Environmental influences on the distribution of sediment within a water column at a tidewater glacier, Jorge Montt

Sarah Huffer

School of Oceanography, University of Washington,

Seattle, Washington, 98195, USA

Non-technical summary

Temperate tidewater glaciers pour off more sediment per unit volume of area than all other ice formations. The terminus of tidewater glaciers are grounded within bodies of water. They are considered wet glaciers because as they advance and retreat, they slide over substantial amounts of basal melt water. Tidewater glaciers are continuously eroding the underlying earth down to bedrock. In the process, sediment is entrained, transported, and released into the marine environment. This study took note of the transmissivity throughout the water column at multiple stations. Sediment concentration values (mgL^{-1}) were assigned to the transmissivity (volts) by calculating a calibration curve. This curve was estimated by physically measuring the sediment concentration within several surface samples collected within the fjord. The general pathway of sediment throughout the water column was determined. The purpose of this study was to determine how certain factors present in the environment helped to direct the distribution of sediment within the water column. The developing behaviour of the sediment was documented along a transect leading away from the tidewater glacial source. Sediment layers were observed at concentrated depths at the ice face of the tidewater glacial. Sediment concentration decreased with increased distance from the ice face. It was determined that the sediment concentration per unit volume of water controlled the distribution of sediment within the depth of the fjord, while the bathymetry controlled the distribution along the length of the fjord.

Acknowledgements

This research could not have been possible without some amazing people who have been either directly involved in the development of my research, helped provide the data for my research, or have made themselves available for some serious scientific moral support. I would like to thank those involved in Charles Nittrouer's Lab. Chuck, Kristin Lee, Katie Boldt, and Andrea Ogston have played all three of those roles. Chuck and Katie were directly involved in the collection of the data at Jorge Montt Glacier in Chile and have provided invaluable support since. Andrea has been very patient with my random sediment transport inquiries, and Kristin has helped a lot with the general development of my research. Kathy Krogslund, Kathy Newell, as well as the Sediment Lab itself has provided much appreciated equipment for use collecting and analyzing my data. Many thanks as well to Bernard Hallet and the Chilean scientists at Centro de Estudios Cientificos, Valdivia, Chile, as well as the crew of the SeaBear and Huemueles, who worked with our team from the University of Washington to collect data and begin the processing of data. Lastly, and definitely not the least, thanks to the senior advising team instructing Ocean 443/444 making this entire experience possible and providing valuable insight to my research.

Abstract

Tidewater glaciers discharge large amounts of sediment-entrained water as they recede. This study explored the environmental factors controlling the delivery of the eroded material being supplied by the retreat of Jorge Montt Glacier in the Southern Patagonian Icefield in Chile. Actual sediment concentrations were measured at sites where transmissivity was measured. A calibration curve allowed the sediment concentration to be determined throughout the water column, allowing the distribution of sediment in the fjord at Jorge Montt to be documented. Profiles indicative of Baker Channel, Pascua River, and Jorge Montt Glacier were clearly documented. Sediment at the ice face was concentrated at approximately 100 m, along the grounding line of the tidewater glacier, and was as high as 26 mgL^{-1} about 150 m from the ice face. This concentration decreased to 6 mgL^{-1} 6 km from the ice face before increasing the broad layer of sediment bunched up against the bathymetry of the fjord. This led to the conclusion that the topographical features of the seafloor controlled lateral transport of sediment within the fjord at Jorge Montt Glacier. The depth of sediment advection was observed to be dependant upon it's concentration per unit volume of water. The density of the sediment entrained freshwater had to equilibrate with density that was based primarily on salinity within the fjord.

Introduction

The ice fields of Patagonia contain some of the world's largest tidewater glaciers. Due to their high rates of retreat and hence fresh water run off, they contribute the equivalent of approximately 0.105 $mmyr^{-1}$ towards sea-level rise (Rignot et al. 2003, Aniya et al. 1997). Tidewater glaciers carve out fjords as they advance and result in high rates of erosion as they retreat (Koppes & Hallet 2006). The retreat of tidewater glaciers create erosive rates that are much greater than grounded glaciers (where the terminus is on land rather than a marine environment), and any type of river system (Koppes & Hallet 2006). This was clearly documented in a study completed by Koppes & Hallet (2006) where a parallel was drawn between the rate of erosion and the rate of retreat at Tyndall Glacier, located in Icy Bay, Alaska (Koppes & Hallet 2006). The contribution of tidewater glaciers to sea-level rise via melt water is an indicator of the erosive processes occurring within the Patagonian Icefields.

Jorge Montt is a tidewater glacier located in the northern extent of the Southern Patagonian Icefield. It is located within the northern region of Bernardo O'Higgins National Park in Chile, grounded within a fjord flowing into Baker Channel (Fig. 1). Jorge Montt Glacier has an accumulation area of 348 km^2 (Aniya et al. 1997), and covers a total area of 464 km^2. Jorge Montt is approximately 17 km from the farthest shallow moraine formed during the Last Glacial Maxima north of the fjord (Bernard Hallet, pers. comm., Figs. 1, 2). The presence of this series of shallow moraines may increase the residence time of the sediment-entrained melt water by hindering subsurface flow. The Inner Basin is approximately 380 m deep, ranging from the ice face of Jorge Montt Glacier to d approximately 11 km along the length of the fjord

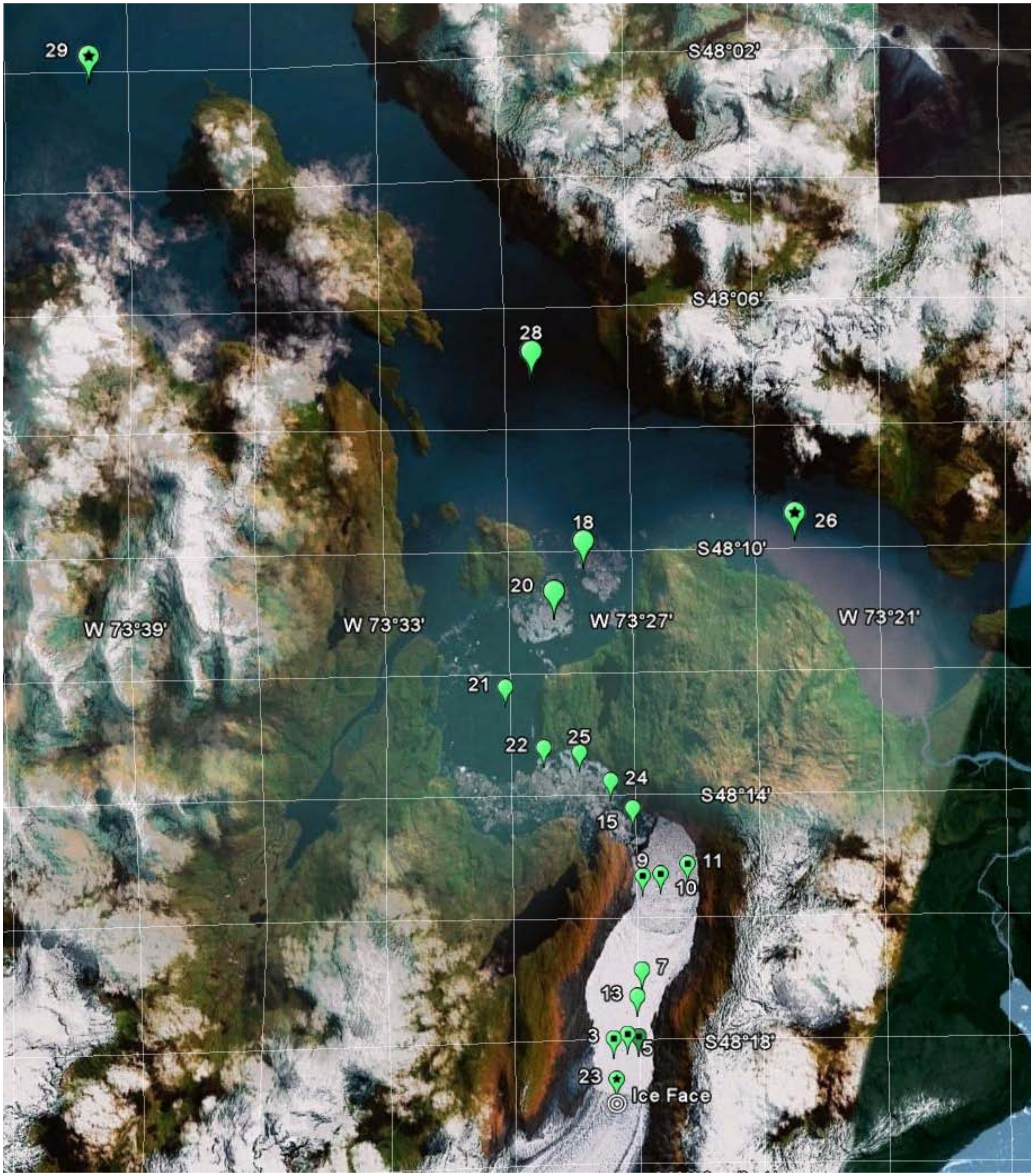

Figure 1: Map of study area. Jorge Montt Glacier recedes to the south, having carved out the fjord leading into Baker Channel to the north. Balloons depict locations of vertical CTD casting sites of interest. Stars depict clear signals of ocean, river, and glacial profiles discussed in text. Squares plot sites illustrate the symmetry of fjord.

