

# A quantitative analysis of the carbon cycle and comparison of carbon remineralization rates in marine sediment to primary production in Glacier Bay, Alaska

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## Abstract

The carbon cycle and the burial of carbon as organic matter in marine sediments is a major process affecting the amount of carbon in the ocean-atmosphere system. To generalize an understanding of this process, carbon remineralization rates in marine sediments were compared to areas beneath surface waters with different levels of primary production. Sediment cores were taken with a Soutar box corer from seven sample stations around Glacier Bay, Alaska in March of 2008 and an oxygen microelectrode was used to determine the oxygen distribution in the sediment sample and the total sediment oxygen consumption rate. Using the Redfield ratio, which is a standard that relates carbon and oxygen concentrations, oxygen consumption rates were converted to carbon remineralization rates which were compared to primary productivity rates. Oxygen penetration depth into the sediments ranged from 3 – 10 mm while oxygen respiration rates in the sediments vary from 1.78 – 5.32  $\mu\text{m}/\text{m}^2/\text{d}$ . Carbon remineralization rates, which ranged from 1.39 – 4.15  $\mu\text{m}/\text{m}^2/\text{d}$ , were generally higher under greater areas of

primary production and had shallower oxygen penetration depths.

## Introduction

The carbon cycle is the term used to describe how carbon is moved among the atmosphere, land and oceans (Cai and Sayles 1996). Understanding the carbon cycle of Glacier Bay, Alaska is important to examine as it will allow us to understand the mechanics of this estuarine fjord. Carbon is a key ingredient of life and it is important to understand the processes that convert one form of carbon to another. Photosynthesis converts inorganic carbon to organic carbon while remineralization converts organic carbon to inorganic carbon (Cai and Sayles 1996). Since the last glacial period, atmospheric  $\text{CO}_2$  has increased which is due to the global anthropogenic input of  $\text{CO}_2$  (Archer and Devol 1992). The extent to which  $\text{CO}_2$  is removed from the atmosphere and subsequently stored in the ocean sediments is dependent upon (1) photosynthetic carbon fixation in the euphotic zone, (2) transfer of some fraction of this fixed carbon out of the euphotic zone as export production, and (3) long-term carbon burial in marine sediments (Devol and Hartnett 2001).

Primary production by phytoplankton, the base of the food web in marine ecosystems, regulates energy availability to higher trophic level species (Hooge 2002). Glacier Bay Alaska is known to exhibit phenomenally high primary productivity (Etherington et al. 2007). It is known that as phytoplankton in the ocean surface waters photosynthesize, they take up  $\text{CO}_2$  and convert it to organic carbon (Jahnke et al. 1990). When these organisms die or are eaten, they can sink out of the surface waters and although not all of the carbon within the dead organisms makes it to the seafloor, the amount that does sink to the seafloor either becomes buried in the sediments or is remineralized converting the organic carbon to inorganic carbon (Neibauer 2006).

High primary production in the surface waters will potentially result in the transport of an increased amount of organic matter to the seafloor when compared to areas of low primary production. As organic matter sinks through the water column, the majority of it is biologically oxidized (Bricaud and Morel 1986), resulting in decreasing carbon rate with depth and only a small portion being available for sediment burial (Cai and Sayles 1996).

There is very little information linking carbon remineralization rates to primary production in Glacier Bay, Alaska. We know and understand that phytoplankton spring blooms are a recurring phenomenon in Glacier Bay with phenomenally high primary productivity (Etherington 2007). To compare carbon remineralization rates in sediment beneath surface waters with different levels of primary production, sediment cores were taken with a Soutar box corer from seven sample stations within Glacier Bay, Alaska in March of 2008 (Figure 1, Table 1).

An oxygen microelectrode was used to determine the oxygen distribution in the sediment sample and the total sediment oxygen consumption rate. Using the Redfield ratio, which is a standard that relates carbon and oxygen concentrations, oxygen consumption rates

were converted to carbon remineralization rates which were compared to areas of different levels of primary productivity based on rankings calculated with the Spearman rank correlation coefficient from data gathered by Etherington et al. (2007). It is expected that relatively high rates of carbon remineralization in the sediment will correspond with shallow oxygen penetration depths indicative of greater primary production.

