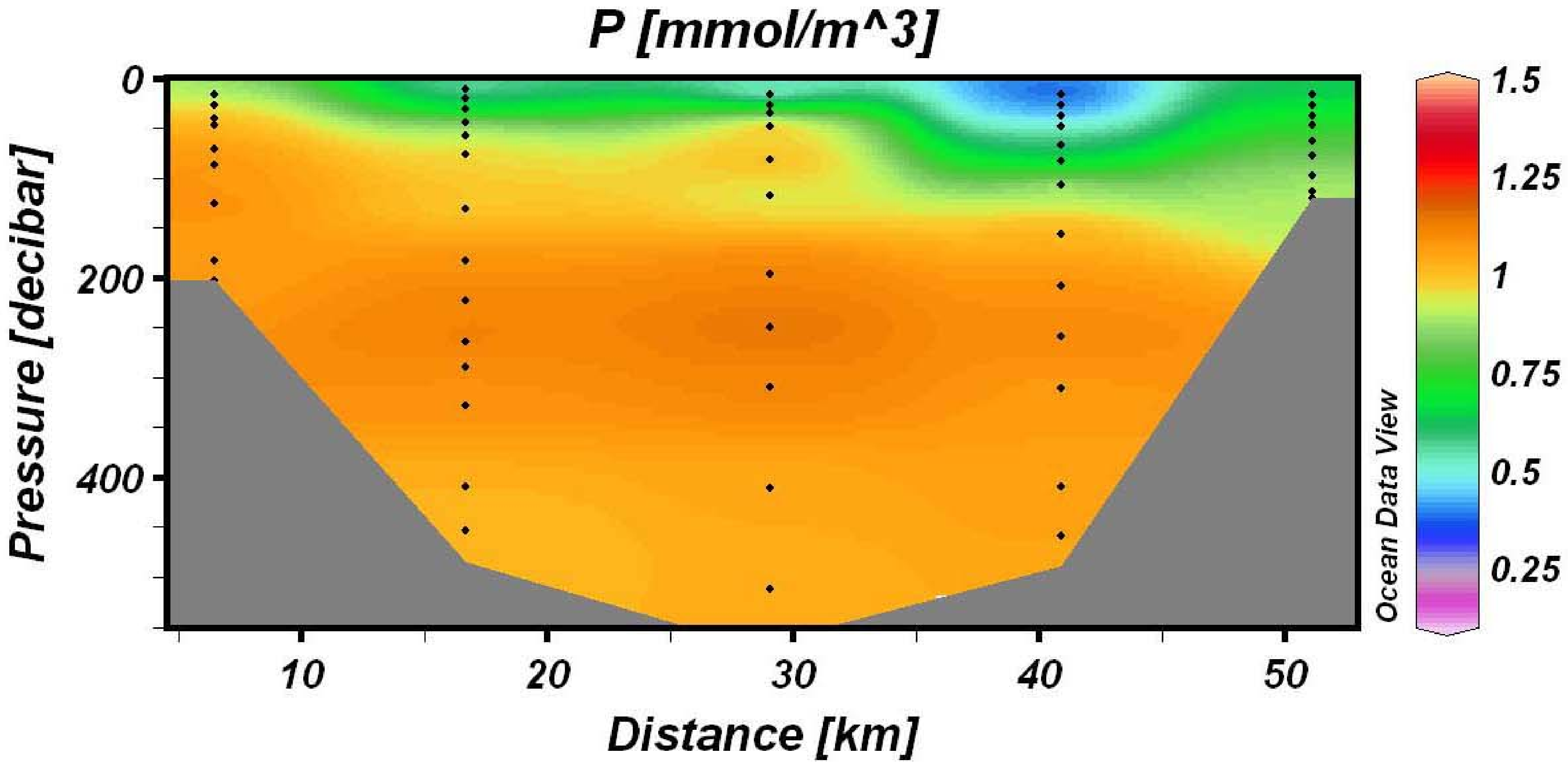


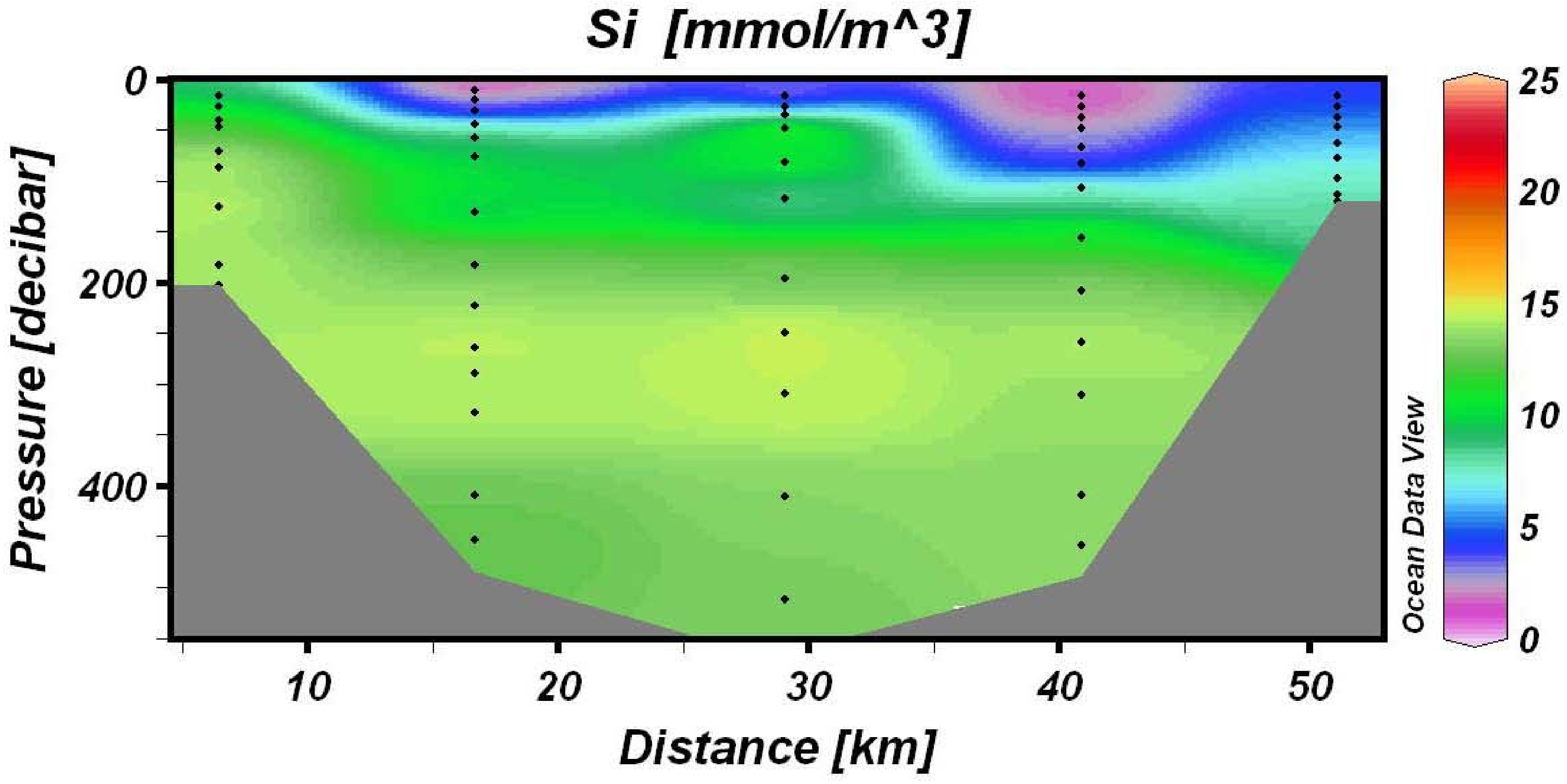

Oxygen Saturation [%]