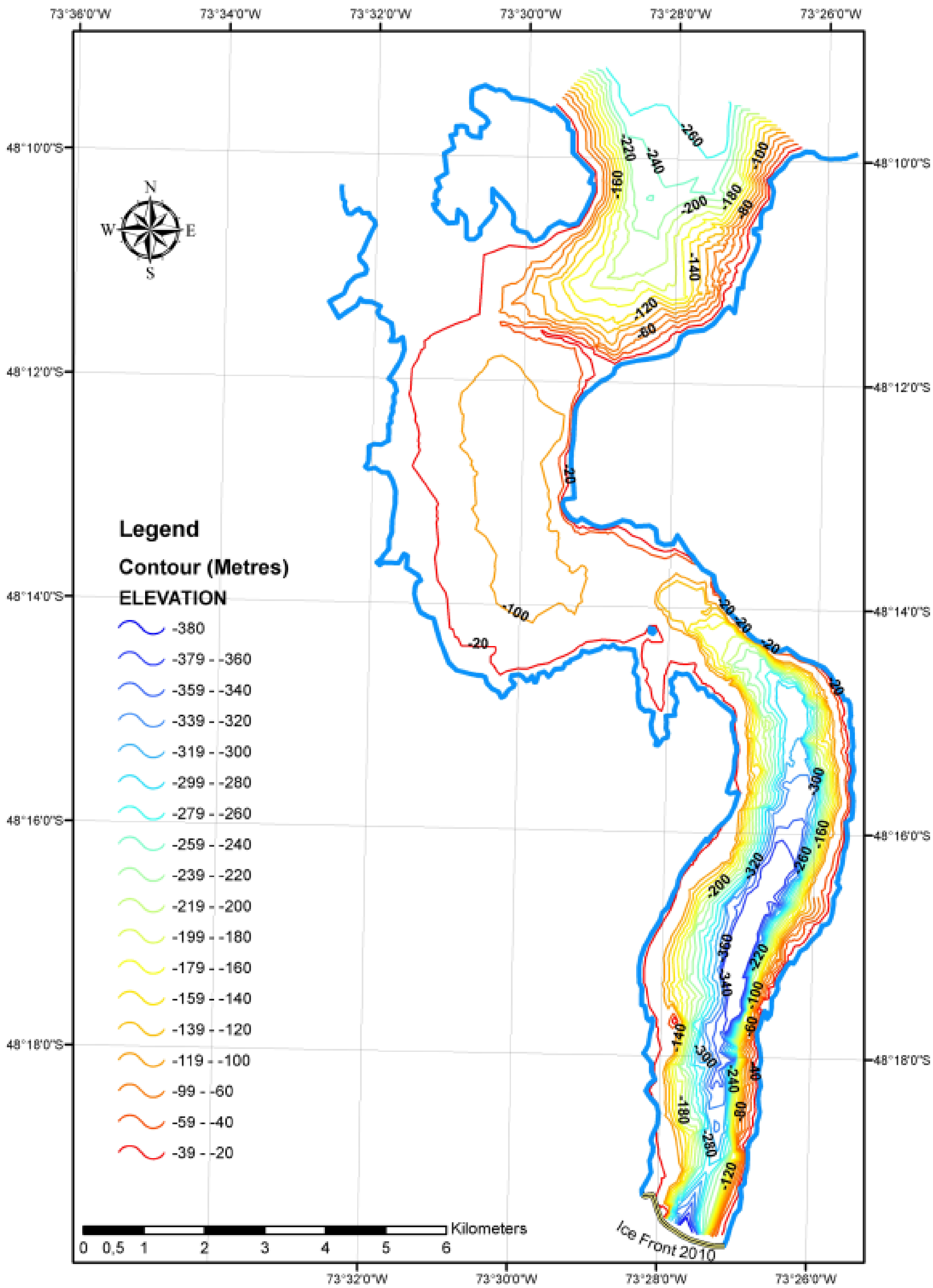

Figure 2: Contour map of fjord at Jorge Montt. Depths were as shallow as 20 m, and reached depths of 380 m (Centro de Estudios Cientificos, Valdivia, Chile, unpublished, 2010).

(Figs. 1, 2). The Outer Basin is approximately 120 m deep, and extends 5.5 km past the Inner Basin boundary (Figs. 1, 2).

The fjord is orientated north-west to south-east, along the same vector as south-easterly winds, thus allowing a longer fetch than would be otherwise anticipated. Some shelter is provided closer to the ice face with fjord widths ranging from 0.25 to 0.8 km (Fig. 1). Previous studies, primarily based on data collected by remote-sensing techniques, focused on changes in overall glacial variation of size and extent (Aniya et al. 2007). Despite the fact that little on-site research has been conducted within the Southern Chilean glacial network, many processes in other tidewater glacial environments have been well studied elsewhere, and are applicable to processes observed at Jorge Montt Glacier. Due to fast rate of retreat, and high annual precipitation, this system likely contributes significant amounts of eroded sediment into the Chilean fjords (Dowdeswell & Cromack 1990).

The temperature of Baker Channel is approximate 8.3 ^{o}C, which is much higher than a tidewater glacier such as Jorge Montt (Hromic et al. 2006). The balance between accumulation and melting continuously modifies the equilibrium line altitude (Barcaza & Aniya 2009). Cold freshwater flows through supra-glacial (surface melt water), en-glacial (within or through the glacier at intermediate depths), and as sub-glacial (under) conduits as the glacier retreats (Fountain & Walder 1998). Fresh fluids exit the tidewater glaciers at the contact point between the terminus and the marine environment (Hunter et. al 1996). The pathways of the sediment entrained in the freshwater enter the fjords within different zones during melting, forming high sediment concentrations. Sediment flows off of the terminus of retreating glaciers in the form of melt-water surface plumes and nepheloid layers. These layers disperse to specific points within the water column by equilibrating at some intermediate depth (Wright et al. 1989). When neutral buoyancy isn't achieved, the packet of sediment entrained water either rises to the surface, or sinks to the bottom.

Nepheloid layers are important pathways for sediment transport. Regional factors (including currents, wind, water temperature, salinity, and contact with the seabed) affect the shape, concentration, and discharge of both the surface plume and the deeper nepheloid layers (Dowdeswell & Cromack 1990). The interrelationship between temperature, salinity, and sediment concentration will be observed to attempt to explain the behaviour of these transport pathways. The combinations of these variables created by the tidewater glacial environment determine a certain density, particular to that packet of water. Depending on what region (surface, intermediate, or bottom) of the tidewater glacier front the sediment entrained layer is introduced to, as well as its specific density determines whether the packet of water will rise or sink to reach neutral buoyancy. One of the goals of this study is to identify specific layers that suspended sediment discharged from the ice face of Jorge Montt travel within, and examine whether bathymetry formed by the retreat of the glacier impacted sediment transport. Bathymetry is one of the primary factors hypothesized to dramatically effect the concentration of sediment carried within nepheloid layers because the elevated topography physically blocks the layers they travel within (Wright et al. 1989). However, there may be other factors within the tidewater glacial environment that act as barriers that create temporary or permanent dual stratification within the water column (Dowdesd & Cromack 1990).

A previous study completed by Dowdeswell & Cromack (1990) at Spitzbergen proposes the potential for dual stratification within a water column at a tidewater glacier. Cold, turbid glacier melt water from multiple glacial sources drains into Signehamna, a 1.5 km marine inlet. The surface freshwater was much colder, entraining higher concentrations of sediment within Signehamna. These conditions should be comparable to those at Jorge Montt Glacier, especially when tidal conditions are considered. The maximum tidal range recorded within Signehamna during the study was 1.5 m, only slightly greater than the one meter tidal range observed at Jorge Montt. This proposes that tidal forcing at both sites is comparable, and would circulate sediment around other barriers experienced within a fjord, such as seafloor topography.