The research proposed here addresses three main questions: (1) Do sediment oxygen profiles and carbon remineralization rates vary in Glacier Bay, Alaska; (2) Is there a correlation between these profiles and primary production in the overlying water column; (3) Is there also a correlation between the carbon remineralization rates and the POC sedimentation rates?

Sediment cores were gathered aboard the *R/V Thomas G. Thompson* in March of 2008 to contribute to the understanding of the analysis and comparison of carbon remineralization rates in marine sediment areas below different levels of primary production. It is assumed that the sediments beneath regions and areas of relatively high primary production rates will exhibit higher carbon remineralization rates and correspondingly, shallower oxygen penetration depths.

## Methods

### Shipboard Collection

In order to determine sedimentary carbon remineralization rates and compare them among regions of differing levels of primary production, observations were made aboard the *R/V Thomas G. Thompson* from March 15, 2008 to March 26, 2008 in Glacier Bay, Alaska. Seven sampling stations (Table 1, Figure 1) were investigated in this research experiment with three of the seven stations being located within the Tarr Inlet, three in Geikie Inlet and one station in the East Arm. These seven sample stations were selected according to the expected availability of

Station Number	Latitude	Longitude	Depth (Meters)
11a	59°0'42.47	136°58'40.59	338
11	58°58'57.66	136°54'48.19	322
12	59° 2'53.16	137°0'21.06	260
16	58°53'77.11	136°0'45.49	290
22	58°40'14.51	136°21'30.20	155
22a	58°38'5.14	136°24'59.21	155
23	58°36'33.62	136°30'01.37	150

**Table 1:** Station locations and depths for sediment that were obtained from 15-26 March 2008 research. Also see Figure 1 for station locations.

sediment, patterns of chlorophyll *a* distribution and the various depths at each of the station sample sites.

During the cruise, the seafloor was mapped in search of sediments suitable for sampling. Upon arrival at each station, the presence of sediments was confirmed by C. Llaneta using the 3.5 kHz sub-bottom profiler which emitted a single pulse that was reflected off the seafloor and its underlying layers. When that pulse returned back to the surface, a profile was created that provided information on the sediment layers, thickness, composition, and the seafloor shape.

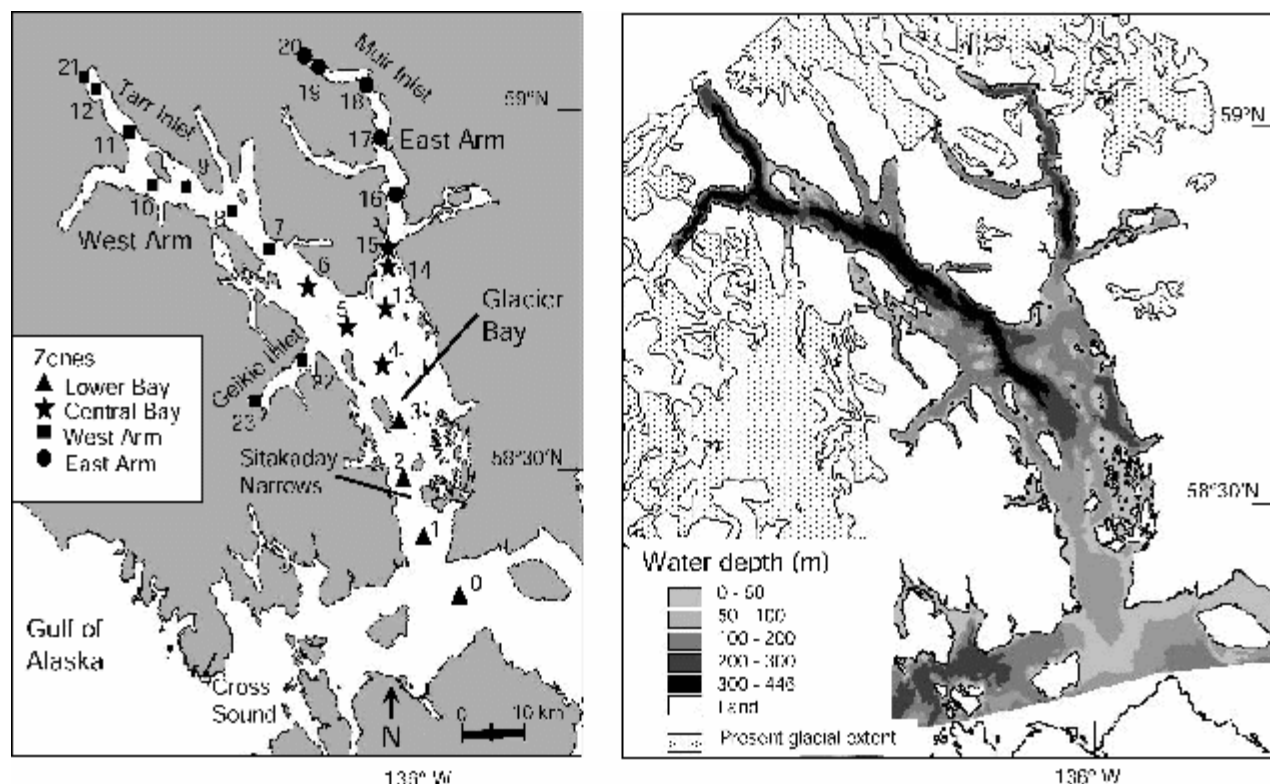
At each of the seven sampling stations, profiles of chlorophyll *a* fluorescence with depth were estimated using the CTD-mounted fluorometer. To measure phytoplankton fluorescence, which comes from the photo pigment chlorophyll *a* an in situ fluorometer was attached to the CTD and made a profile of the fluorescence and chlorophyll *a* of the water column (Bricaud and Morel 1986). Since the CTD-mounted fluorometer only measures relative fluorescence, the fluorescence was calibrated to actual chlorophyll *a* concentrations while primary production measurements were collected from Etherington et al. (2007).