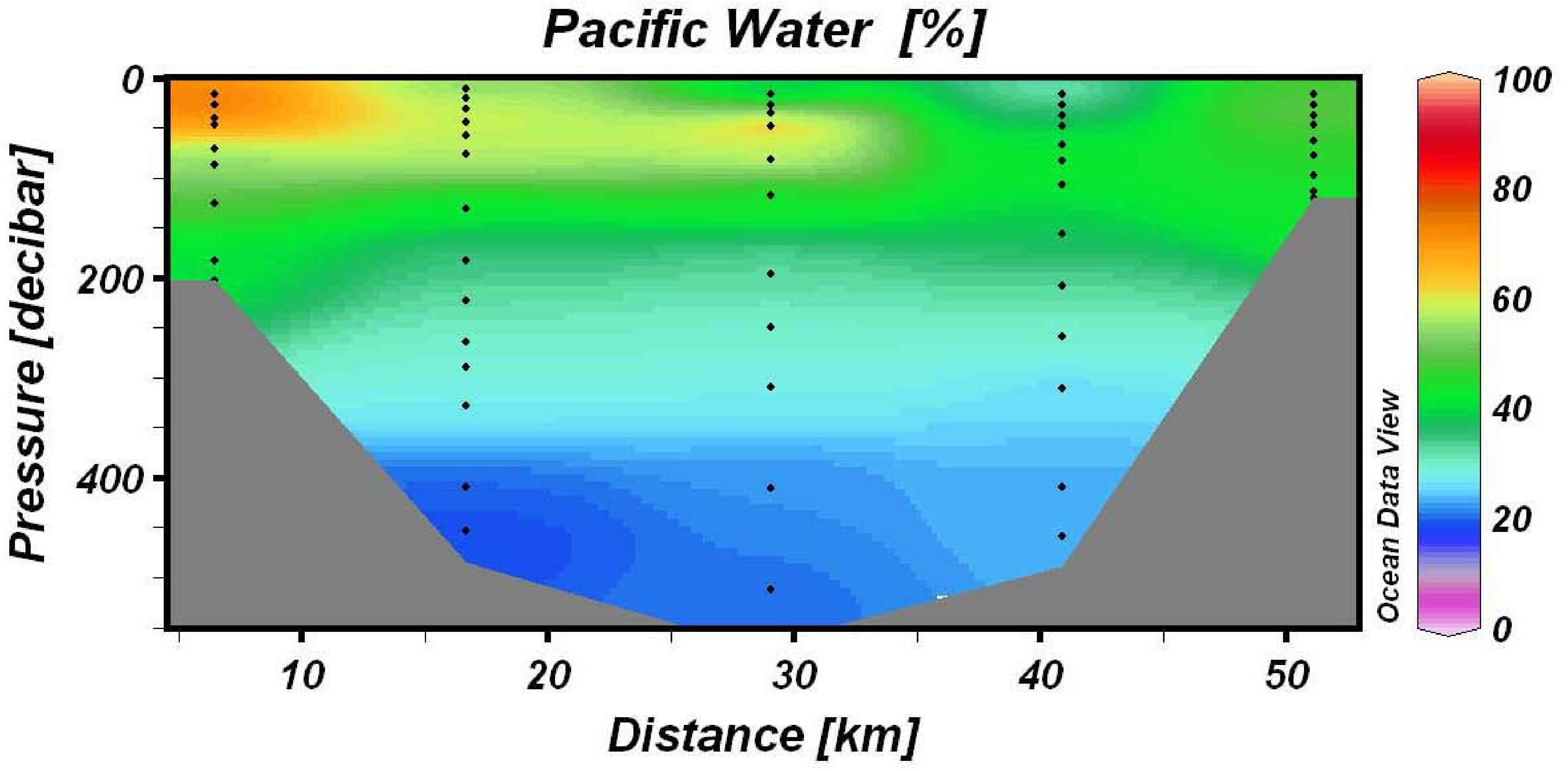

Potential Temperature [DEG C (ITS68)]