Multiple studies have been completed concerning water movement over a sill, in both active tidewater glacial environments and fjord systems. A study completed by Farmer & Smith (1979) in Knight Inlet in British Columbia involved quantitative insights into circulation about a sill. Although these suppositions cannot be quantitatively examined in this particular study, insights made at Knight Inlet allow the possibility for tentative conclusions to be reached regarding the brief observations made of processes occurring at Jorge Montt.

The purpose of this study is to provide insight into how environmental variables and sub- aqueous topography can affect the pathway of suspended sediment released from a tidewater glacier. This will be accomplished by focusing on the bathymetric morphology and the environmental conditions present. These variables will then be correlated with the observed distribution of sediment within the water column along the length of the fjord at

Jorge Montt Glacier. Specific morphologic structure can be considered when determining how seabed morphology affects the fate of sediment particles derived from terrigenous sources dispersing into the marine environment. Data collected by Charles Nittrouer, Katie Boldt, and their associates affiliated with the Centro de Universidad de Concepcion in Chile provide the snapshot of the conditions to be studied at Jorge Montt. This study involves the organization of this data, both qualitatively and quantitatively, and will give insight into the degree to which environmental conditions play a role in sediment transport.

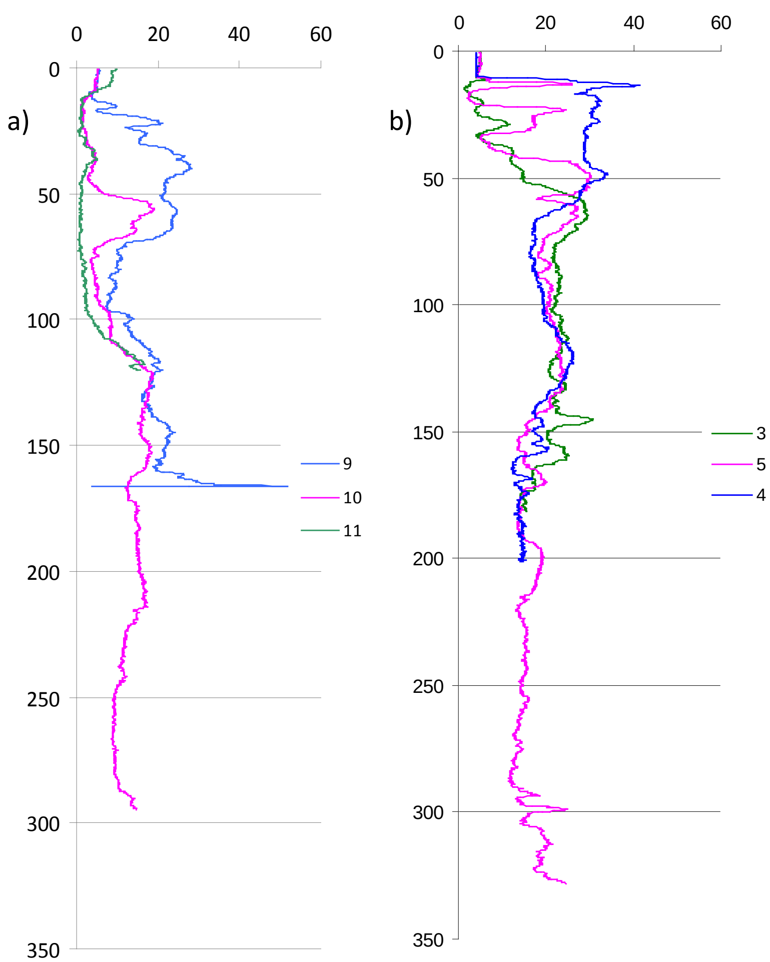

Figure 3: Casting profiles of sediment concentration within the water column for a) stations 9, 10, and 11, 6.5km from ice face, across the width of the fjord. b) Stations 3, 4, amd 5, located 1.5 m from the ice face, across the width of fjord. Stations 10 and 5 are clearly defined as the thalwegs.

Methods

Water column- Vertical cast locations were generally completed along the thalweg, which is the deepest point in the channel, although not necessarily the center (Fig. 3). Sites chosen for CTD casts were based on the depths measured by the echo sounder and depth gauge, both of which were a part of the ships systems. The stations were located along a transect perpendicular to the ice face in one nautical mile increments (Fig. 1). Three CTD casts were made across the width of the fjord along each transect progressing away from Jorge Montt. The coordinates for the stations located close to the ice face were adjusted when the boats had to maneuver around calving ice. Effort was made to align transect lines with key features in the bathymetry in order to examine differences in the water column.

The CTD used in this research was a Seabird 25 owned by Carlos Moffat from the Universidad de Concepcion. In addition to temperature, pressure, and conductivity sensors, the instrument was also mounted with a dissolved oxygen sensor, and an optical backscatter sensor. Data collected was downloaded from the Seabird and formatted into a text file. The data sets n imported into Excel and organized into spreadsheets. The data was imported into Golden Software's Surfer program and contour plots were created for each variable. Steps were taken to convert the transmissivity values into sediment concentrations (see below).

Calibration curve-The calibration curve was created to convert voltage signals recorded with the Optical Back Scatter (OBS) device on the CTD into corresponding concentrations of sediment for the particular environment being studied. The collection of surface water samples was completed at sixteen of the CTD stations that CTD casts were made (Table 1). The sediment within the surface water samples was extracted with a hand pump filtration system aboard the ship the SeaBear. The pre-weighed 0.45 glass-fiber filters were used to determine the amount of sediment collected per unit volume of water. Filters were placed in the oven at 60°C for 24 hours. A maximum of five samples were removed from the desiccator cabinet at a time and weighed to avoid rehydration of the sample. A linear equation was calculated on Excel from a trend line fit to a scatter plot graphing the sediment concentration at each station versus the transmissivity measured from the same location and depth. This equation was used to translate transmissivity values into suspended sediment concentrations for all values measured at each depth for all OBS profiles recorded.

Table 1: Water was collected at the surface at each of the specified stations. Locations are specified in Figure 12. Transmissivity values were input into the equation calculated from the slope of the line presented in the results section.

Station	Transmissivity (volts)	Weight Sediment (mg)	Water Vol (L)	Concentration (mgL^{-1})
3	2.41	1.56	0.505	3.09
5	2.34	3.1	0.75	4.13
7	3.71	4.82	0.75	6.43
10	2.59	3.7	0.75	4.93
11	4.88	5.42	0.75	7.23
12	1.86	3.1	0.75	4.13
14	2.94	4.9	0.75	6.53
21	5.12	8.33	0.75	1.11
22	3.4	4.9	0.75	6.53
23	1.88	4	0.75	5.33
24	5.33	7.3	0.75	9.73
25	4.75	5.8	0.5	11.60
26	8.49	8.3	0.5	16.60
27	6.93	7.2	0.5	14.40
28	3.35	3.3	0.5	6.60
29	1.48	2.3	0.5	4.60

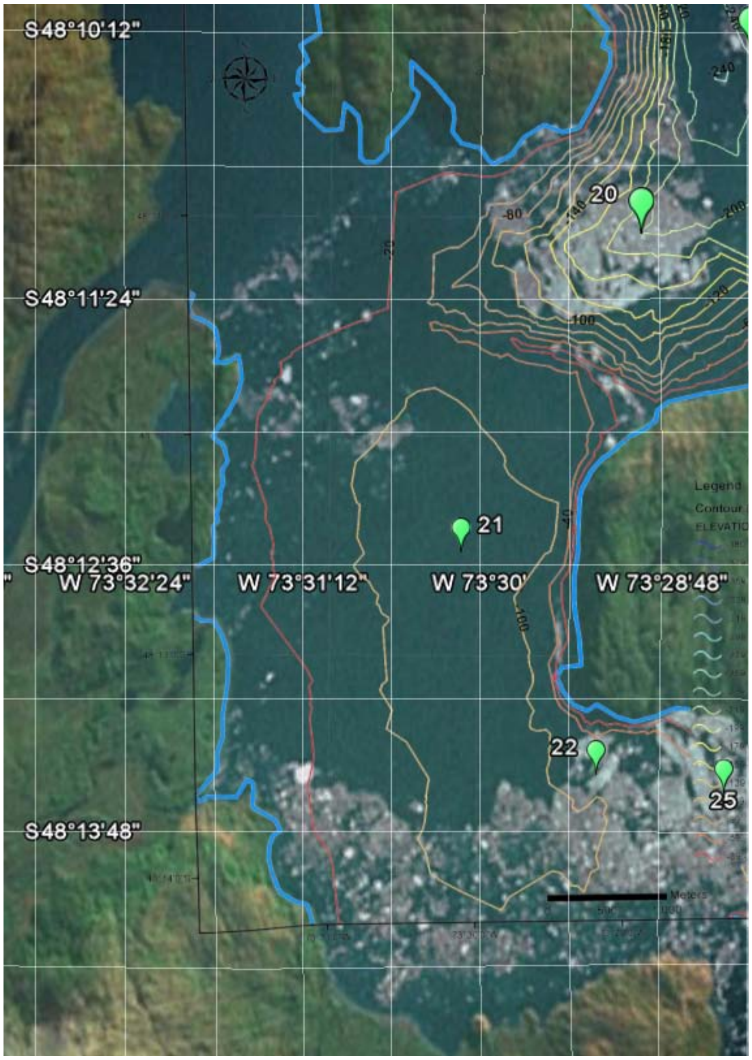

Figure 4: Bathymetric overlay of boundary between outer basin and Baker Channel (Centro de Estudios Cientificos).