The coring method was used to physically extract the sediment from the bottom of Glacier Bay, Alaska at each of the seven sample stations. A Soutar box core was deployed at each of the seven stations to collect sediment

samples. This specific corer preserves the water and sediment interface while keeping the surface sediment intact and in its original state. Once the sediment Soutar box core was recovered, it was immediately and gently sub-sampled with PVC (polyvinyl chloride) core liner tubes (7.5 cm diameter, 20.0 cm length). In order to sub-sample the sediment in the Soutar box core, the overlying water above the sediment was siphoned out of the Soutar box until roughly ten inches of the water column remained. One to four replicate sub-samples from each box core were taken with the PVC core liner tubes in order to calculate and obtain an average carbon remineralization rate for the sediment samples at each of the seven stations. The CTD was utilized to collect bottom-water at all seven stations so that the bottom water could be added to the respective sub-samples, taking extra care to avoid disturbing the top layer of sediment.

## Laboratory Measurements

After each core was sub-sampled, the sub-sampled cores were immediately taken to the chemistry lab on the *R/V Thomas G. Thompson* where a Diamond General 760/761 polarographic oxygen-needle microelectrode was used to determine the dissolved oxygen profile for each the sub-sampled sediment cores. The profiles for all sediment samples were recorded immediately



**Figure 1:** Map of Glacier Bay, Alaska, USA and surrounding waters with the USGS oceanographic stations surveyed in this study. View of Glacier Bay bathymetry and location of present glacial extent. Gray and black shadings represent deeper portions of the Bay, while light gray shading represents shallower depths. Map was adapted from Etherington et al. (2007).

upon retrieval of transporting the core out of its natural environment to minimize changes in the atmospheric oxygen supply. The oxygen microelectrode was inserted into the sub-sampled sediment cores from above with the assistance of a micromanipulator that was attached to a ring stand (Revsbech et al 2001). An Ag/AgCl electrode was used as a reference during the oxygen measurements and an electric potential between the silver reference electrode and the glass-insulated platinum electrode was produced using a small battery black box connected to the electrodes. The electrodes were calibrated during the weeks prior to boarding the ship. In order for the two electrodes to come into electrical equilibrium, oxygen was reduced at the platinum cathode and silver was oxidized at the reference anode. This movement of electrons produced a current, which was measured with a

microvolt ammeter. An average current reading from the overlying water above the sediment sample was taken. After the defining the average water oxygen concentration, the microelectrode was lowered to the point where the tip of the microelectrode just touches the sediment surface. At this particular point, a significant deflection in the electrode current occurred and was used to confirm that the electrode was in fact at the surface of the sediment. The oxygen microelectrode was then lowered into the sub-sampled cores at 1.00 mm increments using the micromanipulator while volt ammeter readings were measured and recorded until the current readings for oxygen concentration measure zero for four of the 1.00 mm increments. This value was called 'zero' and was used to convert the current readings to oxygen concentrations by the following equation (Neibauer 2006):

## Calculations

$$[O_2] = C_{bw} \frac{C_S - Z_V}{C_W - Z_V}$$

where  $C_S$  is the current reading at each sediment interval,  $Z_V$  is ‘zero,’  $C_w$  is the current reading of the overlying water in the sub-core and  $C_{bw}$  is the oxygen concentration of the bottom water ( $\mu\text{mol kg}^{-1}$ ).