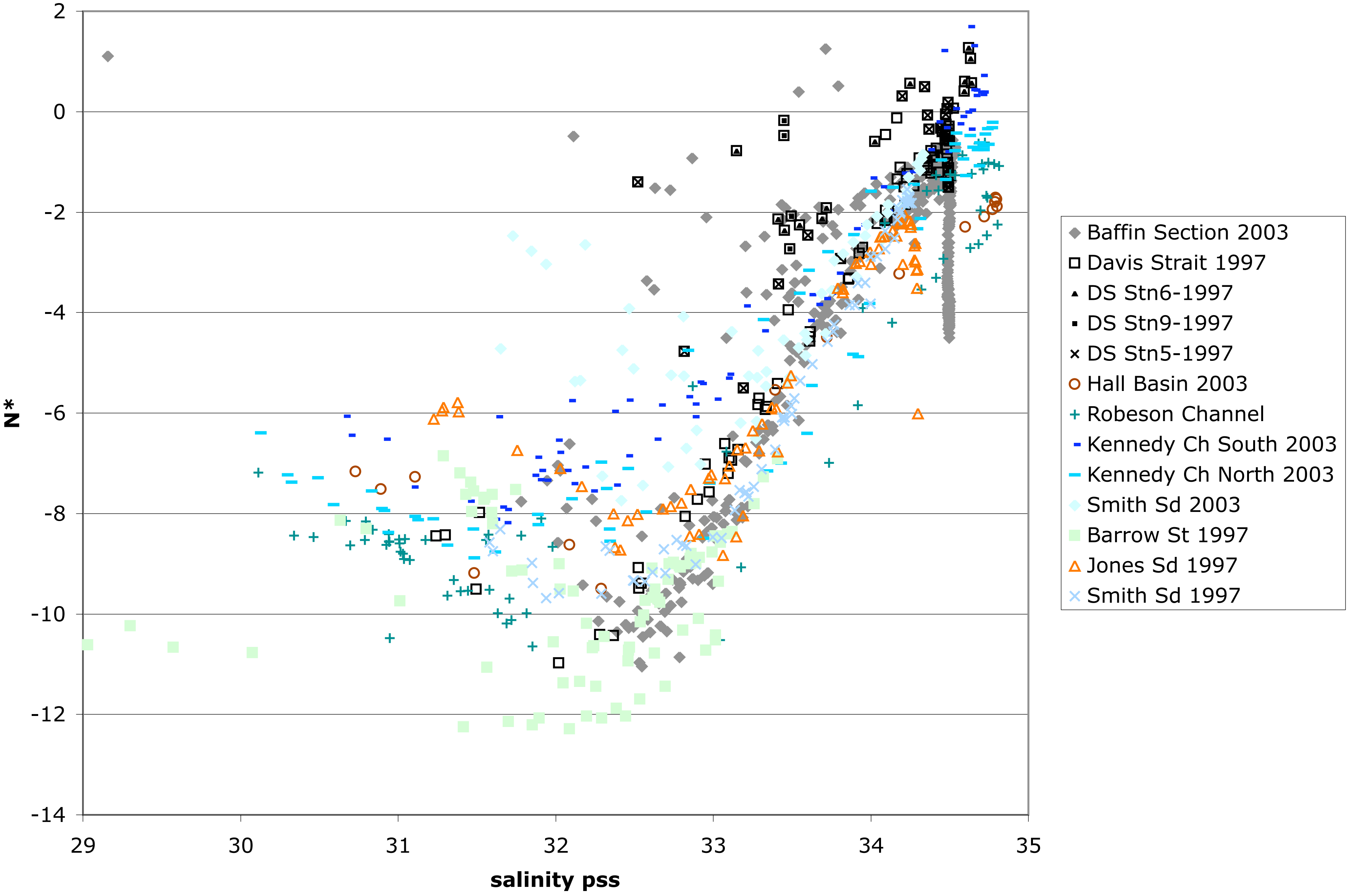

Salinity [PSS-78]


TIN [mmol/m^3]