Bathymetric Analysis- Bathymetry was collected during field work, compiled and mapped (Fig. 4). Depths were determined from this unpublished bathymetric chart prepared by scientists at Centro de Estudios Cientificos, in Chile. The chart was converted into an overlay and imported into Google Earth. Distances from the ice face were determined at stations and at topographically significant points along the length of the fjord. Values were imported into Surfer as a polygon file where they were used to create a mask on the contour plots to represent seafloor topography.

Results

Calculation of calibration curve- Water samples were collected from sixteen points within Jorge Montt fjord. The surface water samples were collected from approximately 150 m in front of the ice face to over 40 km distance into Baker Channel. The water samples collected were limited to the surface waters lending a small but significant relationship was determined.

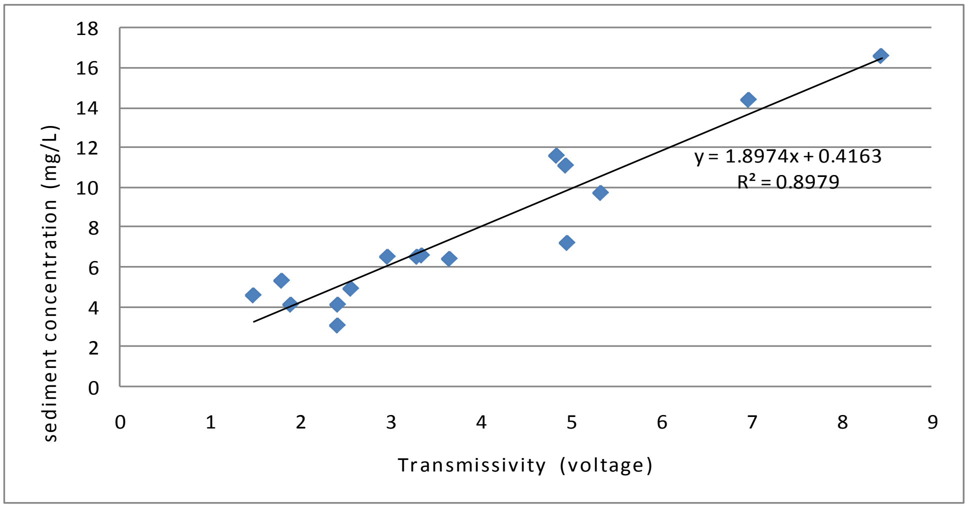

Figure 5: Calibration curve calculated from surface water samples collected within Baker Channel, and the fjord being carved out by the advance of Jorge Montt.

Sediment concentrations ranged from 3.09 mgL^{-1} to 16.60 mgL^{-1}, with a mean value of 7.69 mgL^{-1}.

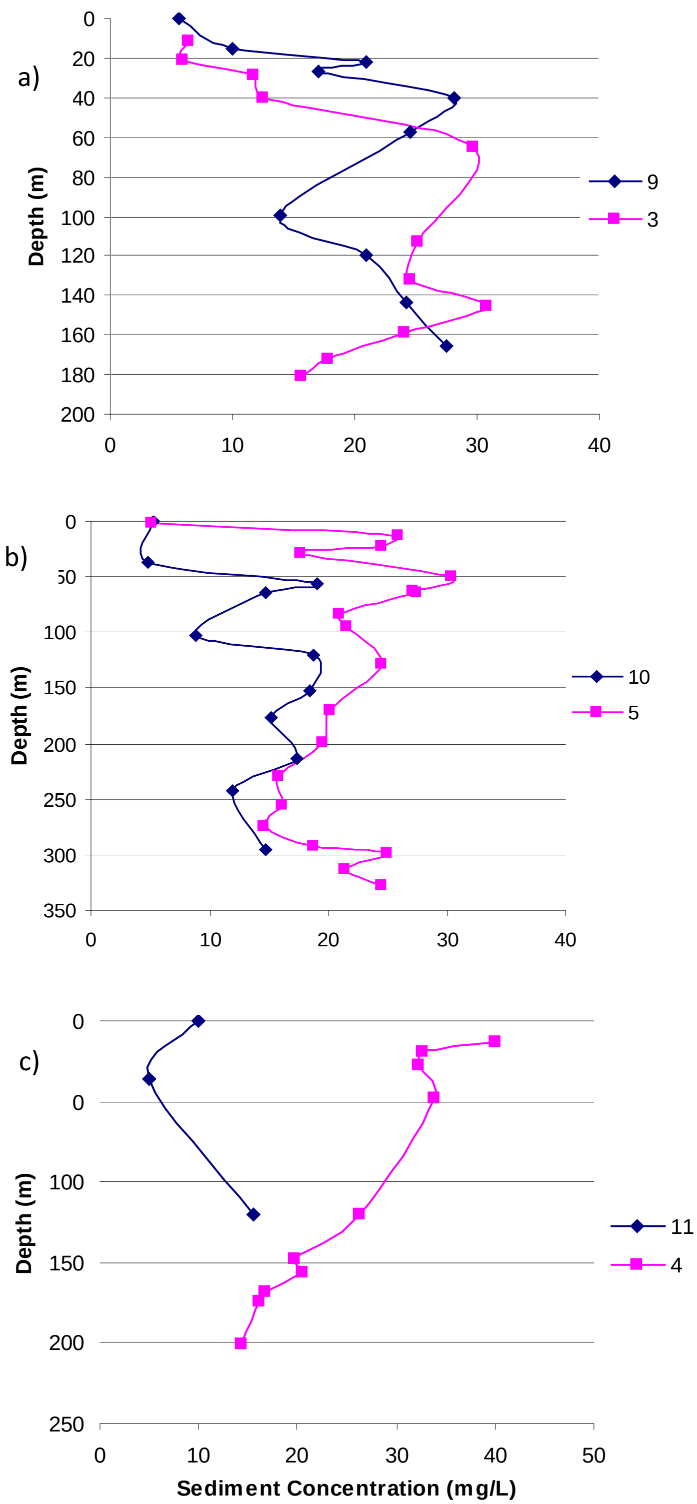

Figure 6: a) Stations 3 and 9 located along the western edge of the fjord at Jorge Montt. b) Stations 5 and 10 and 5, located along the thalweg of the fjord. c) Stations 4 and 11 located along the eastern edge of the fjord. Stations 3, 4, and 5 are closer to the tidewater glacier ice face and have higher sediment concentrations compared to Stations 9, 10, and 11 located nearly 5 km farther along the fjord.

Symmetry within fjord- Stations 3, 4, and 5 are located 1.5 km from the ice face, and Stations 9, 10, and 11 are located 5 km (Fig. 1). The spatial distribution of the sediment across the width of the fjord is not constant according to these two sections of the fjord analyzed. The concentrations clearly monotonically increase from west to east across the transect at Station 10 (Fig. 4a). This increase occurs at across Station 5 as well, but with a higher degree of interference from the tidewater glacier (Fig. 4b).

Characterization of system profiles- Measurements of transmissivity at stations that were primarily influenced by ocean, river, and a tidewater glacier were distinctly different. The vertical casts executed at stations 23, 29, and 26 were compared, illustrating this fact (Fig.