The depth-integrated oxygen consumption rate in sediments were calculated by linearly regressing the obtained oxygen concentration profile as a function of depth and calculating the diffusion gradient across the sediment water-interface. The diffusion gradient represents the total flux of  $O_2$  into the sediments, reflecting the total oxygen consumption within the sediments. Knowing the gradient of oxygen consumption in the sediments as well as the respective  $O_2$  diffusion coefficient allows for the calculation of the  $O_2$  consumption rate (Murray and Grundmanis 1980). Oxygen was then converted to carbon using the modified Redfield ratio of  $C_{106}:O_{138}$  (Hedges et al. 2002) to estimate the rate of carbon remineralization.

## Results

Primary production rates were unspecified based on data from Etherington et al. (2007) and ranked in order of area with the greatest amount of primary production to the area with the least amount of primary production using the Spearman rank correlation coefficient (Table 2). The station with the highest rank of primary production was at station 22 and the station with the lowest rank of primary production was at station 12. According to Etherington et al. (2007), the area with the greatest abundance of primary production was located in Tarr Inlet followed by Geikie Inlet and the East Arm.

All sub cores that were taken from all seven stations in Glacier Bay, Alaska (Figure 1, Table 1) exhibited relatively uniform profiles similar to the undisturbed profile of Sayles, F.L.

and Goudreau, J. (unpubl.; Figure 2) with the exception of 11a (Figure 3). The oxygen concentration profiles through the sediment were not sporadic and did not feature multiple subsurface variations that you would normally find with a burrow effect, which were thus not present in these samples with the exception of station 11a. Station 11a was more sporadic with multiple subsurface variations, including one apparent burrow effect (Figure 3). Oxygen penetration depths in the sub-sampled sediment cores ranged from 3 mm – 10 mm (Table 2). The shallowest oxygen penetration depth was at located station 22 (3 mm) which was in the Geikie, Inlet while the deepest oxygen penetration depth was at station 16 which was in the East Arm (10 mm). Bottom water oxygen concentration was measured by the CTD and was roughly the same at each station ranging from 4.38 – 4.48 mg/L.

The greatest rate of carbon remineralization,  $4.15 \mu\text{mol/m}^2/\text{d}$ , along with the shallowest oxygen penetration depth, 3 mm, was exhibited at station 22. The lowest rate of carbon remineralization,  $1.52 \mu\text{mol/m}^2/\text{d}$ , along with the deepest oxygen penetration depth, 9 mm, was exhibited at station 11. Rates of carbon remineralization for each station can be found on Table 2.

The greatest rate of oxygen respiration in Glacier Bay, Alaska was located in the East Arm followed by Geikie Inlet and Tarr Inlet. The fastest rate of oxygen respiration was  $5.32 \mu\text{mol/m}^2/\text{day}$ , while the slowest rate of oxygen respiration is  $1.78 \mu\text{mol/m}^2/\text{day}$  (Figure 3). It was calculated using a ‘back of the envelope calculation,’ that the area of Geikie Inlet has  $6.7 \times 10^9 \mu\text{mol}$  of  $O_2$  with the sediments in that area using up  $1.2 \times 10^5 \mu\text{mol}$  of  $O_2$  per day. Roughly calculated, it would take 152 years for the sediment to use up all oxygen in Geikie Inlet if the source of oxygen were to ever stop.