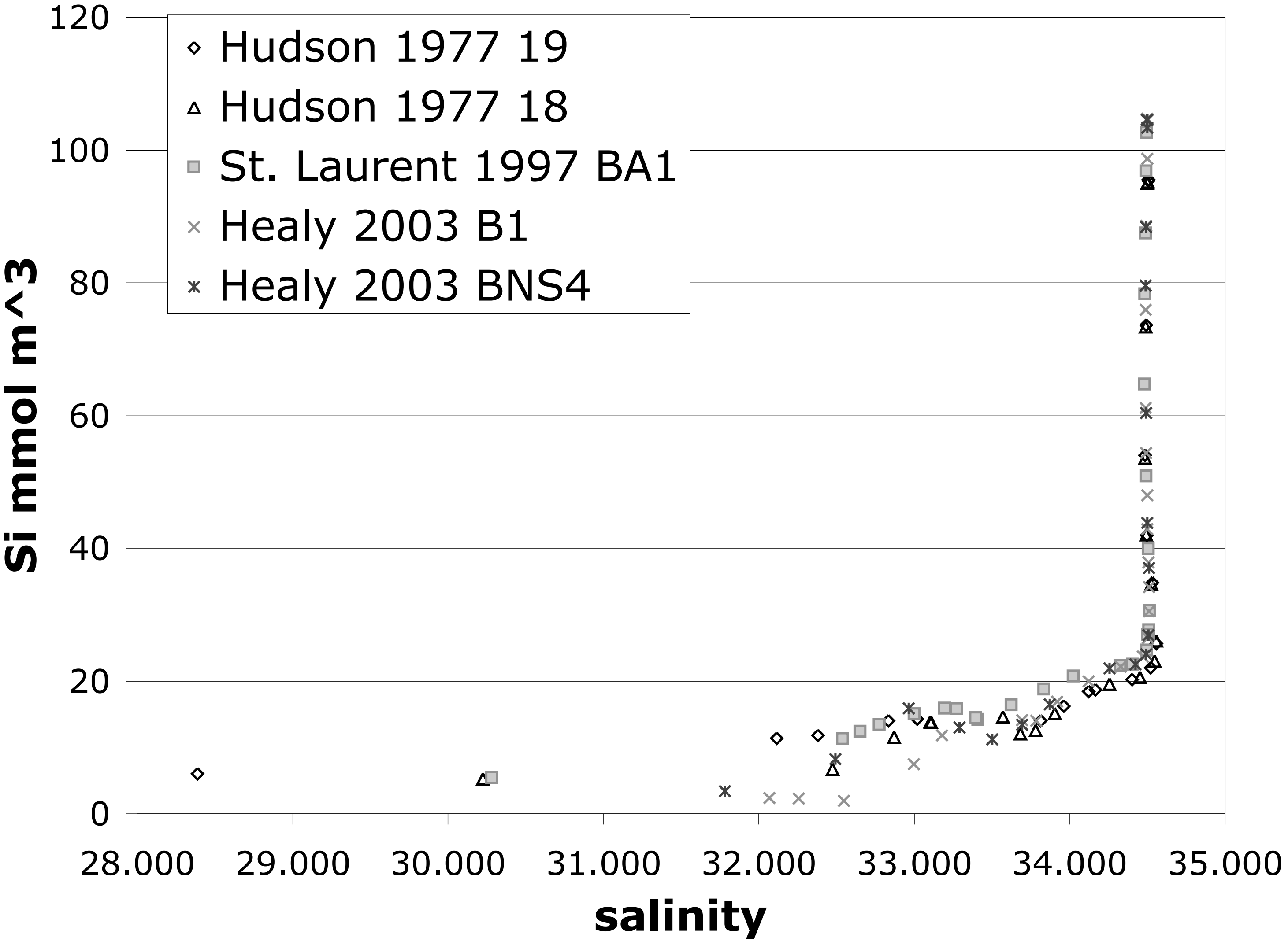

P [mmol/m^3]


Si [mmol/m^3]


Pacific Water [%]