7). The cast at the mouth of the Pascua River has substantial surface plume reaching 17.1 mgL^{-1}, and reached to a depth of 19.2 m at the time measurements were made. The profile measured farthest far out into Baker Channel had a surface plume as well, but achieving concentrations reaching 3.9 $mgL^{-1}$and to a depth of 16.2 m. The tidewater glacier surface-sediment concentrations comparable to those in Baker Channel, but at the depth where the ocean profile degraded, the concentrations at the tidewater glacier spiked up to 33.7 mgL^{-1} at 22.6 m depth. Sediment remained at high densities

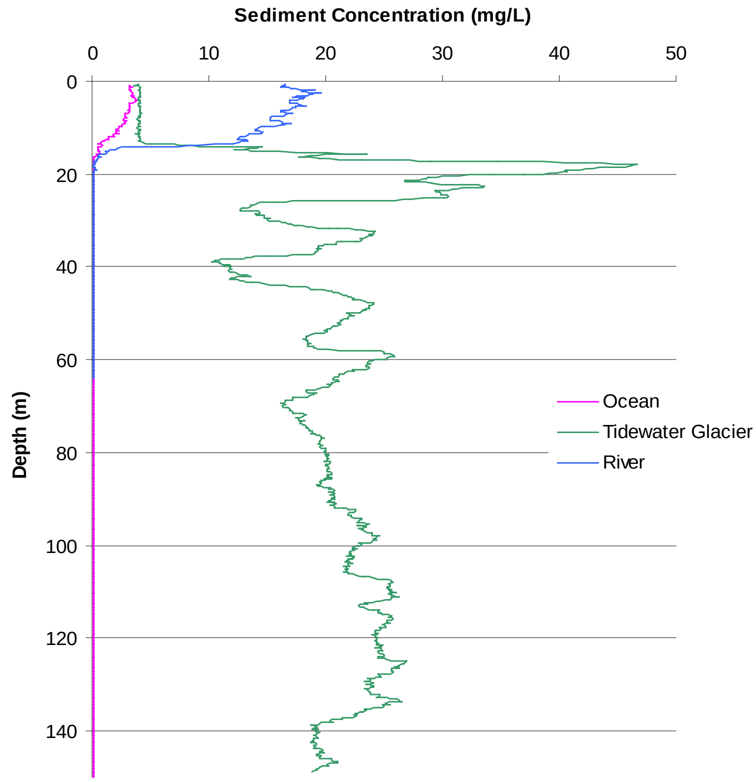

Figure 7: Sediment concentration profiles within three defined systems: the ocean, a tidewater glacier, and a river. The ocean extends to over 350 meters. Insignificant concentrations of sediment were in the water column below an abbreviated surface plume of less than 5 milligrams per liter. The river profile depicts a substantial surface plume, terminating at the same depth as in the ocean. The tidewater glacier profile is entirely different, with higher sediment concentration values at the same depth where the other two profiles reduce to zero.

Temperature within the fjord- Temperature of the fresh glacial melt water 150 meters from the terminus of the glacier was as low as 3.6°C, increasing to 7.75°C from 240 m depth to the seabed at 380 m (Fig. 8a). At the surface, the temperature increased to 7.5°C before decreasing back to 7.25°C when the first morainal feature was encountered that reached . At the peak of this feature, temp again increased monotonically across the increasingly shallow sea bed topography out of the Inner Basin. Temperature increased steadily towards the mouth of the fjord across the Outer Basin until the bathymetry became as shallow as 20-40 m. Marine water from Baker Channel was over 10^{o}C within the first 100 m, decreasing to 8.3^{o}C beyond the Outer Basin.

Sediment Concentration within the fjord- Sediment concentration at the tidewater glacier terminus increased progressively towards the mouth of the fjord (Fig. 8b). Sediment concentrations increase at 150 m from the ice face as depth increases. Sediment reached concentrations of 24.5 mgL^{-1} 1.5 m from the ice face at the benthic boundary layer at the bottom of the morainal feature that Jorge Montt is braced against. Sediment was entrained within the entire water column just inside the boundary of the Inner Basin reaching concentrations of 15 mgL^{-1} at approximately 100 mdepth. Sediment concentrations decreased at an increasing rate across the Outer Basin, forming a dually stratified system across the shallow outer moraine.

Salinity within the fjord- The salinity across the entire length of the fjord was a two layer system, changing abruptly from approximately 2 $^{o}/_{oo}$ to 29 $^{o}/_{oo}$ from the surface to the sea floor (Fig. 8c). Values reached up to 30.6^{o}C at approximately 4 km and 8.5 km from the ice face within the deepest region of the Inner Basin, and within the progressively shallow bathymetry at Station 24 (Fig. 2). Salinity increases at a steady rate within the Outer Basin, resulting in a thing freshwater lens. Salinity at 20 m $29^{o}/_{oo}$, progressing to $33^{o}/_{oo}$ at 80 m at the outer morainal feature.

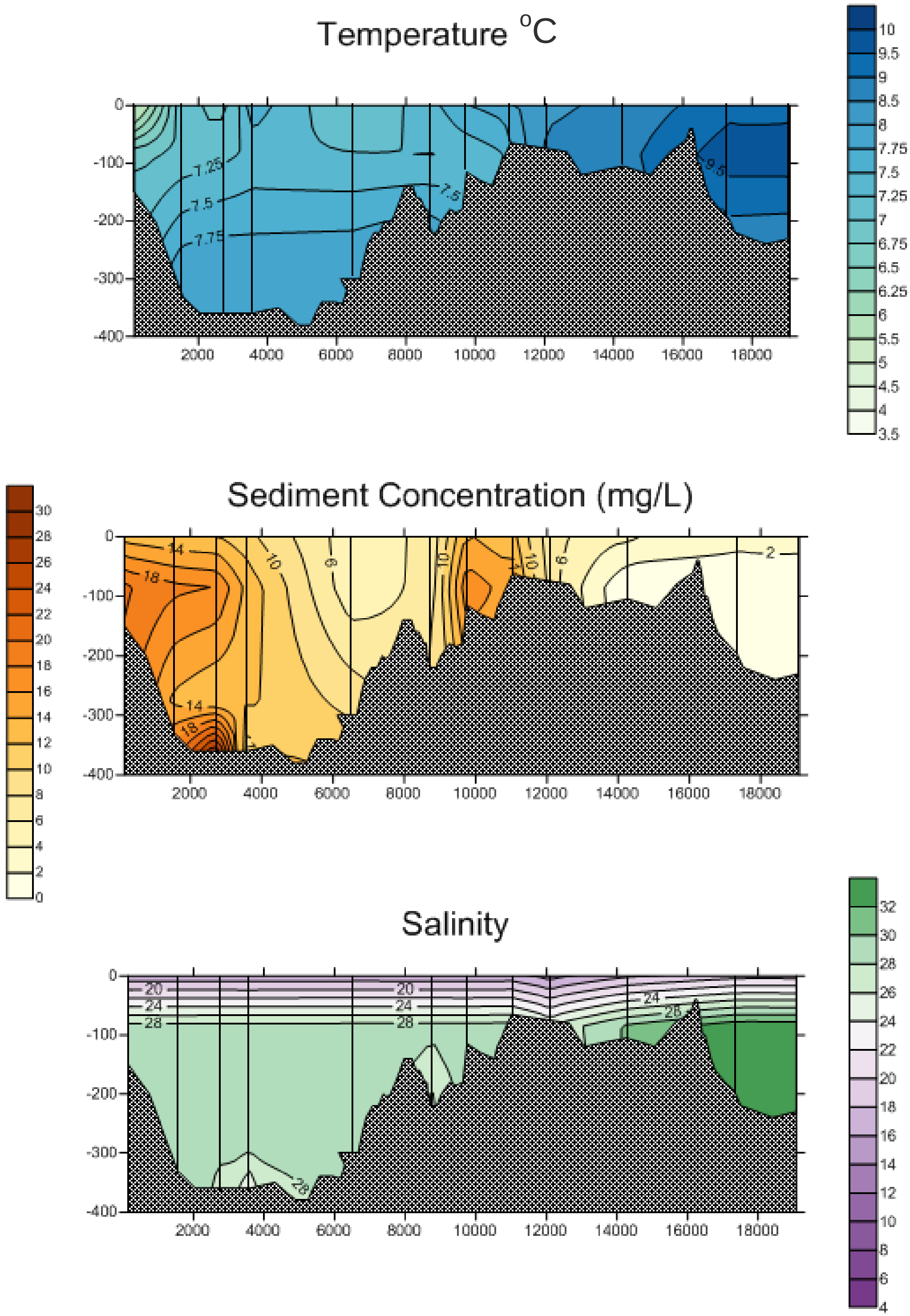

Figure 8: Contour plots of a) Temperature b) Turbidity and c) Salinity within the fjord at Jorge Montt.