The visual analysis of the sediment cores did not reveal benthic organisms present in the sediments at any of the stations although the data provides evidence of bioturbation at station

Station and Core Number	O <sub>2</sub> Respiration Rate ( $\mu\text{mol}/\text{m}^2/\text{d}$ )	O <sub>2</sub> Penetration Depth (mm)	BWO (mg/L)	Depth (Meters)	CO <sub>2</sub> Remineralization ( $\mu\text{mol}/\text{m}^2/\text{d}$ )	Primary Production (Rank)
<b>11a-c1</b>	4.57	5	4.44	338	3.57	2
<b>11-c1</b>	3.15	5	4.46	322	2.46	9
<b>11-c2</b>	1.94	9	4.46	322	1.52	11
<b>12-c1</b>	2.50	9	4.43	260	1.95	10
<b>12-c2</b>	1.85	8	4.43	260	1.44	13
<b>16-c1</b>	4.68	9	4.48	290	3.65	8
<b>16-c2</b>	4.54	10	4.48	290	3.54	12
<b>22-c1</b>	5.32	3	4.38	155	4.15	1
<b>22-c2</b>	4.09	4	4.38	155	3.20	5
<b>22a-c1</b>	4.57	8	4.38	155	3.57	2
<b>22a-c2</b>	4.52	5	4.38	155	3.53	4
<b>23-c1</b>	3.75	7	4.38	155	2.93	6
<b>23-c2</b>	3.73	7	4.38	145	2.92	6

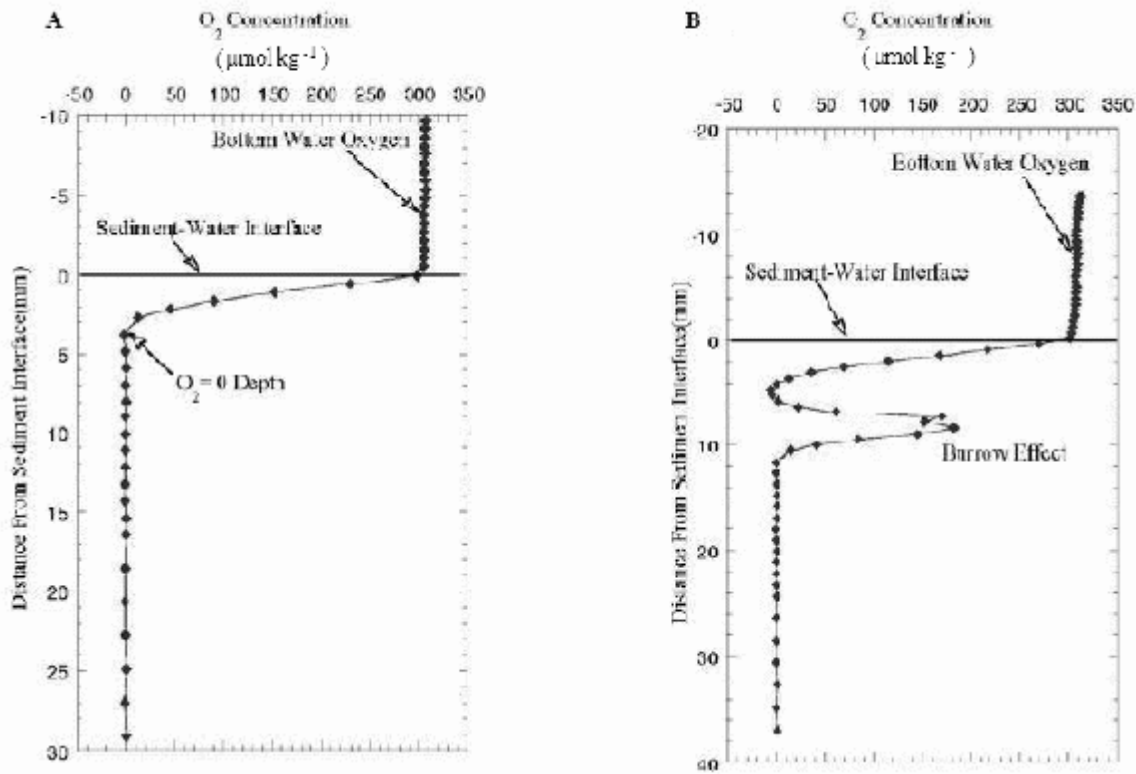
**Table 2:** Station and individual core numbers showing oxygen consumption, oxygen penetration depth, bottom water oxygen concentration, station depth, carbon remineralization rates and primary production rank.

11a. The surface-most layer of the sediments at the stations was smooth with texture, with a few areas of lumpiness. Percent organic carbon was calculated by A. Theiss and ranged from 0.09% at Station 11 in Tarr Inlet to a high of 0.81% at Station 23 in Geikie Inlet. Stations 22, 22A, and 23 in Geikie Inlet have higher values of percent organic carbon than Stations 11, 11a, 12, and 21 in Tarr Inlet.