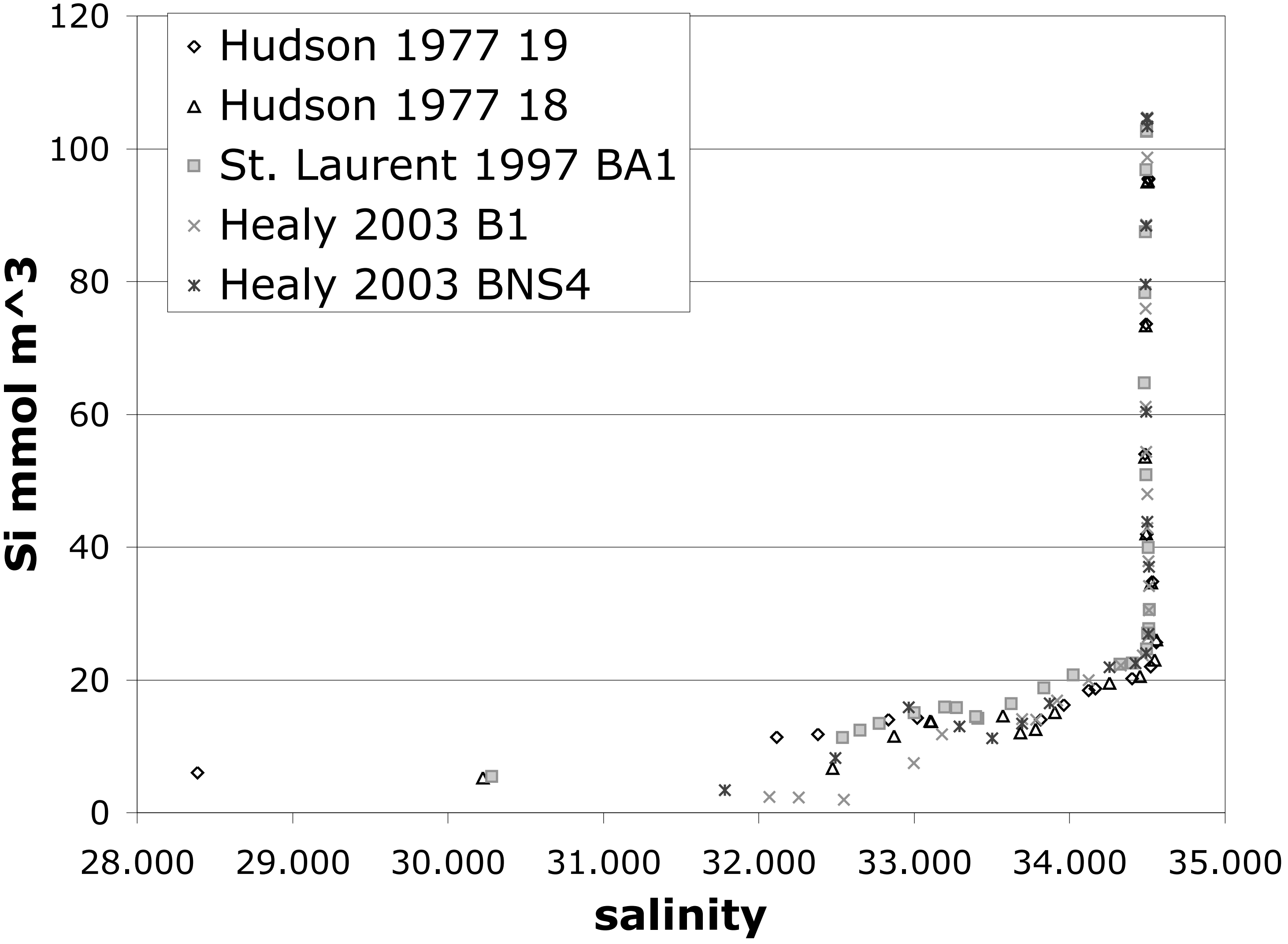

2
0
-2
-4
-6
-8
-10
-12
-14
N*
29
30
31
32
33
34
35
salinity pss
Baffin Section 2003
Davis Strait 1997
DS Stn6-1997
DS Stn9-1997
DS Stn5-1997
Hall Basin 2003
Robeson Channel
Kennedy Ch South 2003
Kennedy Ch North 2003
Smith Sd 2003
Barrow St 1997