Density within the fjord- The density contour plot shows a dually stratified system as observed in the salinity contour plot (Figures 9a, 8c). Density increased across the length of the channel at a stead rate from 1.2 kgm^{-3} at the surface to approximately 14.3 kgm^{-3} at 10 m depth. At this point, density abruptly progresses to kgm^{-3} at a monotonically rate until approximately 100 m, from which density remains steady. Low density patches of water were observed at unlikely points along within the benthic zone. At approximately 1.5 km at Station 7 (Fig. 1) from the ice face a density patch averaging 16.8 kgm^{-3} within the deepest part of the Inner Basin. Another low density patch decreasing to 24.5 kgm^{-3} was observed midway across the increasing bathymetric elevation at Station 24 (Fig. 1) towards the boundary containing the Inner Basin. Density of the water increased at an increasing rate from the Inner-Outer Basin boundary and across the Outer Basin and shallow morainal feature. Density along the seafloor at Station 18, over 19 km from the ice face (Fig. 1) rose to 26.4 kgm^{-3}, the highest observed within the fjord at Jorge Montt.

Oxygen within the fjord- The profile was similar to the density and salinity profiles, decreasing from 7.8 $mL0_2L^{-1}$ the length of the fjord to the outer moraine of the Outer Basin (Figure 9b). Oxygen decreased with increased depth at a generally steady rate to approximately 120 m to roughly 5.4 $mL0_2L^{-1}$. Within only the Inner Basin, observed oxygen decreased to 3.8 $mL0_2L^{-1}$ at its lowest point at Station 7 (Fig. 1) which is 3.5 km from the ice face. Outside the outer moraine within Baker Channel, oxygen levels decreased at a fast rate at the surface decreasing to 5.4 $mL0_2L^{-1}$ at a depth of 60 m rather than 120, deceasing to insignificant levels at approximately 200 m.

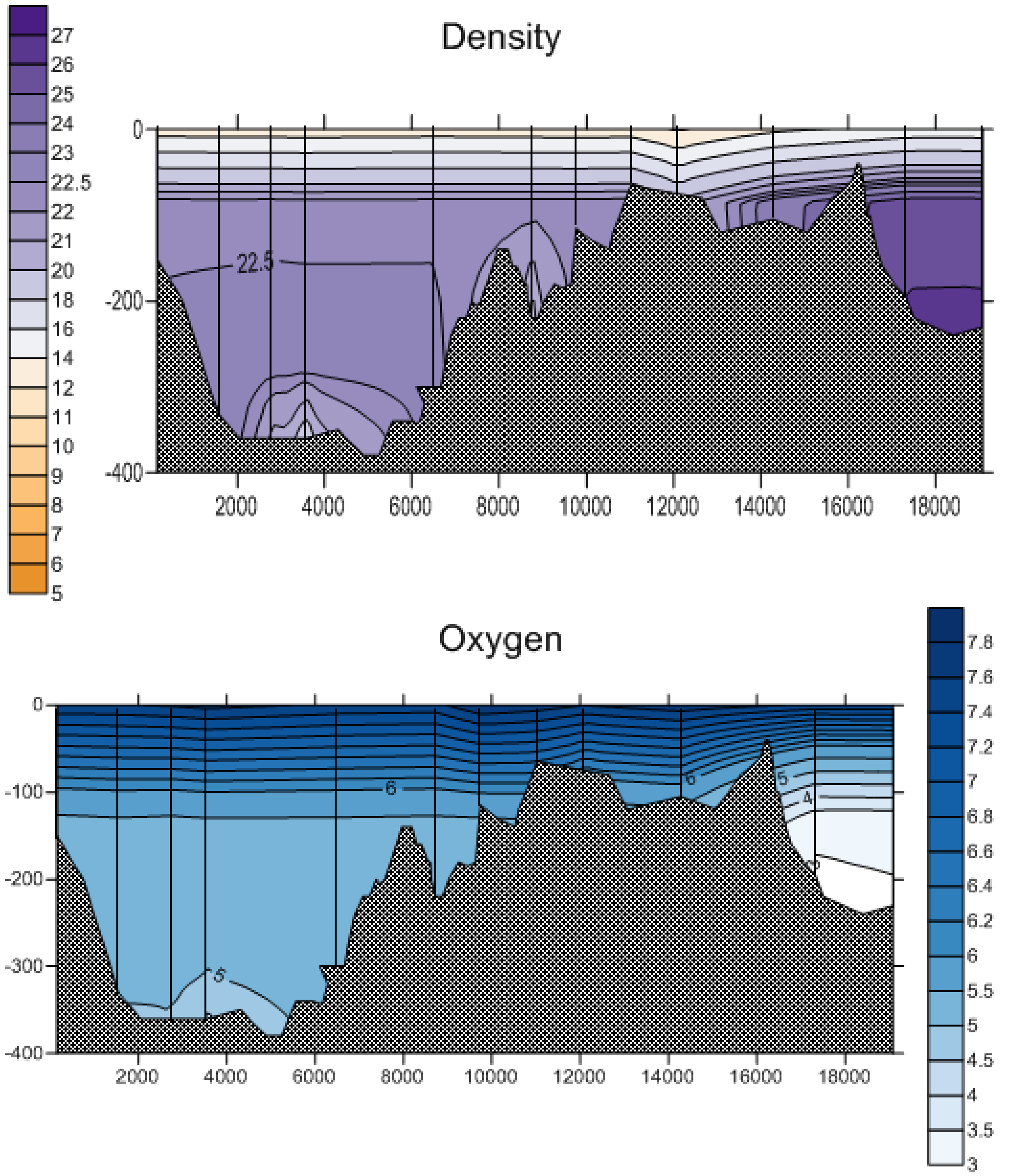

Figure 9: Density (a) and Oxygen (b) contour plots within the fjord at Jorge Montt.

Discussion

The fate of tidewater glaciers are important to study because run-off from the glaciers significantly impact local and global sea-level by 0.105 $mmyr^{-1}$ per year (Rignot et al. 2003). Results from remote-sensing equipment including data collected via oblique and vertical aerial photographs, Landsat MSS, Landsat TM, SPOT HX, and SPOT HP indicate that most Patagonian glaciers are receding (Aniya et al. 1997). Only two of the fifty glaciers that make up the Southern Patagonian Icefield are currently in an advancing state (Aniya et al. 1997). As recently as the 1800's, during the beginning of the Industrial Revolution, at least 20% of the glaciers within the Southern Patagonian Icefield were advancing (Masiokas et al. 2009). Receding glaciers have a much higher rate of glacial erosion, meaning the sediment they discharge is important to the process of sediment transport into a fjord system formed by a retreating tidewater glacier (Meigs et. al 2006), especially under rising sea level conditions. The tidewater glacier at Jorge Montt is retreating 0.62 $kmyr^{-1}$ (Aniya et al. 1997). The spatial distribution determined along the length of the fjord at Jorge Montt Glacier was the first step in determining the extent of sediment transport due to a retreating glacier in one region of the Chilean fjords.

The calibration curve was calculated from samples collected from the surface at sixteen stations within the fjord at Jorge Montt (Fig. 5). Niskin bottles were not available to collect samples throughout the water column as per standard procedure. In addition, the OBS was not available to simulate field conditions in the lab. Despite this, a significant linear relationship was found between the measured transmissivity and the mass per unit volume of the surface water measured (R=0.8979). This degree of significance is decent considering the potential for error in relying solely on surface water samples in an estuarine environment. Short term conditions can be present within the surface waters that can alter surface sediment measurements. Waves influence the upper regions of the water column and can be manipulated by the wind. Since the fetch along Jorge Montt is quite long, the effect of wind on surface currents is significant. Residual currents can create flow convergences in which sediment concentrations can become higher than expected (Kim & Voulgaris). Higher values within a narrow range can dramatically affect the slope of the line calculated, and the values of sediment concentration transcribed.

The transmissivity of the surface samples that were measured ranged from 1.5-8.4 volts. That is very narrow considering the maximum and average voltage values recorded in this study were 52.3 and 11.5 volts, respectively. It is not usually statistically viable to apply the trend of such a narrow range to the behavior of related data at a different scale. In addition, the small numbers of surface samples used in calculating the slope cause the conclusions drawn from the data to statistically only apply to a sample- set rather than the population we are applying it to. Despite these concerns, the coefficient of determination was acceptable within this environment and could be applied to the remainder of the water column.

The concentrations of sediment calculated were primarily applied at stations that measured the transmissivity along the fjord at Jorge Montt towards Baker Channel. Concentrations measured along the width of the fjord at Stations 5 and 10 suggested that they were not consistent along the width of the fjord (Fig. 7). Sediment concentrations along the western edge of the fjord were the highest, reaching 25-30 mgL^{-1} at Stations 4 and 9 (Fig. 1). Sediment concentrations at Stations 3 and 11 along the eastern edge of the fjord were the lowest, while Stations 5 and 10 along the thalweg had concentrations midway. Within large dispersal systems, and in the open ocean within a geostrophic gradient, it would be expected that Coriolis may influence the transport of particulate matter in the water column. However, the fjord at Jorge Montt is approximately 2.5 km wide, comparable to Signehamna Inlet which was only 1.5 km (Dowdeswell & Cromack 1991). Therefore, the Coriolis most likely does not deflect sediment transport to the left explaining the flow along the western edge in the fjord at Jorge Montt.