## Discussion

Determining the timing, duration, and magnitude of the spring phytoplankton bloom is a central objective of biological oceanography. The onset of the spring bloom in Glacier Bay, Alaska is the result of favorable light conditions and stabilization of the water column that confines phytoplankton to nutrient-rich surface waters while

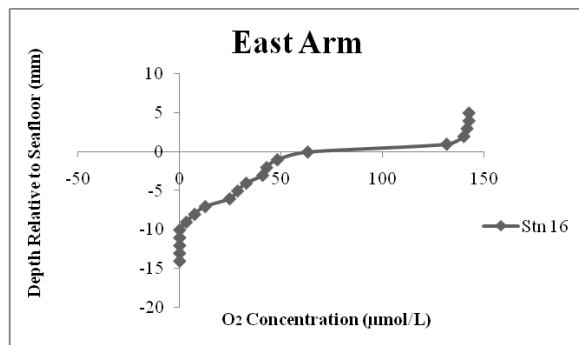
available light allows photosynthesis (Etherington 2007). In Glacier Bay we expect an increase in primary production during May, when the degree of stratification within the Bay increases dramatically. Instead, primary production concentrations substantially increased in March (Etherington 2007). This seasonal pattern of phytoplankton biomass contrasts with classical models of nutrient limited systems which finds the maximum spring peak followed by depressed levels in summer and a secondary moderate peak in fall and with observed patterns within many mid-latitude systems, fjords worldwide as well as Alaska estuaries. The observations made in Etherington et al. (2007) suggest that Glacier Bay is replenished with nutrients to moderately stratified surface waters, which could lead to a highly productive system that fuels an abundance of higher trophic levels.



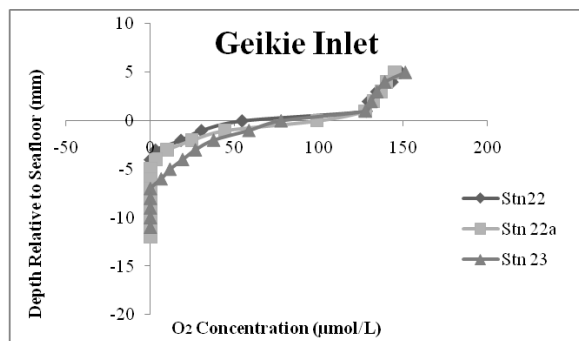
**Figure 2:** Shows the typical distribution of oxygen in (A) undisturbed sediments and (B) sediments disturbed by burrowing organisms. The effect of burrowing (bioturbation) is to increase the permeability of the upper sediment layers, thereby permitting deeper penetration of oxygen-rich waters through sediments. Figure was adapted from Sayles, F.L. and Goudreau, J. (unpublished).

Based on oxygen profiles, it appears that there is a steady decline in oxygen concentration with depth (Figure 3) although there are some variations in oxygen concentration which may be the result of varying grain sizes or chemical make-ups in the different layers. Further studies could be done in which exact grain-size analysis and more extensive examination of biota and chemical composition of sediments are performed. A better understanding of these areas would offer better constraints from which to draw comparisons among sediments underlying areas of high and low productivity. Based on the oxygen profiles of all the stations, it appears that there is no evidence of bioturbation with the exception of station 11a. Station 11a has subsurface variations and an apparent burrow

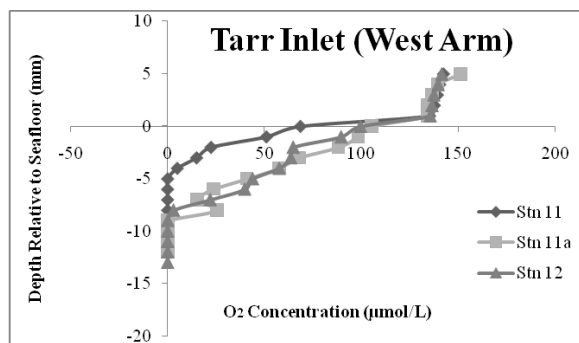
effect, both implying disturbed sediments. All other stations show a relatively steady decline of oxygen concentration with depth. It is expected that increased bioturbation (Eukaryote diversity following re-oxygen of the ocean) will lead to higher rates of remineralization. The effect of burrowing (bioturbation) is to increase the permeability of the upper sediment layers, thereby permitting deeper penetration of oxygen-rich waters through sediments. Less carbon accumulation in sediments offsets lower weathering rates, so atmospheric  $CO_2$  may be kept from reaching extremes. However, station 11a, which was the only station that had evidence of bioturbation did not have the highest carbon remineralization although it did not have one of the highest oxygen penetration depths in