Jones Sd 1997
Smith Sd 1997

Baffin Bay



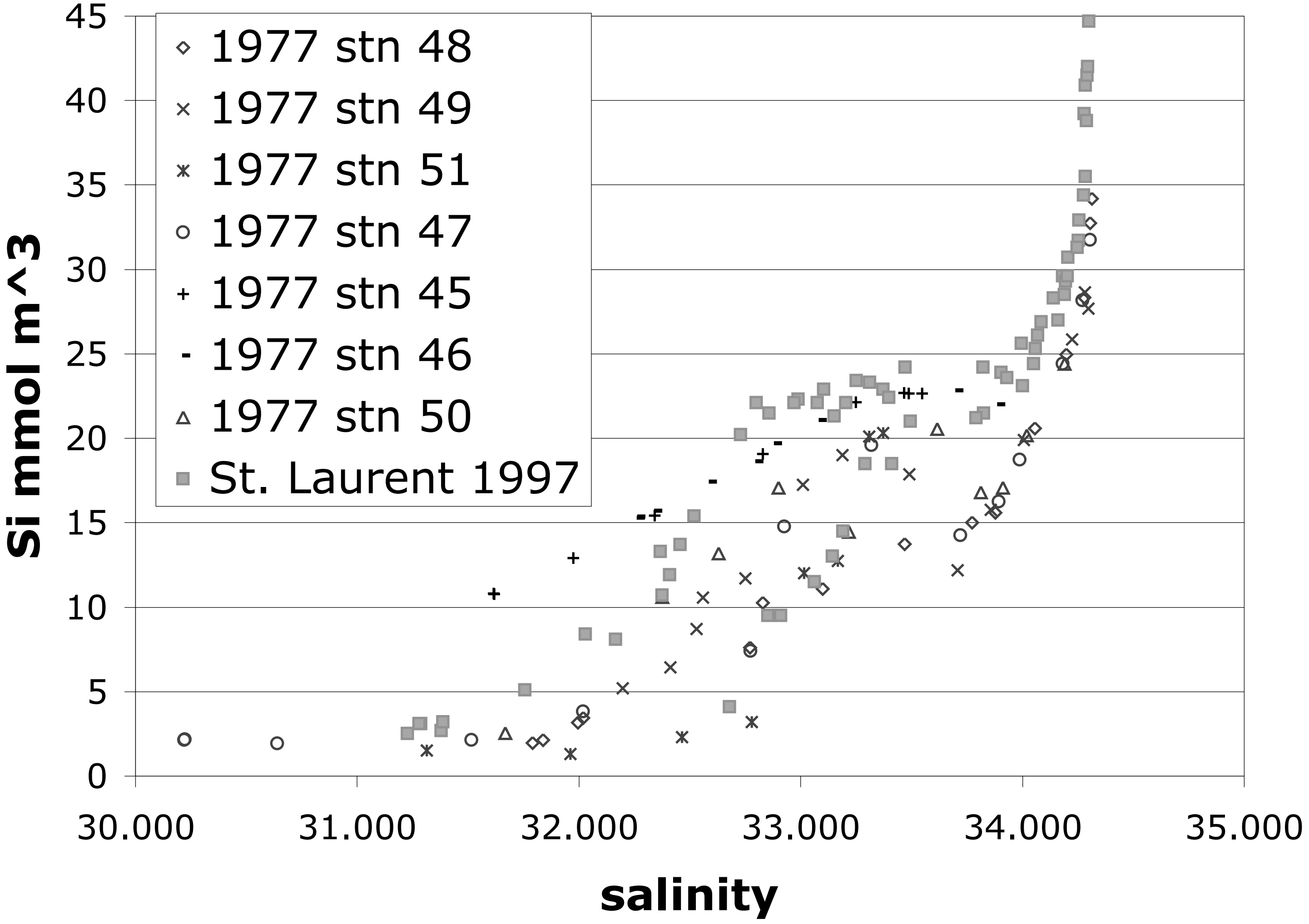
Si mmol m^3
salinity
120
100
80
60
40
20
0
28.000
29.000
30.000
31.000
32.000
33.000
34.000
35.000
◇ Hudson 1977 19
△ Hudson 1977 18
■ St. Laurent 1997 BA1
× Healy 2003 B1
✱ Healy 2003 BNS4