The increase of sediment throughout the entire water column closer to the ice face was another interesting trend observed within the fjord. Stations 9, 10, and 11 were nearly five kilometers from the ice face, removing them from direct input from the tidewater glacier. There may be some sediment input from the steep slopes of the fjord, but compared to the mass of sediment released from the tidewater glacier, bluff erosion would be minimal (Fig. 3). However, Stations 4, 5, and 6 are only 1.5 kilometers from the ice face. Surface sediment concentrations were lower than at Station 10, which was more removed from supra-glacial tidewater influence. The sediment concentration profiles at Stations 3, 4, and 5 are blended together from 100 meters depth to the seafloor at each vertical cast. This is caused by the spreading of sediment from en-glacial and/or sub-glacial flows spreading from approximately this depth into the marine environment (Fig. 8b, 9).

At an ice-marine interface, unlike a terrestrial glacier, flow trajectory is always pointed at a downward angle, increasing the rate of ice loss at the face (Anderson et. al 1983). The presence of morainal deposits has a significant impact on the stability of a receding glacier,

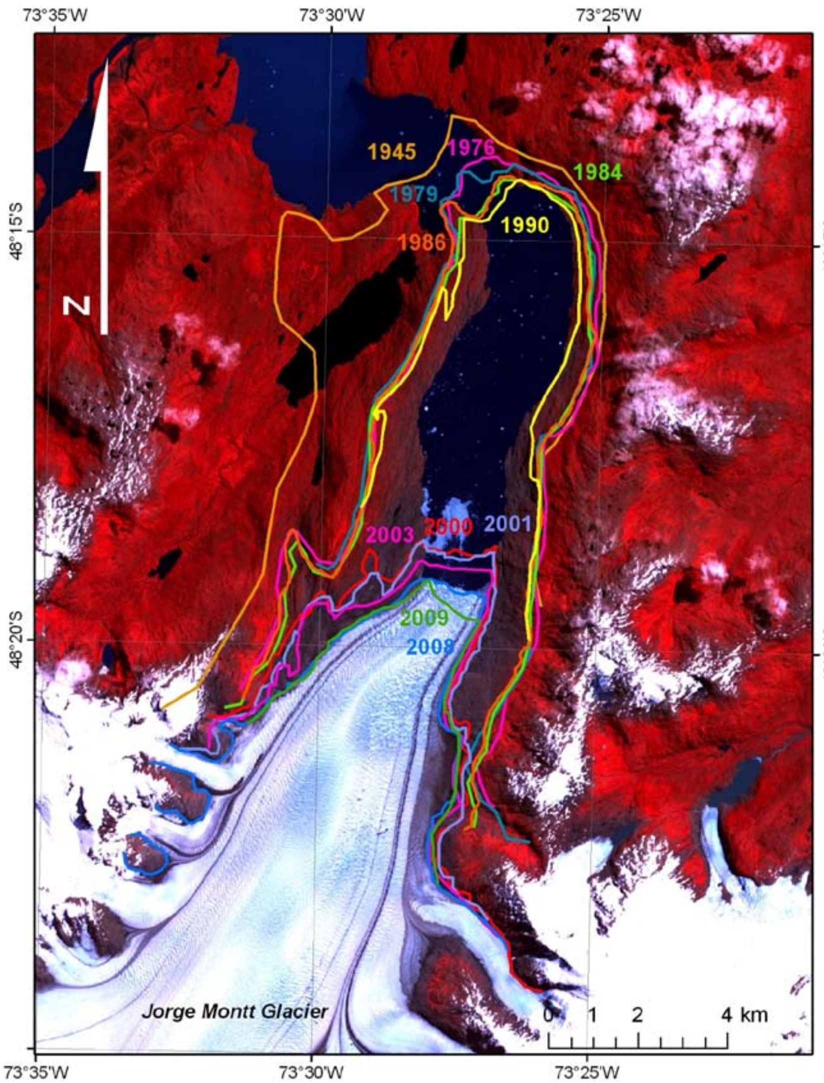

Figure 10: Map of Jorge Montt and fjord showing retreat of ice. Ice reached north of the extent of the map, over the shallowest morainal feature (Fig 8, 9) between Stations 18 and 20 during the late Holocene. Jorge Montt was grounded between Stations 24 and 25 in 1945, at the boundary between the Inner and Out Basin(Bernard Hallet, personal communication). Station 24 is directly over the small morainal feature formed in 1976, and Station 15 is just outside another deeper, yet more robust bathymetric feature the tidewater glacier grounded at until 1990. Jorge Montt is now considered a fast retreating tidewater glacier due to the fact that It took 7500 years to reatreat less than 8.5 km, and only 65 years to retreat nearly 11 km since 1945. (Centro de Cientifico, Valdivia, Chile)

slowing the rate of recession, if not temporarily halting it (Boyd et. al 2008, Koppes & Hallet 2006). Moraines can rise to significant heights towards the surface of a fjord. When a tidewater glacier is nestled up against such a feature, a large portion of the ice face is insulated from the warmer seawater, lowering the rate of freshwater melt. Jorge Montt is a fast retreating tidewater glacier (Fig. 10), there fore the presence of an arborescent hydraulic system allowing basal melt-water to flow out sub-glacially (Fig. 11, Fountain & Walder 1998), delivering sediment to

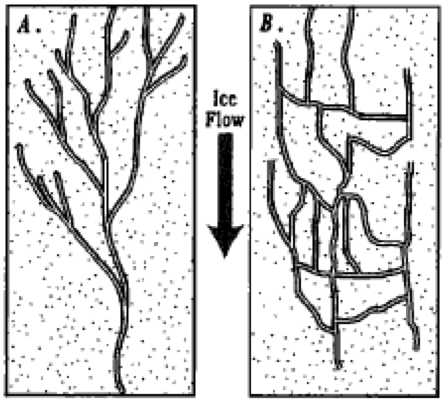

Figure 11: Depiction of arborescent (left) and nonarborescent (right) hydraulic systems, or fast and slow retreating systems. Jorge Montt is considered a fast retreating tidewater glacier. (Fountain & Walder 1998)

specific depths within the water column (Wright et al. 1989).

This occurred within the sediment dispersal system at Huanghe River before it underwent major work, redirecting flow into an irrigation network. The Jorge Montt tidewater glacial system and the Huanghe River on the Chinese Margin are very different environments. However, they both deliver relatively concentrated amounts of sediment along specific layers of their marine environments. Sediment can be delivered in the Huanghe River system via hyperpycnal and hypopycnal flows (Wright et al. 1989). Sediment at Jorge Montt is delivered along specific layers by means of en-glacial and sub-glacial flows.

These entrainments were observed to continue along the fjord towards Baker Channel, forming nepheloid layers that appear to disperse after leaving the influence of the tidewater glacier input (Fig. 8b). Along this western edge at both Stations 3 and 9, along the thalweg at Stations 5 and 10, and along the eastern edge at Stations 4 and 11, similar sediment concentration trends can be seen throughout the depth of the water column in the form of peaks (Fig. 6). Along the thalweg, at both 1.5 and 6.5 kilometers, Stations 5 and 10, respectively, similar peaks can be observed in both profiles. Sediment is probably being entrained within a layer close to the depth that the tidewater glacier delivers to it after allowing for buoyancy adjustment (Wright et al. 1989). The nepheloid layers appear to exist at different concentrations across the width of the fjord.

The density of the ambient fluid within the fjord is primarily affected by the resulting salinity in this estuarine system (Fig. 8c, 9a). Temperature input had very little impact (Fig. 8a). The structures of the density and salinity contours had similar structures, resembling a dually stratified system. However, this structure did not extent to the structure of sediment concentration in the water column. The sediment concentration contour plot did not resemble the density contour in the least (Fig 8b, 9a). It can be concluded that the high concentration of the sediment within a specific volume of water is the cause for creating a negatively buoyant packets of water (Wright et al. 1989). This can cause the sediment entrained water to remain within relatively deeper waters than fresh water would otherwise be found in. Sufficient amounts of sediment within a packet of water can even cause the packet of water to sink completely to a lower layer of water until neutral buoyancy is reached, or until it sinks to the sea floor (Wright et al. 1989). This can be seen at 2.5 kilometers distance from the tidewater glacier where a high concentration of sediment appears to have gained enough mass per unit volume of water to roll down the morainal feature Jorge Montt is current insulated behind and settle to the sea floor (Fig 3c).