(a)



(b)

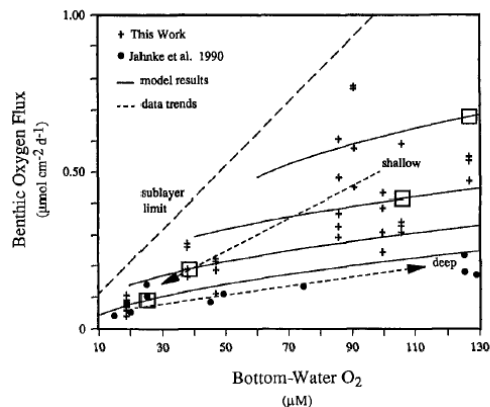


(c)

**Figure 3:** Distribution of oxygen concentration in undisturbed sediment in Glacier Bay, Alaska at the USGS oceanographic stations surveyed throughout this experiment.

the sediment at 5 mm (Table 2).

The data that was received from the seven USGS stations sampled from Glacier Bay, Alaska shows that shallower oxygen penetration depths and greater rates of carbon remineralization are associated with areas of higher primary production, which may reflect a greater



**Figure 4:** Calculated benthic oxygen flux plotted against bottom-water  $O_2$ . Data plotted is from Jahnke et al. (1990) and Archer and Devol (1992). Figure was adapted from Archer and Devol (1992).

deposition of organic matter to marine sediments. Supporting this, Gehlen et al. (1997) analyzed the effect of increasing amounts of organic carbon on  $O_2$  consumptions rates, which were converted to carbon remineralization rates for the purpose of this study. Gehlen et al.'s study station, located in the western Mediterranean, which is characterized by fine mud sediments and is 2300 m in depth, showed an increase in the rate of carbon remineralization from  $1.12 \times 10^{-6}$  to  $1.62 \times 10^{-6} \mu\text{mol cm}^{-2} \text{s}^{-1}$ , with increasing amounts of organic matter. A decrease in the depth of oxygen penetration from 1 to 5 cm was also observed. The rate of carbon remineralization exhibited in Glacier Bay, Alaska was higher than those in western Mediterranean when the values were converted from  $\mu\text{m}^2/\text{d}$  to  $\mu\text{m}^2/\text{s}$ . When compared to the results in Gehlen et al. (1997), the results of this study showed deeper oxygen penetration depths, which changed more than carbon remineralization rates relative to the primary production ranks. The greater oxygen penetration depth implies overall remineralization was greater than observed in the western Mediterranean by Gehlen et al. (1997).

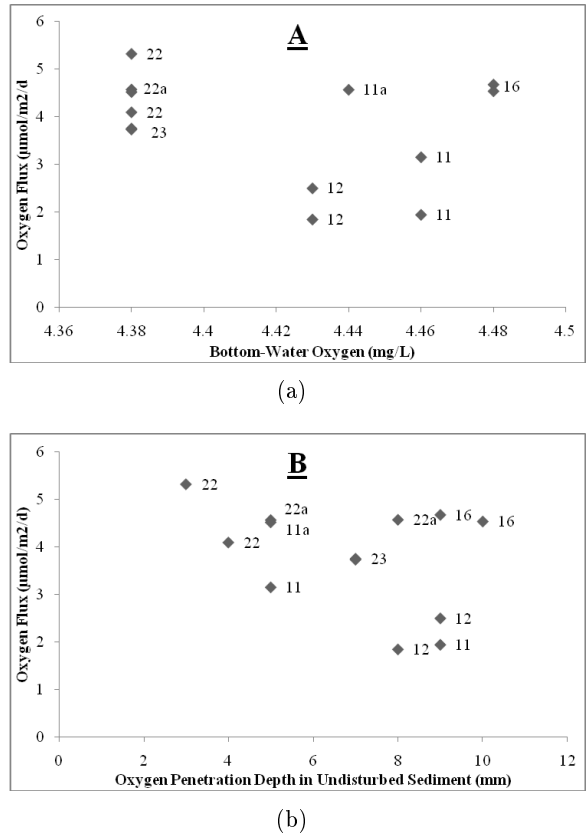
One factor contributing to the difference in rates the different area of the bay may have been



the phytoplankton composition and size. When compared to larger phytoplankton, smaller phytoplankton sinks out of the surface waters more slowly and may be susceptible to grazing, resulting in less material reaching the seafloor (Martin et al. 2000).