Baffin Bay

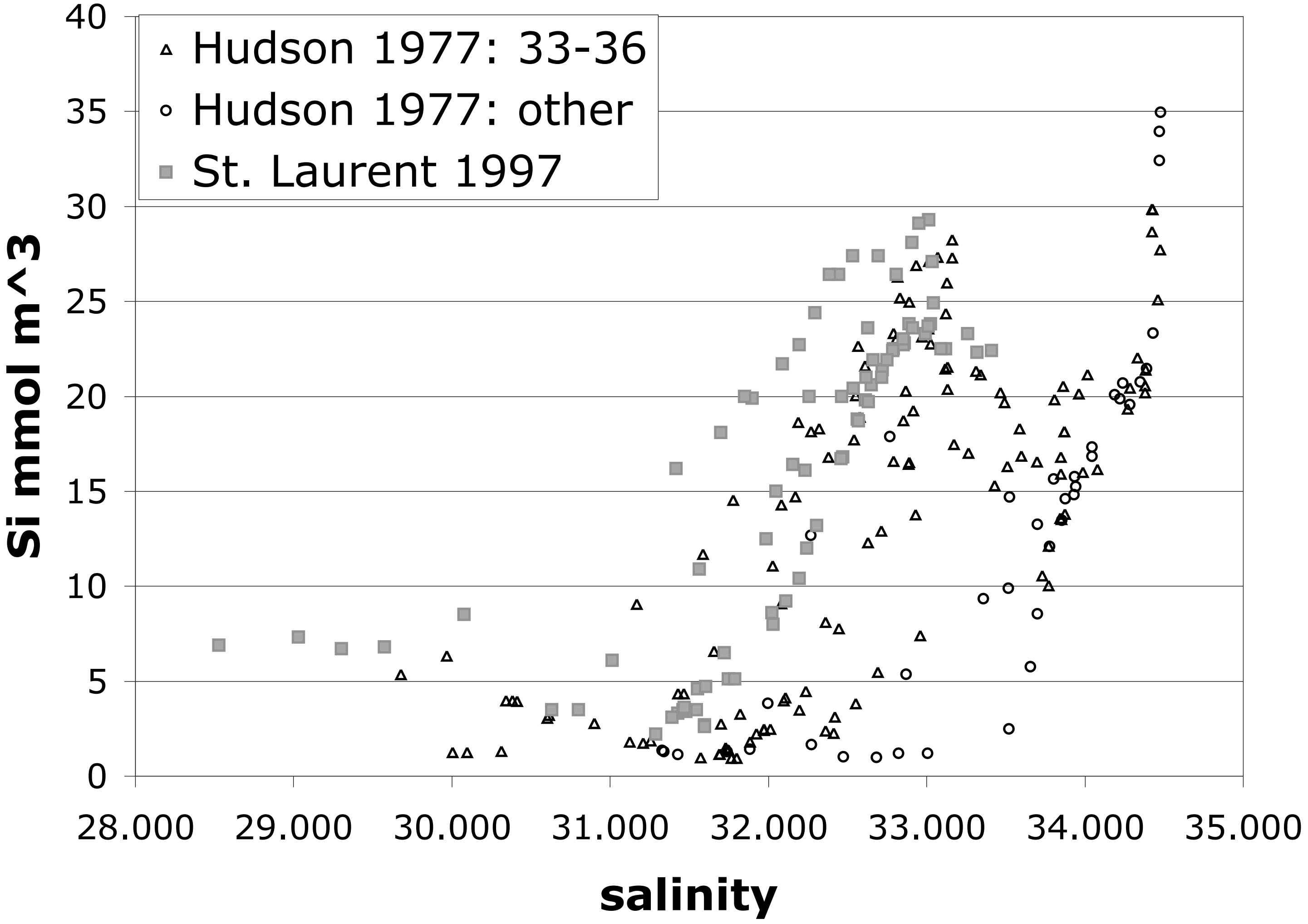


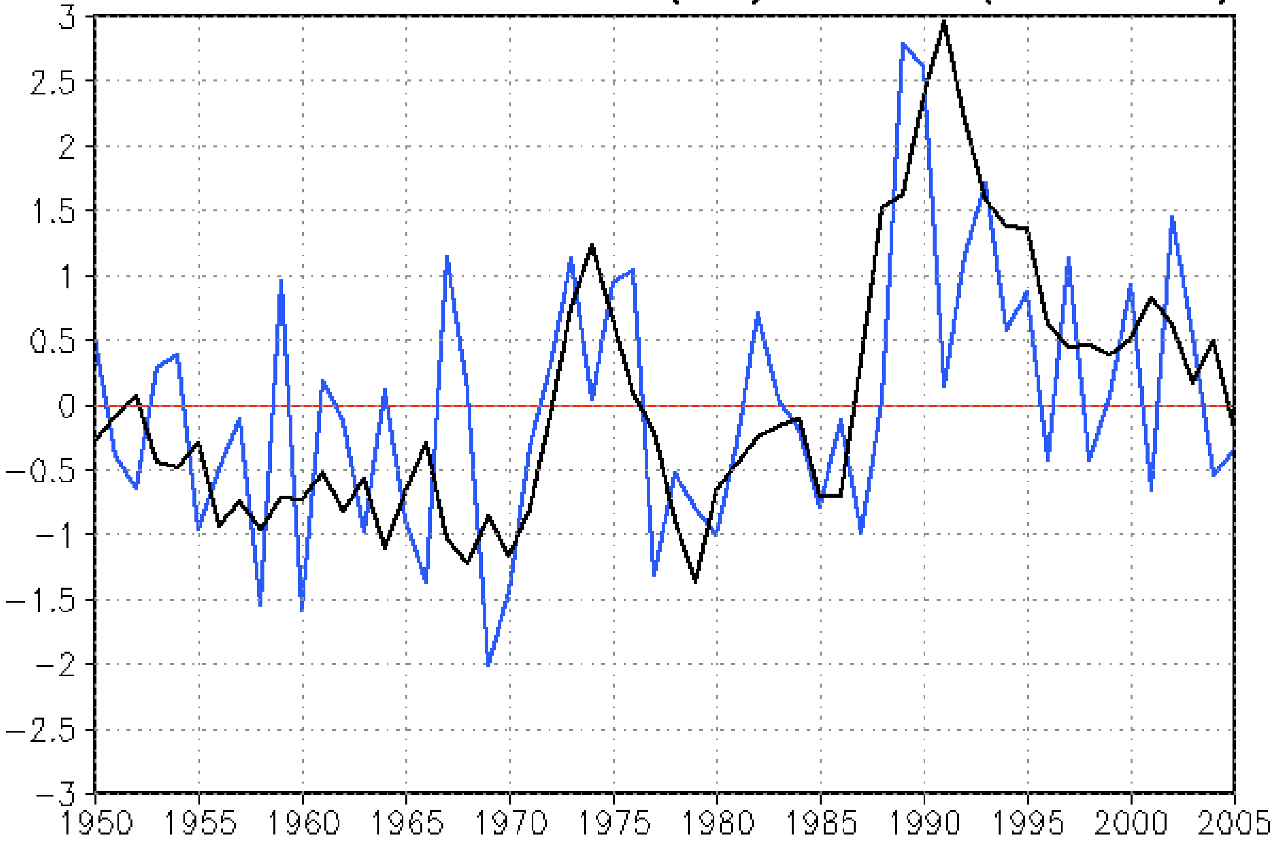
120
100
80
60
40
20
0
Si mmol m^3
◇ Hudson 1977 19
△ Hudson 1977 18
■ St. Laurent 1997 BA1
× Healy 2003 B1
✱ Healy 2003 BNS4
28.000
29.000
30.000
31.000
32.000
33.000
34.000
35.000
salinity

Jones Sound


45
40
35
30
25
20
15
10
5
0
Si mmol m^3
30.000
31.000
32.000
33.000
34.000
35.000
salinity
1977 stn 48
1977 stn 49
1977 stn 51
1977 stn 47
1977 stn 45
1977 stn 46
1977 stn 50
St. Laurent 1997

Lancaster Sound & Barrow Strait





Standardized Seasonal Mean (JFM) AO index (1950–2005)