Sediment concentration itself seems to be the primary factor controlling the distribution of sediment in the water column along the length of the fjord. It does this by controlling the vertical placement of sediment entrained water packets. A secondary factor controlling the

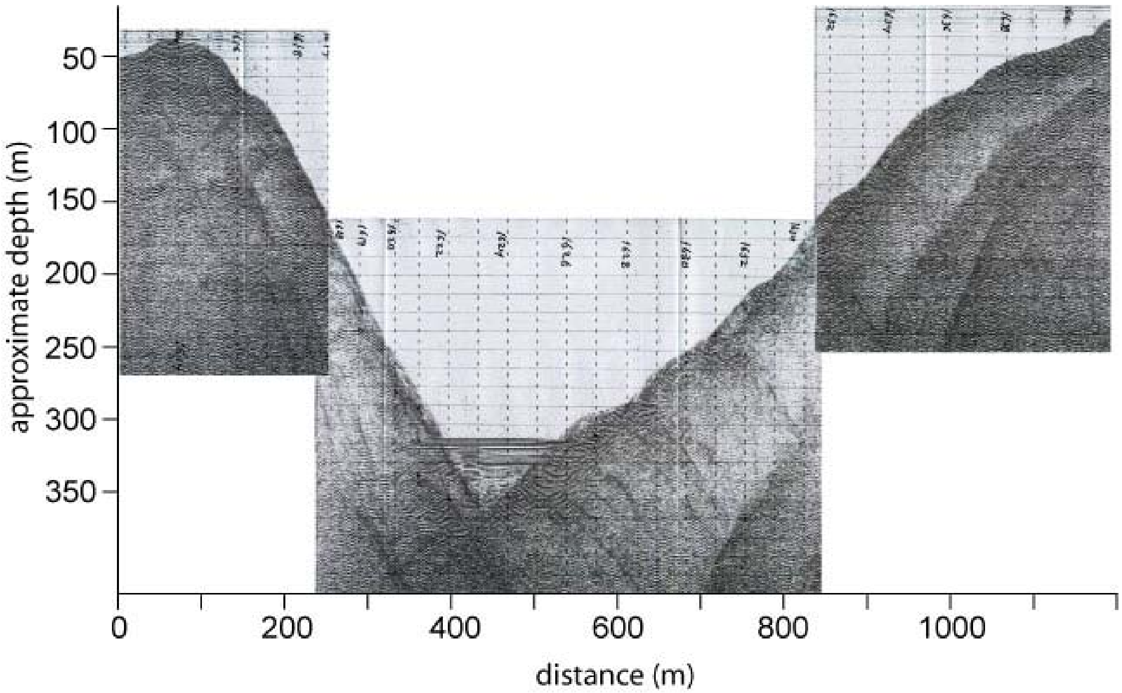

Figure 12: Seismic profile across width of Jorge Montt fjord. Sediment accumulation at this location was approximately 60 m deep.

distribution of sediment is the bathymetry of the seafloor. The extent of the sea floor topography appears to control the distribution along the horizontal axis of the fjord by physically blocking the movement of sediment to the mouth. It appears that once the sediment entrained water enters the lower recesses of the Inner Basin, it doesn't rise back up to exit the fjord. Sediment is actively infilling the V-shaped channel carved out by the advance of Jorge Montt. Sediment thicknesses are approximately 60 m (Fig. 12). Without calculating residence times, it appears from oxygen values measured within the deep waters of the Inner Basin that oxygen isn't being refreshed. This means that water movement is minimal at these depths, and that existing currents would not be sufficient to move any significant amount of sediment (Figure 9b).

Conclusions

Sediment concentration is the primary control on sediment distribution over the depth of the water column. Salinity is the primary control of the density of the water that sediment entrained water must equilibrate with. Sediment is accumulating at the bottom of the Inner Basin as well as escaping along the surface as suspended sediment.

Bathymetry within the fjord is the primary control over the sediment distribution along the length of the fjord. Sediment that had negative buoyancy sank to accumulate along the thalweg of the fjord. Tidal currents and waves were not energetic enough to resuspend sediment at depths of 380 m.

Jorge Montt is a fast tidewater glacier delivering high concentrations of sediment at particular depths. Sediment appeared to be delivered primarily along the basal boundary at the grounding line of the tidewater glacier.

References

Aniya M., S. Hiroaki, R. Naruse, P. Skyarca, and G. Casassa. (1997) Recent glacier variations in the Southern Patagonia icefield, South America. Artic Alpine Res. **29**:1-12.

Barcaza, G., and M. Aniya. (2009) Satellite-derived equilibrium lines in northern Patagonian Icefield, Chile, and their implications to glacier variations. Arctic Antarctic and Alpine. **41**:174-182.

Boyd, B.L., J.B. Anderson, J.S. Wellner, and R.A. Fernandez. (2008) The sedimentary record of glacial retreat, Marinelli Fjord, Patagnia: regional correlations and climate ties. Marine Geology. **255**:165-178.

Dowdeswell J.A., and M. Cromack. (1991) Behavior of a glacier-derived suspended sediment plume in a small arctic inlet. J. Geol. **99**:111-123.

Farmer, D.M., and J.D. Smith. (1979) Tidal interaction of stratified flow with a sill in Knight Inlet. Deep Sea Res. **27A**:239-254.

Fountain A.G., and J.S. Walder. (1998) Water flow through temperate glaciers. Rev. Geophys. **36**:299-328.

Gilbert, R.. (1982) Contemporary sedimentary environments on Baffin Island, N.W.T., Canada: glaciomarine processes in fjords of eastern Cumberland Peninsula. Artic and Alpine Res. **14**:1-12.

Hill, P.S., J.M. Fox, J.S. Crockett, K.J. Curran, C.T. Friedrichs, W.R. Geyers, T.G. Millgan, A.S. Ogston, P. Puig, M.E. Scully, P.A. Traykovski, and R.A. Wheatcroft. () Sediment delivery to the seabed on continental margins.

Hoskin, C.M., and D.C. Burrell. (1972) Sediment transport and accumulation in a fjord basin, Glacier Bay, Alaska. The J. of Geol. **80**:539-551.

Hromic T., S. Ishman, and N. Silva. (2006) Benthic forminiferal distribution in Chilean fjords: 47oS to 54oS. Marine Micropaleontology. **59**:115-134.

Hunter, L.E., R.D. Powell, and D.E. Lawson. (1996) Flux of debris transported by ice at three Alaskan tidewater glaciers. Journal of Glaciology. **42**:123-135.

Kim, Y.H., and G. Voulgaris. () Estimation of suspended sediment concentration in estuarine environments using acoustic backscatter from an ADCP.

-Koppes, M., R. Sylwester, A. Rivera, and B. Hallet. Variations in sediment yield over the advance and retreat of a calving glacier, Laguna San Rafael, North Patagonian Icefield. (2010) Quaternary Research. **73**:84-95.

Koppes, M., and B. Hallet. (2006) Erosion rates during rapid deglaciation in Icy Bay, Alaska. J. Geo. Res. **111**:F2, doi:10.1029/2005JF000349.

Masiokas, M.H., A. Rivera, L.E. Espizu, R. VIllalba, S. Delgado, and J.C. Aravena. (2009) Glacier fluctuations in extratropical South America during past 100 years. Palaeogeogr. Palaeoclimatol. Palaeoecol. **281**:242-268.

Meigs, A., W.C. Krugh, K. Davis, and G. Bank. (2006) Ultra-rapid landscape response and sediment yield following glacier retreat, Icy Bay, southern Alaska. Geomorphology. **78:**207-221.

Rignot, E., A. Rivera, G. Casassa. (2003) Contribution of the Patagonia Iceields of South America to sea level rise. Science. **302**:434-437.

Rivera, A., J.C. Aravena, and G. Casassa. (1997) Recent fluctuations of Glaciar Pio XI, Patagonia: discussion of a glacial surge hypothesis. Mountain Research and Development. **17**:309-322.

Swift, D.A., P.W. Nienow, N. Spedding, and T.B. Hoey. (2001) Geomorphic implications of subglacial drainage configuration: rates of basal sediment evacuation controlled by season drainage system evolution.

Glasser, N.F., S. Harrison, and K.N. Jansson. (2009) Topographic controls on glacier sediment-landform associates around the temperate North Patagonian Icefield.

Wright L.D., W.J. Wiseman Jr, Z.-S. Yang, B.D. Bornhold, G.H. Keller, D.B. Prior, and J.N. Suhayda. (1989) Processes of marine dispersal and deposition of suspended silts off the modern mouth of the Huange (Yellow River). Cont. Shelf Res. **10**:1-40.