Diffusive oxygen fluxes into the sediment plotted against bottom water oxygen concentration from the Santa Catalina Basin in California and Puget Sound in Seattle, Washington (Figure 4) were adapted from Archer and Devol (2001). According to these results, as  $O_2$  decreases with depth, the diffusive oxygen flux decreases nearly proportionally. Diffusive oxygen fluxes into the sediment plotted against bottom water oxygen concentration from Glacier Bay, Alaska (Figure 5A) shows the same trend at stations 16, 11, 11a and 12 exhibited in California and Washington (Figure 4). These figures suggest that the oxygen flux into the sediment may be caused by the overlying water. The observed penetration depths of oxygen (Table 2, Figure 5B) into the sediments generally are deeper when there is a higher oxygen flux into the sediment. The depth of oxygen penetration into the sediments should vary with the overlying water concentration, when everything else remains constant. When more sediment (and therefore organic C) is bathed in oxygenated waters, the reaction flux should be greater, establishing a link between the overlying water concentration and diffusive flux (Archer and Devol 1992).

The rates of carbon remineralization did not generally increase with increasing water depth. A greater rate of carbon remineralization implies that a smaller percentage of delivered carbon is being stored in the sediments. The high rate of carbon remineralization exhibited at station 22 compared to the other station does not necessarily mean that lower amounts of carbon exist there. However, station 22 was ranked first in primary production meaning that this could instead translate to greater amounts of organic carbon in the surface water overlying station 22. This would mean that greater



**Figure 5:** Calculated oxygen fluxes plotted as a function of oxygen bottom water concentration (A) and calculated oxygen fluxes plotted as a function of oxygen penetration depths (mm) in undisturbed sediments (B) at the USGS oceanographic stations surveyed throughout this experiment.

amounts of carbon transferred to the seafloor, and possibly higher amounts of carbon in the sediments despite larger remineralization rates.

Higher levels of percent organic carbon seem to not correspond to deeper depths of oxygen penetration depths and higher levels of carbon remineralization. Percent organic carbon was calculated by A. Theiss and ranged from 0.09% at Station 11 in Tarr Inlet, which had an oxygen penetration depth of 9 mm, to a high of 0.81% at Station 23, which had a oxygen penetration depth of 7mm in Geikie Inlet (Table 2). Stations 22, 22A, and 23 in Geikie Inlet have higher values of percent organic carbon than Stations 11, 11a, 12, and 21 in Tarr Inlet.

The amount of oxygen in Glacier Bay, Alaska is extremely abundant. It was calculated using a ‘back of the envelope calculation,’ that the area of Geikie Inlet has  $6.7 \times 10^9$   $\mu\text{mol}$  of  $\text{O}_2$  with the sediments in that area using up  $1.2 \times 10^5$   $\mu\text{mol}$  of  $\text{O}_2$  per day. Roughly calculated, it would take 152 years for the sediment to use up all oxygen in Geikie Inlet if the source of oxygen were to ever stop. Compared to an area in Seattle Washington, it would only take Puget Sound roughly 1 to 3 years for the sediments to use up all the oxygen (Warner 2001).

## Conclusion

Glacier Bay, Alaska is a highly complex fjord. Although all the stations showed visual evidence of biological activity (worms, shell fragments, etc.), the oxygen profiles did not show evidence of disturbance with the exception of one station. Sediment at station 11a had the presence of worms and oxygen profiles that were disturbed by bioturbation. The comparison made in this study suggested that greater rates of primary production in the surface waters were associated with shallower oxygen penetration depths and greater rates of carbon remineralization in the sediments. Thus, sedimentary carbon remineralization in the area reflects regional variability in surface-water processes. Carbon remineralization rates were generally higher in Glacier Bay than other areas compared to in this manuscript. Sampling throughout a year long period or more, is necessary to learn about the entire carbon cycle of a productive, sub-arctic, estuarine-fjord like Glacier Bay, Alaska.

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